POLITECNICO DI MILANO
DEPARTMENT OF ARCHITECTURE AND URBAN STUDIES

Mapping Urban Climate and Air Quality for City Planning, from Multi-Scale Modeling to Real-Time Air Sensing

A dissertation submitted in partial fulfillment of the requirements for the degree of
Doctor of Philosophy in Territorial Design and Government

Doctoral dissertation of:
Aldo Treville

Supervisor:
Prof. Eugenio Morello
Co-supervisor:
Prof. Rex Britter

Tutor:
Prof. Angela Poletti

The Chair of the Doctoral Program:
Prof. Rossella Salerno

2014 – XXVI CYCLE

ABSTRACT

Urban planning is facing the environmental questions posed by climate change and air pollution in urbanized and increasingly crowded areas in both the developed and developing world: how can cities alleviate their responsibility and address proper measures? While current studies are exploring mitigation and particularly adaptation solutions to be applied to target locations, data and urban models are mostly available at the regional/city level, with little information available at the local/neighborhood level, and the “people's level”.

However, new available sensing technologies are pushing a paradigm shift: from traditional top-down climate/environmental modeling and scarce governmental monitoring to innovative diffused sensor networks and participatory sensing scenarios. The opportunities for spatial and environmental planning are vast: mapping at a local scale and at a fine-grained resolution can enhance UHI and pollution concentration studies, and allow hotspots spatial and temporal variation studies. In addition, real-time information supports the creation of an urban smart information platform for interdisciplinary communication and collaboration, ultimately used by planners and decision makers, for planning more sentient, resilient, and responsive cities.

The research aims to investigate the potential of mapping urban climate and air quality with the help of air sensing; mapping by air sensing can be a way of transferring the climatic and environmental knowledge into planning languages, bridging the gap between urban climatology, meteorology, air studies, city planning and urban design.

Limits of air sensing, in its technology and cost, are the biggest barriers for current planning processes. Therefore, exploring air sensing opportunity, obstacles and strategies to overcome them, and providing recommendations for its integration into urban planning, is the final scope of this research.

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INTRODUCTION

- INTRODUCTORY DEFINITIONS

In order to clarify the research framework of this work, some introductory definitions are presented, starting from the thesis title key words. In fact, while the concepts recalled by the first line title words are somehow consolidated in literature, a better clarification of the second line title keywords might be beneficial for introducing this research.

Mapping is here referred to as the visual language technique in urban studies research, used for its rich potential in investigation and exploration, observation and interpretation, analysis and communication of small scale and large-scale urban environments. Static or dynamic, bi- or multi-dimensional, the most relevant attribute in this context is the ability of transferring sectorial outcomes into planning language, and increasing the base knowledge for urban studies and for urban planning and policy decisions.

Urban Climate, which will be explored through mapping in this work, is referred to as the object of urban climatology, the sectorial branch of climatology concerned with the interaction between urban areas and the atmosphere. Temperature, humidity and Urban Heat Island formation and climate change effects, such as heatwaves, are the main studied factors (Oke, 1987), as they ultimately affect the urban environment and the quality of life of its citizens, and strategies to better govern them are an object of urban planning and design measures. Mapping urban climate is quite recent but promising for this purpose (Ren, Ng, and Katzschner, 2011).

Air Quality, which will also be explored through mapping in this work, as an established object of environmental studies, is referred as the state of outdoor ambient air in urban environment. Because the concentration of air pollutants has associated human health risk, mapping air quality is the knowledge base for urban planning and design for a more conscious urban government and chosen pattern of urban development. Mapping air quality goes through modeling and sensing air pollutant concentration and dispersion in urban areas (Britter and Hanna, 2003b).

City Planning is the research framework of this work and planners are the final target audience for the research contribution. While in planning literature some authors distinguish city planning from urban planning (Gleye, 2014), emphasizing its design-oriented planning, rather than its policy planning, the meaning here is wide. Both the physical space and the socio-economic space are considered the recipient of city planning, and its role in shaping the city is meant as both governing the existing and managing the predicted development. Mapping urban climate and air quality is therefore a base knowledge that city planning can use to implement strategies across both the physical space and the socioeconomic space. In fact, they are both involved in city functions and urban activities that affect the outdoor ambient air (urban cover and land use, urban fabric and materials, urban morphology and density, urban service and function), and in (the new) urban science, streams of computational social science and urban metabolism are object of the complex dynamics of cities (Batty, 2013).

Multi-Scale is referred to here as both the temporal scale and the different urban spatial scales of the urban environment, from the city scale to the local scale. Exploring the proper temporal and spatial scale for mapping urban climate and air quality is a specific research goal, as there is a complex relationship between the air phenomena, the urban environment and its citizens living in outdoor spaces. In particular, for the purpose of this research, the spatial "local" scale is the one that best fits the urban planning role and responsibility in urban climate and air pollutant concentration, and the proper scale for short and medium-term interventions manageable at the local scale. However, the "local" scale, as intended here, does not exactly correspond to any of the traditional levels of climatology or environmental science, and is a scale in between the "canopy" and the "canyon" level, between the "city" and the "street" scale. This is due to the fact that while those levels are defined for describing physical phenomena, the focus of this work is on their effect on the urban environment, and on the people living within it. Therefore, the scale considered here can be defined as the "people's scale", the scale describing the "outdoor air of a walking pedestrian" (which can be related to 10^1-10^2 meters, at a height of up to 2 meters from the ground), in some cases recalled as the "neighborhood scale". The temporal scale is directly connected to the spatial scale, in relation to the heat and the pollutant permanence in the urban atmosphere (from hours to days) and to their harmful effect on human health (from 1 to 24 hours). Urban planning can intervene at this scale, by mapping urban climate and air quality and implementing local measures where needed, ultimately improving citizens' comfort, well-being and health.

A more detailed discussion of the temporal and the spatial scale considered is explored in this work, since it also requires deeper considerations on the proper (temporal and spatial) "resolution" to describe air phenomena within the considered scale.

Modeling is referred here as an antithesis to "sensing", recalling the use of mathematical predictive tools instead of direct observations (for mapping urban climate and air quality in this context). However, urban modeling is always somehow based on, and integrated with, urban sensing and measurements, and as "an experimental design based on theory" (Batty, 1976, pp. V–XXI,1–16) aims to search for a relevant understanding of urban structure and phenomena and to help planners to predict, describe and invent the urban future. While city modeling was prosperous during the last few decades since the late 1950s, and urban technological innovation, via ICTs, brought to the "city of bits", the "virtual cities" (Dodge, Doyle, Hudson-Smith, and Fleetwood, 1998), the "computable city" (Batty, 1997), on the other hand, the recent paradigm shift brought to emerging fields in urban studies, developing concepts such as the "ubiquitous city" (Jang and Suh, 2010; H. Lee et al., 2008), the "geocomputation revolution" making cities grow and evolve (Diappi, 2004), and ultimately "city sensing" (Borga, 2014). In the field of urban climate and air quality, several models are available, with challenges in scale and representativeness (C. S. B. Grimmond et al., 2010; Kumar, Ketzel, Vardoulakis, Pirjola, and Britter, 2011).

Real-Time connects to the technology-based concepts already recalled by modeling/sensing, with an emphasis on the time scale and prompt-actions. This aspect is relevant for urban climate and air quality studies, since promptness in city response might be needed in certain situations, such as heatwave alert systems or hazardous air quality warnings. Recent concepts are emerging In this research framework, such as the "real-time city" (Calabrese, Colonna, Lovisolo, Parata, and Ratti, 2011; Kitchin, 2014), and the "responsive city" (Goldsmith and Crawford, 2014).

(Air) Sensing, as already mentioned in contrast to modeling, is here referred to as the direct observation of urban phenomena (urban climate and air quality in this context) using "sensors" in traditional stationary governmental sensing networks (Muller and Chapman, 2013), and more recently, in local networks or mobile sensing using portable devices. In fact pervasive sensing has recently become feasible and affordable, thanks to the diffusion of low-cost sensors (Snyder et al., 2013), and the knowledge about our environment can be enriched thanks to the availability of diffused fine-grained and real-time information layers. Considering ICT development and its related effect on urban studies, the focus here is on the consequences of the availability of sensors becoming smaller, more accurate and networked, leading to the idea of a "smart dust". In fact, considering the reality of the idea of an "electronic skin" on our cities and that "Everyware" vision (Greenfield, 2006) became reality, from "ubiquitous computing" the research attention in the last decade shifted to "pervasive sensing". The aforementioned paradigm shift from modeling to sensing largely discussed in this work, as a result of the diffusion of ICT and sensing technologies and enhanced the smart city concept as sentient, or "senseable" city (Martino et al., 2010; "MIT SENSEable City Lab," n.d.).

However, one of the essential components of sensing in contrast to modeling, as addressed in this work, is the opportunity of citizens' participation and enhancement of bottom-up awareness. City sensing, in fact, is here intended in its inclusion of "crowdsourcing sensing", where data is coming from people providing information with their direct participation, also called "participatory sensing" (Burke, Estrin, and Hansen, 2006). In the field of urban climate and air quality, in particular the people's scale is the most relevant for urban outdoor ambient air sensing, and the diffusion of low-sensors for public and personal exposure ("wearables") is increasing opportunities for involving "citizen science". Community and web-based self-organized sensing initiatives are therefore fruitful bottom-up approaches creating opportunities for people-centric sensing, both increasing awareness and increasing data for local mapping (from "everyware" to "everyaware").

More details about the keywords here preliminary introduced can be found in chapters 1 and 2.

Cited references

Batty, M. (1976). *Urban modelling*. (L. Martin & L. March, Eds.) (p. 381). Cambridge, UK: Cambridge University Press.

Batty, M. (1997). The Computable City. *International Planning Studies*, *2*(2), 155–173.

Batty, M. (2013). *The New Science of Cities* (p. 520). The MIT press.

Borga, G. (2014). City Sensing. *Milano IT: Franco Angeli*.

Britter, R., & Hanna, S. R. (2003). Flow and dispersion in urban areas. *Annual Review of Fluid Mechanics*, *35*(1), 469–496.

Burke, J., Estrin, D., & Hansen, M. (2006). Participatory sensing. In *World Sensor Web Workshop, ACM Sensys 2006, October 31, 2006* (pp. 1–5). Boulder, Colorado, US.

Calabrese, F., Colonna, M., Lovisolo, P., Parata, D., & Ratti, C. (2011). Real-time urban monitoring using cell phones: A case study in Rome. *Intelligent Transportation Systems, IEEE Transactions on*, *12*(1), 141–151.

Diappi, L. (2004). *Evolving Cities: Geocomputation In Territorial Planning*. Burlington: Ashgate.

Dodge, M., Doyle, S., Hudson-Smith, A., & Fleetwood, S. (1998). Towards the virtual city: VR & internet GIS for urban planning.

Gleye, P. H. (2014). City Planning versus Urban Planning: Resolving a Profession's Bifurcated Heritage. *Journal of Planning Literature*, 1–15.

Goldsmith, S., & Crawford, S. (2014). *The Responsive City: Engaging Communities Through Data-Smart Governance*. John Wiley & Sons.

Greenfield, A. (2006). *Everyware: The dawning age of ubiquitous computing*. New Riders.

Grimmond, C. S. B., Blackett, M., Best, M. J., Barlow, J., Baik, J. J., Belcher, S. E., … Zhang, N. (2010). The international urban energy balance models comparison project: First results from phase 1. *Journal of Applied Meteorology and Climatology*, *49*(6), 1268–1292.

Jang, M., & Suh, S.-T. (2010). U-city: new trends of urban planning in Korea based on pervasive and ubiquitous geotechnology and geoinformation. In *Computational Science and Its Applications–ICCSA 2010* (pp. 262–270). Springer.

Kitchin, R. (2014). The Real-Time City? Big Data and Smart Urbanism. *GeoJournal*, *79*(1), 1–14.

Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., & Britter, R. (2011). Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment—a review. *Journal of Aerosol Science*, *42*(9), 580–603.

Lee, H., Han, H., Leem, T., Yigitcanlar, T., Ho Lee, S., Hoon Han, J., & Taik Leem, Y. (2008). Towards ubiquitous city: concept, planning, and experiences in the Republic of Korea. *Knowledge-Based Urban Development: Planning and Applications in the Information Era*, 148–170.

Martino, M., Britter, R., Outram, C., Zacharias, C., Biderman, A., & Ratti, C. (2010). Senseable City. *Digital Urban Modelling and Simulation*.

MIT SENSEable City Lab. (n.d.). Retrieved December 30, 2014, from http://senseable.mit.edu/

Muller, C., & Chapman, L. (2013). Sensors and the city: a review of urban meteorological networks. *International Journal of Climatology, 33*(7), 1585–1600.

Oke, T. R. (1987). *Boundary layer climates* (Second., Vol. Routledge, p. 435). London and New York: Routledge.

Ren, C., Ng, E. Y., & Katzschner, L. (2011). Urban climatic map studies: a review. *International Journal of Climatology*, *31*(15), 2213–2233.

Snyder, E. G., Watkins, T. H., Solomon, P. a, Thoma, E. D., Williams, R. W., Hagler, G. S. W., … Preuss, P. W. (2013). The changing paradigm of air pollution monitoring. *Environmental Science & Technology*, *47*(20), 11369–77.

- MISSION

The overall objective is improving knowledge on urban climate and air quality at the local and neighborhood level, so that cities can address policies, plans and measures to face current challenges at the proper level. Mapping is necessary to identify hotspots, to study the spatial and temporal variation of heat and pollutant concentration within cities, to assess vulnerability, and to study morphology and urban structure responsibility on urban climate and air quality (i.e. emissions, lack of green areas).

Going beyond the current model based on scarce high-scale governmental monitoring stations, this research aims to contribute to the current discourse regarding the use of air sensing devices, in order to collect data at a fine-grained resolution and local scale, the "people's scale". In fact, new available sensing technologies are pushing a paradigm shift: from traditional top-down climate/environmental modeling to innovative diffused sensor networks and participatory sensing scenarios. The mission of this work is to explore the opportunities of sensing for urban planning: mapping at a local scale and at a fine-grained resolution can enhance UHI and pollution concentration studies and real-time information supports the creation of an urban smart information platform for interdisciplinary communication and collaboration, ultimately used by planners and decision makers, for planning more sentient, resilient, and responsive cities.

The research therefore aims to investigate the potential of mapping urban climate and air quality with the help of air sensing; mapping by air sensing can be a way of transferring the climatic and environmental knowledge into planning languages, bridging the gap between urban climatology, meteorology, air studies, city planning and urban design.

Limits of air sensing, in its technology and cost, are the biggest barriers for current planning processes. Therefore, exploring air sensing opportunity, obstacles and strategies to overcome them, and providing recommendations for its integration into urban planning, is the final scope of this research.

- RESEARCH GOAL AND METHODOLOGY

The introductory definitions mentioned urban climate and air quality (UC+AQ) problems are of interest to planners, and the main arguments arising from the evidence of the need for improving the mapping approach, profiting from sensing opportunities.

How is urban climate and air quality currently being mapped? Exploring both "mapping by modeling" and "mapping by sensing" is a preliminary step in order to compare the two approaches. Since it is necessary to map at the people scale, a research goal is exploring how to map UC+AQ in cities at a "local" scale with high resolution.

Can this new paradigm shift, from modeling to sensing, help improve mapping and ultimately UC+AQ in cities? From the short description of the mapping

process for urban climate and air pollution, it is evident how modeling is traditionally the essential component, whereas sensing is a recent approach that is growing thanks to the cost reduction and performance enhancement of sensor technology.
However, there are several unsolved research challenges for city sensing in mapping urban climate and air quality, among which some can be identified as the following:

- How can it improve scale and resolution, which seems to be fundamental for exposure studies at the people's level? What are its accuracy, location precision, cost efficiency and real-time fidelity for this purpose?
- Since low-cost sensing technology is recent but pervasive, what is the trade-off between cost and technology, affordability and data reliability?
- What are the challenges and limits of sensing for UC+AQ, in terms of transparency, communication, and privacy ethics?
- what is the impact on urban planning and design, how can they benefit from city sensing? Is it possible to enhance public participation and expand the conversation with citizens and communities?

The goal of this work is to contribute to these research challenges, see ch. 3 for a more detailed argumentation about the research questions.

The methodology pursued in this work included a two-step process. Preliminary steps were, the study of existing literature about urban climate and UHI, air quality and pollution, and about the role of urban planning. In addition, a literature review of modeling and sensing used for mapping was conducted, aimed at identifying the most noteworthy existing studies and projects worldwide. Further steps relate to the objective of studying air mapping in a practical case (Milan); firstly modeling was studied and developed, and secondly the need for sensing emerged from the work, and a final step was consequently planned. An existing case study was selected (Cambridge, MIT), and additional fieldwork was designed, in order to explore the potential and limits of air sensing, both stationary and mobile. After data analysis, the potential and limits of air sensing were therefore explored (see ch. 3).

With a two-step research strategy. In order to explore the current status of city sensing, the first step includes studying strengths and challenges in worldwide city sensing cases. In the second step, a specific project is designed, in order to experiment in the field with its limits and explore the opportunity of this innovative approach for urban planning to study urban climate and air quality at the people scale. In fact, considering the limits of stationary sensing network in reaching a proper resolution for air quality and urban climate mapping, a mobile sensing campaign was needed.
Therefore, a field experiment was designed and executed, by testing and using sensors and exploring sensing opportunity in mapping air quality and urban climate parameters.

- Research Background and Related Work

This research profits form the academic studies and work conducted during the PhD program.

During my early collaboration with ENEA (Italian National Agency for New Technologies, Energy and Sustainable Development) about environmental assessment models based on LCA, I started developing my research about solutions and tools for urban planning aimed at improving environment and health in cities. Environmental impact and impact on public health were assessed using indicators and a database of unit values from validated studies. During my GIS course under the PhD program (Geographical Information Systems and Territorial Government) and the collaboration with regional EPA and with the regional Government Authority (Region Emilia Romagna, Northern Italy) about SEA, EIA and HIA (Strategic Environmental Assessment, Environmental Impact Assessment and Health Impact Assessment), I explored urban models and the complexity of inter-relationships between factors involved in understanding, predicting, controlling and monitoring cities' health. This complexity, on the other hand, seemed not to be addressed in the current approach of designing urban measures, for example in the filed of mitigation and adaptation to Climate Change. During my participation in the European project LoCaRe (Low Carbon Regions), I became aware that despite scientific evidence international, national and local urban policies are commonly being addressed without sufficient understanding of urban phenomena and rarely acknowledge their contribution to climate and health. I visited and investigated best practices and case studies (i.e. Sondeborg masterplan), and I took part in several notable environmental and climate conferences (UPE10 Sydney, ICLEI Resilient Cities 2012 Bonn, Tyndall Centre conference 2013 Cardiff), looking for urban models for studying the inter-relationships between climate effects and the built environment (urban morphology, land use, energy and mobility) for designing low-carbon and resilient cities.

But it was during my collaboration with the SENSE project (Smart building ENvelope for Sustainable urban Environment, PRIN'09), within the framework of UHI (Urban Heath Island), that I based my research interest on two key points. Firstly, the need for simulation, modeling, visualization, assessment, communicating, and managing urban data. I realized that the huge amount of data coming from and stored in multiple devices and sources (official environmental data from EPA, volunteer associations data, public infrastructure data, single citizens data as single users with hand-held devices) is hardly managed in a useful and effective way. This leads to the second key point: the need for integrating urban sensing to urban modeling, where sensors are seen as technology devices and people, providing real-time data. Heatwaves, for instance, are climate change phenomena that affect urban microclimate (UHI) and citizens health (discomfort) but the lack validated models, and of local data (i.e. temperature at the street level), makes it difficult to understand, preventing decision makers from addressing public and private efforts (on urban form, energy and anthropogenic heat waste, green areas, etc.). I explored surface

urban energy balance models for a case study in Milan, but the need for real-time data, for sensing data, led me to a further step of my research.
Senseable City Lab (SCL) at MIT, is one of the most advanced research groups addressing urban sensing and the use of big data for building sustainable and resilient cities, for smart cities: an interface between people, technologies and the urban structure. My visiting period at SCL lent a tremendous boost to my research, as I heard and discussed new ideas regarding platforms for the collection, processing, integration and re-distribution of real-time data in the urban context. Also, the supervision with Prof. Carlo Ratti and Prof. Rex Britter helped me in advancing my research, while being able to test sensors and to work on case studies. Two projects in particular contributed the most to my research, as I extensively assisted in their design, implementation and analysis process: an air sensing project aimed at studying local air pollution, and their impact on students health, inside the MIT campus (Clairity+Hotspots) and a sewage sensing project aimed at providing public health information through the collection of biomarkers (Underworld).
A critical approach and review of the projects, and their potential extension and diffusion, led my research to some considerations and suggestions for future work, in particular the proposal for "planning Milan as a responsive city". Based on the work done and on a personal interpretation of the projects, the thesis summarizes the main arguments about urban sensing for cities health from a new perspective.

Publications and work related to the PhD research

Book (research report):

- **A. Treville**, M. P. Dosi (2012). *New Climate Analysis - Regions moving towards a low carbon economy*. Emilia Romagna Region, Bologna, ISBN 978-88-907370-4-6. (also available at: www.locareproject.eu)

Articles in Book:

- **A. Treville**, L. Vandini, R. Cegna (2014), *The Visual Language Technique in Urban Studies Research: Investigation, Interpretation and Communication of City Complexity* (cap. 14). In: Cocchiarella (The Visual Language of Technique). Springer, ISBN:978-3-319-05340-0C.

Refereed Articles in Journals:

- Mattioli, **A. Treville** (2013). *Rural farmsteads as safeguards and network nodes of relational networks: environmental protection and territorial care practices in suburban areas* (in Italian); PLANUM (ISSN:1723-0993), (pp. 1-8), 27.
- **A. Treville** (2012). *Effectiveness of Strategic Environmental Assessment of urban and regional planning in Northern Italy: limitation of risks and impact of land consumption* PLANUM (ISSN:1723-0993), (pp. 1- 7), 25.
- A. Di Stefano A., R. Mazzoni R., **A. Treville**, R. Zavattini (2010). *The procedure of assessment the effects of certain plans and programmes on the environment* (in Italian) VA - Environmental Assessment (ISSN:1826-2201), (pp. 53- 58), 17.

Conference Proceedings:

- **A. Treville** (2013). *Heatwaves and UHI: Modeling the inter-relationships between climate effects and the built environment for designing resilient cities* (pp. 1-5). In: Musco F., Zanchini E. (Editors) (2013), Proceedings of climate changes cities Conference on climate adaptation in urban areas, Venice, 23-24 May 2013, Corila, Venice. ISBN 9788889405253.
- A. Buoli, C. Mattioli, G. Minucci, M. Romanato, **A. Treville**, B. Vendemmia (2012). *Living the crisis in the territories between Milan and its belt. Scarcity of resources and adaptation practices in Milan* (in Italian) (pp. 87-101). In: Bellomo M. et al. (Editors) (2012), Proceedings

of International Seminar Days “Inhabiting the new/inhabiting again in times of crisis” 2a Edition, Naples, 12-13 December 2012, Clean, Naples. ISBN: 978-88-8497-236-1.

- **A. Treville** (2011). *Proposal of an impact prediction tool for the environmental assessment of projects and spatial planning, based on LCA*. European Cooperation in Science and Technology (COST), (pp. 708- 715). In: C.J. Koroneos, D.C. Rovas & A.Th. Dompros (eds.), ELCAS2011: Proceedings of the 2nd International Exergy, Life Cycle Assessment and Sustainability Workshop & Symposium. 19-21 June 2011, Nisyros Island, Greece, ISBN 978-960-243-679-0.
- **A. Treville** (2011). *LCA methodology as a support tool for decision makers in policy and planning for sustainable development. Case study for a Developing Country*. European Cooperation in Science and Technology (COST), (pp. 691- 698). In: C.J. Koroneos, D.C. Rovas & A.Th. Dompros (eds.), ELCAS2011: Proceedings of the 2nd International Exergy, Life Cycle Assessment and Sustainability Workshop & Symposium. Nisyros Island, 19-21 June 2011, Ziti Publications, Thessaloniki, Greece, ISBN 978-960-243-679-0.

Abstracts:

- **A. Treville**, M. P. Dosi (2012). *Low Carbon Planning and Resilient Cities/Regions: linking energy and sustainable resource management, resilience and prosperity in some European experiences* (pp 1). In: Aesop2012 E-Book of Abstracts, 26th Annual Congress of the Association of European Schools of Planning, 11-15 July 2012, Ankara, Turkey. ISBN: 9789754293067.
- **A. Treville** (2012). *Planning to achieve sustainability and resilience, planning to avoid impact, planning to adapt* (pp 1). In: Aesop2012 E-Book of Abstracts, 26th Annual Congress of the Association of European Schools of Planning, 11-15 July 2012, Ankara, Turkey. ISBN: 9789754293067.
- **A. Treville**, M. Dosi (2012). *Contribution of Low Carbon Economy to New Energy and Climate Future in Next European Cities* (pp. 6- 1). In: UPE10 Next City. Planning For a New Energy & Climate Future, 24-27 July 2012, Sydney, Australia. ISBN: 9781742102818.
- **A. Treville** (2012). *Linking territorial resilience and low carbon economy in European regions and cities* (pp 190-191). In Networked Regions and Cities in Times of Fragmentation: Developing Smart, Sustainable and Inclusive Places. 13-16 May 2012, Delft, NL. ISBN 978-1-8977221-41-4.

Other publications:

- **A. Treville**, T. Li, R. Britter, C. Ratti (2014). *Urban Hot-Spots: A Smart Reat-Time Sensor Network for Urban Climate Stress and Air Quality Mapping*; US- EPA Air Conference: 2014: A New Frontier Monitoring, Technology for Today's World, 9-10 June 2014, EPA's Research Triangle Park Campus, North Carolina (web publication at: https://sites.google.com/site/airsensors2014/final-workshop-materials, accessed 10-27-2014).
- **A. Treville** (2012). *Web-GIS for environmental assessment of Public Administrations: application for EIA and SEA in Northern Italian Regions* (in Italian); 13a Esri Italian Conference, 18-19 April 2012, Roma.
- **A. Treville**, G. Minucci (2012). *Low Carbon Planning as an opportunity to build a more resilient city* (pp 2-3). In: Resilient Cities 2012, 12-15 May 2012, Bonn, DE.
- A. Buoli, C. Mattioli, G. Minucci, M. Romanato, **A. Treville**, B. Vendemmia (2012). Living the crisis in the territories between Milan and its belt. Crisis, urban resilience, adaptation (in Italian) Proceedings of the Italian conference of the European Network for Social Policy Analysis (Espanet) 5a Edition, 20-22 September 2012, Rome.
- **A. Treville** (2012). *Monitoring soil consumption: strengths, weaknesses, and effectiveness of different monitoring approaches in italy*. Emilia-Romagna Region - Geological Seismic and soil Survey, Bologna: (pp. 121- 122). In: 7th EUREGEO - EUropean congress on REgional GEOscientific cartography and Information systems. 12-15 June 2012, Bologna.
- **A. Treville** (2011). *Strategic Environmental Assessment as a tool for limiting land consumption*. (pp. 1- 8). In: Special Conference on Strategic Environmental Assessment, IAIA SEA Prague. 21-23 September 2013, Prague.

- STRUCTURE OF THE THESIS

The thesis is structured in 6 sequential chapters.

The first chapter tackles with the problem definition of the research framework, emphasizing that urban climate and air quality are “urban” problems and urban planning has a big role. In fact, because the phenomena involved have a strong local urban component (i.e. street wideness or car emissions), urban planning can define local measures in order to limits its responsibility. In order to do so, the need of increasing knowledge is evidenced, and mapping at a proper scale and resolution is presented as a effective urban planning tool. Additionally, considering global efforts in the climate change discourse, such as low carbon planning and planning for urban resilience, the need for mapping urban climate and air quality at the local level is underlined, in its integration with the larger scale (i.e. climate action plans).

The second chapter tackles with “mapping” urban climate and air quality, exploring literature examples in theoretical studies and practical examples. Mapping is done by “modeling” and “sensing”, and this chapter emphasizes their differences. Because recent enhancement in sensor technology is shifting mapping from modeling to sensing, this chapter put an emphasis on the need for use and improving sensing in mapping urban climate and air quality.

The third chapter introduces the research goals, which aim to explore the opportunity and limits of sensing in urban climate and air quality mapping. A two-step research strategy is designed, and the methodology is described. In order to explore the current status of city sensing, the first step includes studying strengths and challenges in worldwide city sensing cases. In the second step, a specific project is designed, in order to experiment in the field with its limits and explore the opportunity of this innovative approach for urban planning to study urban climate and air quality at the people scale. In fact, considering the limits of a stationary sensing network in reaching a proper resolution for air quality and urban climate mapping, a mobile sensing campaign was needed. Therefore, a field experiment was designed and executed, by testing and using sensors and exploring sensing opportunities in mapping air quality and urban climate parameters.

The forth chapter therefore presents the main characteristics of the projects from the perspective of the research questions of this work, including collaborating and exploring a local sensor network at MIT (Clairity), planning and executing mobile sensing fieldwork (within MIT campus), and collaborating with city sensing projects.. In fact, in order to explore the research questions, multiple case studies needed to be considered, according to their interference with this work. Clairity was the project that was studied mostly for exploring the first research question (sensing for improving scale), while additional fieldwork project was specifically designed by the author to explore the second research question (sensing for improving resolution). Additional collaboration with other projects was considered beneficial in order to explore the overall research questions, and in particular the last two (challenges of sensing).

The fifth chapter presents data analysis and interpretation from the case studies, and includes all findings that emerged from the data analysis and interpretation of results, on the basis of the fieldwork execution and the data gathered from both the experiment and the collaboration with mapping by sensing projects at SCL-MIT. Strengths and challenges that emerged during this study are underlined. In fact, while great opportunities in sensing for mapping urban climate and air pollution seem to be evident from the following analysis, such as improving scale and resolution, several issues still remain in the use of sensing, such as data quality and communication of results. However, while most of the findings outlined in the previous chapter underlined the challenges of recent sensing technology, rapid development are occurring, and it is likely that low-cost sensors will improve in data quality and be ready to be implemented at a large scale for urban mapping.

The sixth chapter includes recommendations for urban planning, with the aim of contributing to the process of making urban planning ready and profit from the fruitful opportunities offered by sensing, as it has the potential to change the future of urban climate and air quality in our cities. For example, participatory sensing scenarios are beneficial for both increasing data quality and enhancing awareness on environmental and health topics.

In particular, the three sections of this chapter address recommendations for urban planning on three levels, on the basis of the findings outlined from this work.

The first section (§ 6.1) envisions a future where urban planning is more and more focused on governing health and well-being at the people's level, by mapping urban climate and air quality profiting from new (sensing) tools and integrating sectorial knowledge. However, the panoptic top-down concern should be tackled by bottom-up "smartness": promoting crowdsourcing and people-centric sensing will enhance urban sensing in an integrated perspective, both increasing data quality and citizens participation and awareness.

The second section (§ 6.2) provides detailed recommendations in profiting from the opportunities and in dealing with the limitations of using sensing. Urban planning should profit from sensing pervasiveness, its scale and resolution improvement, while at the same time, should overcome barriers, such as data quality and transparency of mapping.

The last conclusive section (§ 6.3) wraps up the overall findings and recommendations, in a project proposal to be applied in the case of Milan. Sensing will integrate modeling in the final aim of mapping urban climate and air quality in the city of Milan.

Summary of contribution and ideas for future work conclude this thesis.

CHAPTER 1

1. URBAN CLIMATE AND AIR QUALITY IN CITIES | PROBLEM DEFINITION

Introduction

Why should we, as planners, care about urban climate and air quality?
This chapter tackles with the problem definition of the research framework, emphasizing that urban climate and air quality are "urban" problems and urban planning has a big role. In fact, because the phenomena involved have a strong local urban component (i.e. street wideness or car emissions), urban planning can define local measures in order to limits its responsibility. In order to do so, the need of increasing knowledge is evidenced, and mapping at a proper scale and resolution is presented as a effective urban planning tool. Additionally, considering global efforts in the climate change discourse, such as low carbon planning and planning for urban resilience, the need for mapping urban climate and air quality at the local level is underlined, in its integration with the larger scale (i.e. climate action plans).

1.1. URBAN CLIMATE AND UHI

What does urban climate refer to in the context of this work?
This section introduces urban climate problems and definitions, the phenomena of urban heat islands formation (UHI) and its impact on the urban environment and on health. The scale considered in this work is herein defined.
In fact, traditionally heat concentration within the urban environment has been the most studied and harmful effect of deteriorated urban climate. UHI is therefore considered in this work as the main component of urban climate.

1.1.A. -Urban Climate from City to Micro-Scale, Urban Heath Island (UHI)
1.1.B. - Impact of UHI on The Urban Environment

1.1.A - URBAN CLIMATE FROM CITY TO MICRO-SCALE, URBAN HEAT ISLAND (UHI)

- Urban climate, urban climatology and urban planning
- Scale definition
- Urban Heat Island

Urban climate, urban climatology and urban planning

"Urban climate" refers to the fact that the atmospheric conditions - the temperature, the humidity, the wind speed/direction, the air quality - tend to be different in a metropolitan area compared to its rural surrounding environment. It is "*the climate peculiar to the city itself, to the climatic characteristics which distinguish the city from its surrounding area, and what gives rise to them*" (Kratzer, 1956, p. 1).
As the main topic of Urban Climatology - the branch of climatology concerned with the interactions between urban areas and the atmosphere - urban climate is

the object of investigation of the impacts they have on one another and of these processes and responses at various scales.
In what it is considered the first study on urban climate, The Climate of London, Luke Howard, a British chemist and an amateur meteorologist, compares his temperature records against those made by the Royal Society, concluding that:

"*the temperature of the city is not to be considered as that of the climate; it partakes too much of an artificial warmth, induced by its structure, by a crowded population, and the consumption of great quantities of fuel in fires*" (Howard, 1818, p. 2).

The main observation was centered on air temperature, and still today, this is the main alteration of climate made by the city to be studied. Other climate parameters are modified and all connected, such as wind and humidity. In this early climatology study, Howard made the first speculation about the causes of this temperature anomaly, observing that certain regions of London with high density of buildings and sparse vegetation were, on average, warmer than those with lesser density and with more vegetation. According to his observation, therefore, the differences in temperature within the London area must be due to the differences in the urban parameters, such as surface geometry, roughness, and the anthropogenic release of heat.
Together with the further same-name study by Tony Chandler (Chandler, 1965), these discoveries stand today as the foundation of modern science in urban climatology, an interdisciplinary field of research.
In fact, Urban Climate studies, involve a large range of disciplines such as meteorology, climatology, geography, physics, geophysics, biology, environmental science, ecology, hydrology, civil and mechanical engineering, mathematics, social science and medicine, building and landscape architecture, building science, and urban planning.

Considering that urban planning is the field of research of this work, urban climate is here considered in its manifestation in relation to urban factors, rather than on meteorological influence. In fact, as already mentioned, the "urban structure" has a main role in determining the urban climate, and urban planning should address it with more emphasis in its practice.
However, the relationship between urban planning and the other disciplines involved in urban climate research is still not well established. Because diverse disciplines' skills and interests often operate independently and in conflict with each other, "the task of the planner should be to coordinate their work, arrive at an optimal design, and reconcile the conflicting desires. This is a Herculean job, especially because large economic values are at stake" (H. Landsberg, 1981, p. 255).
Additionally, it has to be noted how urban climate studies – like general climatology – has been later 'colonized' by a mathematical physics of energy budgets that tend to represent the city as a generic geophysical phenomenon.

This is especially visible in relation to the advances in numerical modeling since the 1960s and, more recently, with the furthering of possibilities of inclusion of cities into large-scale modeling scenarios of anthropogenic climate change (Jankovic, 2013, p. 540).

Timothy R. Oke, from University of British Columbia, a recognized leader in the study of microclimates and foremost authority on urban climate and on the interaction between atmosphere and biological systems, noted how, despite decades of dedicated urban climatology studies, little contribution was made in improving urban planning. He therefore outlined the need for a better involvement of urban planning in the field of urban climate. This process requires improving communication and scientific interaction, in order "bind the subject internally and to more effectively move it into interdisciplinary interaction" (Oke, 2006, p. 179).

As it will be presented in the next section (§ 1.2), for the purpose of this research, air quality is also included in the urban climate discussion, as they both deal with air processes within the urban environment with similar patterns, such as heat and air pollutants trapped within a narrow street. However, the focus of this work is not on "bio-climatic planning" processes, but on urban planning mapping processes, which can be used to increase knowledge on urban climate and air quality in cities, and ultimately on planning processes.

A fundamental clarification regards the scale focus of this work: urban climate phenomena have different characteristics at different scales, as well as urban planning has different role at different level.

Scale definition

Most of the first structured theories and application in urban climate comes from the already mentioned, Oke T. R. He firstly studied (Oke, 1976) the atmospheric process inside the layer of air related to the urban presence (which may be 1 kilometer or more by day, shrinking to hundreds of meters at night), named the "boundary level", and distinguished by two layers with different processes (Figure 1-1).

Firstly, the "urban boundary" layer, the layer of air right above the urban building roofs: air here has completely distinct proprieties analogous to an "urban dome" of turbid air over the city boundaries. Climate here follows local to meso-scale phenomena whose characteristics are governed by the nature of the general urban 'surface' and "roughness".

Secondly, the "urban canopy layer", which recalls the fabric of the city structure as analogous to a "canopy" of a tree. Here solar radiation is trapped and absorbed, and specific wind and humidity conditions may exist. It is the urban space bounded by buildings up to their roofs, where climate is produced by micro-scale processes operating within the streets, between the buildings.

Climate here is an amalgam of small microclimates, each of which is dominated by the characteristics of its immediate surroundings.

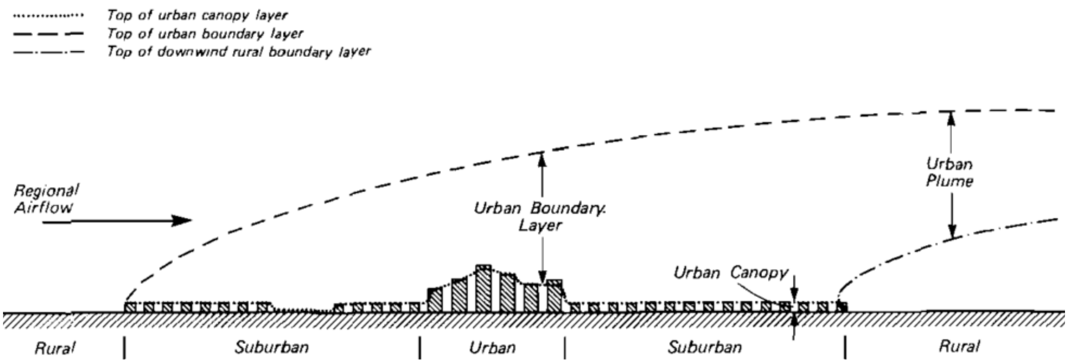


Figure 1-1
Schematic representation of the urban atmosphere illustrating a two-layer classification of thermal modification (Oke, 1976, p. 275)

The first studies on urban climatology posed a strong emphasis on the dichotomy based on “urban against rural” scheme (Oke, 1987). This is probably because most of the studies are traditionally western-based, with little consideration for complex urban structures, such as polycentric cities or “endless” developing cities. Most recent urban climatology has therefore evolved towards a more contemporary classification, with studies focused on local-scale landscapes within the city, such as the definition of “local climate zones”, LCZ (Stewart, 2013).

For the purpose of this study, a smaller and local scale is more relevant for urban planners in their interventions. Urban climate is, in fact, closely related to factors such as: surface cover, urban morphology and urban metabolism (human activity flows of energy and mass), and a proper micro-scale focus fits the scope of understanding the relationship within the canopy level (Figure 1-2)

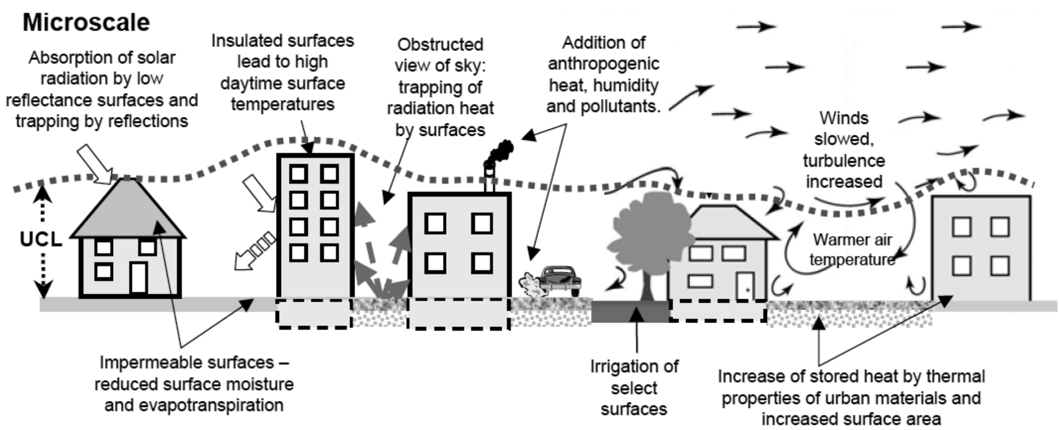


Figure 1-2
Micro-scale and urban canyon level (Voogt, 2007, p. 6)

As Oke (Oke, 1976) emphasizes, the urban canopy level is a micro-scale concept, where climate is mainly dominated by the nature of the immediate surroundings. However, the processes within the urban canopy level differ significantly from one local area to another nearby area, and temperature differences show significant spatial and temporal variability. Temperatures can even change from one side of a street to the other, with the same intensity as the change from a suburb to another, from a park to an industrial neighborhood; additionally the nature of these differences changes over time. It was noted that these patterns are a function of urban morphology, built materials, amounts of vegetation and human activity.

Therefore, a new scale is introduced by Oke (Oke, 1976, 1981) for the street level, using the term "Urban canyon". Here "inadvertent climate modification", strongly depends upon the geometry of the urban area of which the building is part of. For example, considering the parameter "height to width ratio" (H/W, defined as the ratio between H, the mean building height and W, the along-wind spacing), an array of buildings relatively widely spaced (low H/W) makes their flow pattern appear almost the same as if they were isolated. On the contrary, in closer spacing (high H/W) the wake of buildings interferes with that of the next downstream, leading to air turbulence and complex flow patterns, while part of the main flow can start skimming over the building tops and driving a lee vortex in the cavity, contributing to the turbulence within the canyon (Figure 1-3).

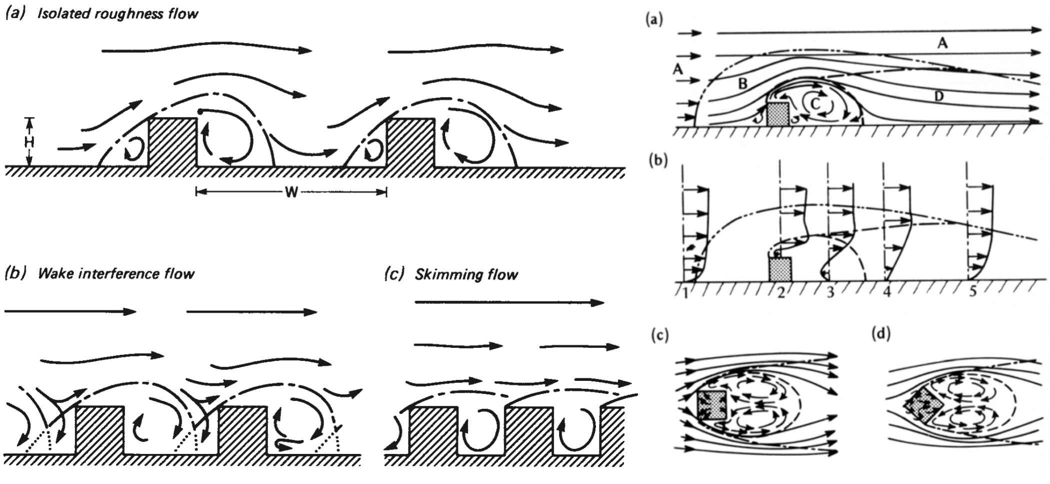


Figure 1-3
Pictured at left: Flow regimes associated with different urban geometries. Pictured at right: Flow patterns around a sharp-edged building. Side view of (a) streamlines and flow zones, and (b) velocity profiles and flow zones with the building oriented normal to the flow. Plan view of streamlines with the building oriented (c) normal, (d) diagonally to the flow (Oke, 1987, pp. 265, 267)

Considering the radiation processes involved in a street or canyon, besides H/W the sky view factor (SVF) is another descriptive geometric parameter, defined as the fraction of sky visible when viewed from the ground up. Narrower streets (with smaller SVF) result in reduced radiative loss and remain warmer compared to more open (higher SVF) areas. Local areas with higher building densities tend to demonstrate higher temperatures. Additionally, different street geometry can

alter wind direction, especially under low wind speed conditions (C. S. B. Grimmond, 2007).
At the urban canyon level, complex climate patterns occur, related also to the local presence of other anthropogenic features, such as heat from combustion for building heating/cooling or for transportation (fuel based cars), or related to the locations of green areas, all influential in creating complex patterns.

- - -
For the purpose of this research, the local scale is the one that best fits the urban planning role and responsibility in urban climate (and air pollutant concentration), and the proper scale for short and medium-term interventions. Larger scales, such as the boundary or canopy, related to regional/city scale are more of interest for climatology, or for urban planning in the settlements of new planned cities. The next section will explain more about this, in relation to the fact that temperature peak changes (and urban heat islands, UHI) depend on some urban parameters, which are manageable at the local scale.
However, the local scale, as intended here, does not exactly correspond to any of the levels presented above; it is a scale in between the traditional climatology levels, the canopy and the canyon level. This is due to the fact that while those levels are defined for climatology purposes, and describe physical phenomena, the focus of this work is on their effect on the urban environment, and on the people living within it. Therefore, the scale considered here can be defined as the scale describing the “outdoor air of a walking pedestrian” (which can be related to 10^0 - 10^2 meters), usually recalled as the “neighborhood scale”. Urban planning can intervene at this scale, by mapping urban climate (and air quality) and implementing local measures where needed, ultimately improving citizen’s comfort, well-being and health.

See § 2.3.B and § 3.1.A for a more detailed discussion of the temporal and the spatial scale considered in this work, since it requires deeper considerations on the proper “resolution” to describe air phenomena within the considered scale

Urban Heat Island

UHI, sometimes visualized as “a dome of stagnant warm air over the heavily built-up areas of cities” (Emmanuel, 2005, p. 104), refers to portions of urban areas where the temperature is higher than the surroundings. As already mentioned, it is traditionally observed comparing the inner center of a city and the rural area surrounding its suburbs, in order to get an estimation of the temperature difference between a built-area and an un-built area. UHI ais therefore an unintentional climate modification caused by urbanization processes, strongly depending on the urban structure configured (see Figure 1-4).

From a climatology point of view, there are three types of heat islands (Voogt, 2004):

- boundary layer heat island (BLHI)
- canopy layer heat island (CLHI)
- surface heat island (SHI)

While the first two types refer to higher temperature observed in two urban atmosphere layers, already mentioned, the last refers to the relative warmth of urban surfaces. Indeed, the image of a dome of warmer air above a city refers to BLHI formation, even if wind flow may often change the dome to a plume shape.
Considering the interest of this work, focused on urban citizens health, it is clear that the CLHI is the one which will be referred to later on. However, there is an evident link between the three types of UHI, and in some studies, CLHI is interfered by SHI, via modeling approximations.

A fundamental difference between them is the sensing processes: while SHI is measured by remote sensors (mounted on satellites or aircraft), CLHI or BLHI are measured by ground sensors, usually thermometers or weather stations. Sensing temperature is traditionally conducted using fixed stations or planning mobile traverse studies according to the temperature gradient. Figure 1-4 shows conceptual isotherm mapping using a dense network of sampling points.

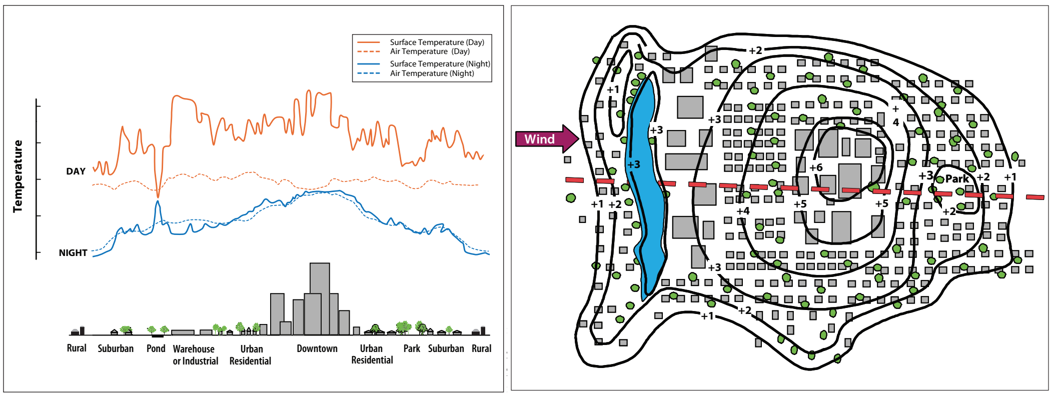


Figure 1-4
Pictured at Left: Surface and atmospheric temperatures vary over different land use areas. Surface temperatures vary more than air temperatures during the day, but they both are fairly similar at night. The dip and spike in surface temperatures over the pond show how water maintains a fairly constant temperature day and night, due to its high heat capacity Pictured at right: This conceptual map with overlaid isotherms (lines of equal air temperature) exhibits a fully developed nighttime atmospheric urban heat island. The dotted red line indicates a traverse along which measurements are taken (United States Environmental Protection Agency, 2008, pp. 4–5).

However, in reality, because of the limitation of sensing (high cost of weather stations and the logistic complexity of deploying the stations in the urban field) few sampling points are usually considered, and the conceptual isotherm often comes from land-use regression models.

On the contrary, thanks to recent mobile sensing studies, a higher resolution of sensing can be reached, since a sensor can move within an urban area collecting several sample points.
Moreover, recent sensing technologies, ubiquitous computing, and low cost air sensors are making more and more sampling points readily available, potentially increasing UHI knowledge by improving the mapping process of UHI and thermal concentrations along space and time within the city.

See chapter 2 for more details on modeling and sensing processes involved in mapping UHI.

1.1.B - IMPACT OF UHI ON THE URBAN ENVIRONMENT

- Causes of UHI: weather, time, space, city planning/design
- Impact of UHI: health
- Impact of UHI: various

Causes of UHI: weather, time, space, city planning/design

As briefly mentioned in the previous section, both experimental (sensing) and modeling studies have found that high temperatures are associated with peculiarity of urban areas, compared to non urbanized areas, such as lack of green space, high building mass, and high production of anthropogenic heat per area.

In fact, more comprehensively and systematically, it can be demonstrated that five categories of factors contribute to the occurrence and intensity of UHI, as described by the following (Voogt, 2004):

- weather
- time of day and season,
- geographic location,
- city form
- city functions

In particular, distinguishing urban planning and design from its role, they can be grouped in three coexisting causes in the UHI formation process. Here follows a very short description.

Firstly, weather and time (of day and season), external to the city control.

Weather. Winds and clouds particularly influence the formation of UHI. Certain combination of weather conditions, such as clearer skies and calm winds, can foster UHI generation. Wind is, in fact, responsible for the air mix, and when winds are increasing, a better mix of the air between UBL and UCL, UCL and urban canyons, potentially reduce the UHI formation. Cloudy skies reduce radiative cooling at night and potentially reduce the concentration of heat in the urban area (see also Figure 1-5).

Time of day. UHI intensity changes during the day, reaching its typical maximum around sunset and a few hours after the predawn hours. During the day, the UHI intensity is typically weak or even “negative” (a cool island, in relation to the average) in shaded parts of the city, while later in the day a lag in warming occurs because of the release of heat storage by building materials.

Seasons. In cities located in the mid latitudes, UHI usually reach their strongest intensity in the summer or winter. In cities located in tropical climates, UHI reach the highest magnitude during the dry season (Voogt, 2004).

While urban planning cannot directly interfere with this group of UHI causes, there are indirect ways of altering UHI, and of adapting to its effect. Considering the occurrence of global climate change, and in particular heatwaves (defined as a run of hot days “commonly defined in terms of percentiles of daily maximum temperature for a specific location”, (International Panel on Climate Change, 2014), it is clear that extreme urban heat is strongly exacerbated by the formation of UHI, and extreme temperature is reached in certain urban areas. Adaptation measures to climate change, and specifically to heatwaves in this case, usually include measures to minimize the UHI effect. See also section 1.3.B. for more about this.

(b) *Variable*	*Change*	*Magnitude of change or comment*
Turbulence intensity	Greater	10–50 %
Wind speed	Decreased	5–30 % at 10 m in strong flow
	Increased	In weak flow with heat island
Wind direction	Altered	1–10°
Tornadoes	Less	
UV radiation	Much less	25–90 %
Solar radiation	Less	1–25 %
Infrared input	Greater	5–40 %
Visibility	Reduced	
Evaporation	Less	About 50 %
Convective heat flux	Greater	About 50 %
Heat storage	Greater	About 200 %
Air temperature	Warmer	1–3°C per 100 years; 1–3°C annual mean up to 12°C hourly mean;
Humidity	Drier	Summer daytime
	More moist	Summer night, all day winter
Cloud	More haze	In and downwind of city
	More cloud	Especially in lee of city
Fog	More or less	Depends on aerosol and surroundings
Precipitation:		
Snow	Less	Some turns to rain
Total	More?	to the lee of rather than in the city
Thunderstorms	More	

Figure 1-5
Urban climate effects for a mid-latitude city with about 1 million inhabitants. Values for summer unless otherwise noted (Oke, 1997, p. 275).

The second group of UHI causes relates to the topography and the geographic location of a town within a region, which both may have the most permanent effect on urban climate and UHI formation. Effects of mountain ranges and altitude, effect of local topography on regional wind conditions, may influence heat islands. Moreover, geographic location, such as the vicinity to sea for coastal cities, may create cooling of urban temperatures in the summer when sea surface temperatures are cooler than the land and winds blow onshore (Givoni, 1998, pp. 275–280; Voogt, 2004).

The third group of causes or factors influencing the formation of UHI is the one more pertinent to urban planning and design, making it directly responsible for the urban climate.
City form and city materials comprise the urban geometry/morphology (the surface characteristics of the city such as the building dimensions and spacing), the urban material properties (and thermal characteristics of buildings and surfaces) and amount of vegetation in the urban area. Relatively dense building materials favor UHI island formation, because of their thermal inertia (slow to warming and cooling) and the storage of energy. Additionally, the replacement of natural areas by waterproofed surfaces, lead to a drier urban area, where less

water is available for evaporation. Moreover, a surface's albedo influences sunlight absorption: dark surfaces such as asphalt roads become much warmer than light-colored or green surfaces (Stone, Hess, and Frumkin, 2010). See more in § 1.3.A.

City functions, and anthropogenic heat emissions, govern the output of pollutants into the urban atmosphere, heat from energy usage, and the use of water in irrigation. The heat generated from human activities, fossil fuel combustion or energy use for building cooling, can be important to heat island formation; in large city core it can create heat island of up to 2-3°C both during day and night (Taha, 1997, p. 102).

For a more detailed framework on the most important urban features responsible for climate and air modification, and the consequent responsibility of urban planning on urban climate, see the following § 1.3.A.

Several climate models (see § 2.1.A) are designed in a way that the factors presented above are included in the simulation of urban climate. However, while factors such as weather, reduced vegetation and properties of urban materials are factors that research communities are traditionally focusing on, urban geometry and anthropogenic heat are an emerging body of literature (United States Environmental Protection Agency, 2008). Recent research is calculating and underlining the significant contribution of anthropogenic heat at the city scale (Narumi, Kondo, and Shimoda, 2009), but high uncertainties occur when estimating the heat release from human activities at a small scale (i.e. in estimating the unit heat demand per floor area). See § 2.1 for a review of existing urban climate modeling, with the factors considered.

From this brief outline, it is possible to notice how urban planning has a big role, and that the local scale is one of significant interest in terms of applicability of measures to alter urban climate. § 1.3 provides a more detailed overview of urban planning and design options.

Impact of UHI: health

The impact of UHI on the comfort and health of individuals, as well as on the energy consumption in cities for heating and cooling of buildings, are the most evident negative effects in the urban environment.

In fact, besides personal factors (i.e. metabolic rate, clothing level) the thermal comfort in outdoor urban environment is largely influenced by the air temperature (see Glossary for "dry-bulb temperature" and "mean radiant temperature"), air speed and humidity[1].

[1] Thermal comfort models study the heat balance based on these parameters in order to define the "predicted mean vote" (PMV) and calculate the "physiological equivalent temperature" (PET). See Fanger's work for more about thermal comfort, analysis and applications (Fanger, 1970).

Considering UHI in climatic zones with hot dry summers, high temperatures from urban heat concentration affect community heath and comfort, especially in existing critical situations and in conditions where adaptation measures are not designed. Additionally, summer heatwaves can exacerbate UHI and can potentially spur serious illness for the urban population. For example, during the summer of 2003 the heatwave in Central and Western Europe was estimated to have caused up to 70,000 excess deaths over a four-month period (European Environment Agency, 2012).

At the same time, higher urban temperatures in the daytime may increase the formation of urban smog, because both emissions of precursor pollutants and the atmospheric photochemical reaction rates increase (Sillman and Samson, 1995, p. 11506). UHI can therefore determine worsening of air quality due to the increase in temperature, and cause health problems related to air pollutants, such as respiratory illness.

With regard to UHI effect on human health, the impact of high temperature in the urban environment (UHI and heatvawes) on human health and comfort is a function of exposure to heat and of the sensitivity of people. In fact, general discomfort, heat cramps, respiratory difficulties, exhaustion, not-fatal stroke, or even morbidity and mortality, can occur in the condition of extreme heat situation (such as combination of UHI and heatwaves) and sensitive people (elderly, small children, people who's health is already compromised) (See Figure 1-6).

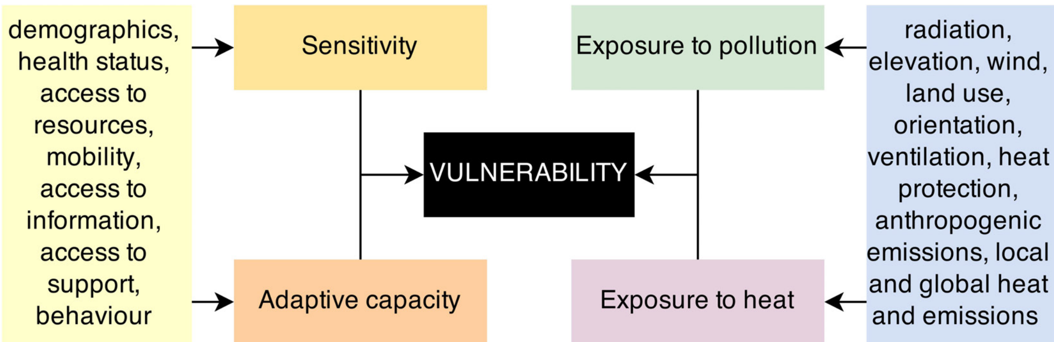


Figure 1-6
Vulnerability to heat and pollution as a combination of exposure, sensitivity and adaptive capacity. Author's adaptation from cited source (Wolf and McGregor, 2013).

Epidemiologic research shows that the city-specific exposure-response function have a J or V shape, with the lowest mortality rates at moderate temperatures and rising progressively as temperatures increase, depending also on humidity and on population difference in acclimatization. According to a renowned European study (Baccini et al., 2008, pp. 714–715), the threshold varies among cities, being 29.4°C for Mediterranean cities, and 23.3°C for north-continental

cities, and the strongest associations between mortality and increase in temperature was found for respiratory diseases and the elderly.
UHI effects are therefore dependent on the population; however, since heatwaves are likely to increase (International Panel on Climate Change, 2014), harmful effects can be prominent in an increasing number of cities and population.
Moreover, the impact of high temperatures and the ability to combat heat stress, and sensitivity, are key aspects for environmental justice and social inequalities, since they vary across populations. For instance, developing and low-income countries have little access to cooling facilities, and the developed world is experiencing a demographic change leading to a progressive increase of the elderly in the urban population, generating an overall increase of the vulnerability.

Urban planning can have a relevant role in managing health related problems. For the purpose of this work, the focus is on the ability of urban planning in identifying proper solutions to address those mentioned heat related problems.
In order to do so, it is necessary to map UHI and vulnerabilities, and to address adaptation solutions to better manage heat related health risks.
Since population characteristics and UHI factors vary at the local level, as mentioned in the previous section, there is an evident need to gather data at the local scale.

As recalled for urban climate research, the lack of studies at the neighborhood level is also evident for urban epidemiology. Despite the existence of active research on epidemiology of urban heat on single individuals, few explicit attempts has been developed to understand the spatial distribution within the city of the impact of heat on health.
Wolfe and McGregor study on the Greater London urban area, is an original research on mapping the heat risk of the population, at a local scale (census district, the smallest scale available data found covering the whole area). The study (Wolf and McGregor, 2013) developed a heat vulnerability index (HVI) and create a mapping of the spatial distribution of population vulnerability to heat, based on a principal components analysis of a range of heat related factors (such as “high population density”, “population above 65 years old”, “receiving any kind of social benefits”).

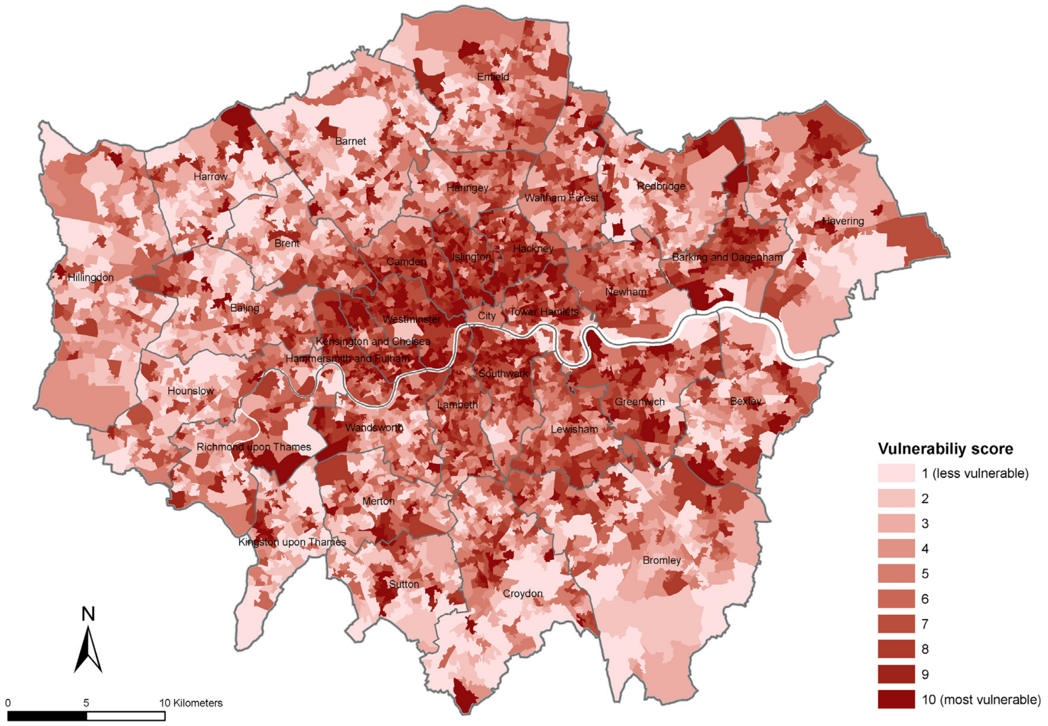


Figure 1-7
Spatial distribution of the heat vulnerability across Greater London as categorized by 10 heat vulnerability classes. Heat vulnerability increases from1 (lowest) to 10 (highest) (Wolf and McGregor, 2013, p. 64).

While temperature variation across the area is not available at the same district scale, and surface temperature used come from remote sensing, mapping UHI showed significant pockets or spatial clustering of areas of high heat vulnerability (i.e. in central areas north of Thames) and the overlap with areas of potentially high heat exposure.

As shown with this example, a local scale is needed in managing UHI effects; mapping heat and heat-related parameters at the local level helps urban planning in identifying the most critical areas, where to concentrate the attention. To this regards, see also the Toronto mapping for heat risk in summer heatwaves in downtown Toronto (Figure 1-13), presented in § 1.3.

Impact of UHI: various

Considering the physiological limits of human heat tolerance, increased temperature above hazardous thresholds affects human health, comfort and working conditions. According to a recent technical study (Sherwood and Huber, 2010, p. 9554), an increase of about 7°C above current temperatures causes surpassing 35°C for extended periods, therefore inducing hyperthermia and making dissipation of metabolic heat impossible. Because UHI make the night-time minimum temperature adjacent to the maximum temperature, heat dissipation becomes inefficient or impossible for prolonged periods.

Impact on health effects, therefore, affects labor productivity; according to labor productivity study (Dunne, Stouffer, and John, 2013, p. 563) working conditions under heat stress, as a combination of temperature and humidity, is worst during the hottest months; considering the climate change scenarios of increase of 3.4°C by 2100 and 6.2°C by 2200 relative to 1861–1960, the global productivity will be globally reduced to 60% in 2100 and less than 40% in 2200.

Regarding cities and urban environment, other UHI impacts are related to potential structure damages to historical buildings (due to heat stress), increase of air pollutants and GHG gases as already mentioned, and impaired water quality. In fact, runoff from urban areas, through the surface urban heat island effect, degrades water quality, affecting aquatic species and their metabolism and reproduction.

However, the main UHI impact can be considered to be the significant increase in local electricity demand for cooling buildings, generating the increase of energy consumption. A different set of literature examines the link between UHI and energy demand (Shahmohamadi, Che-Ani, Maulud, Tawil, and Abdullah, 2011; Taha, 1997). For example, a recognized study for Athens found that the cooling load of urban buildings may be doubled and the peak electricity load for cooling purposes may be tripled and the minimum air conditioner COP value may be decreased by a quarter (Santamouris et al., 2001).
In addition, the waste heat coming from air conditioning systems is released to outdoor urban areas, leading to the increase of the anthropogenic heat itself, and finally to an increase of the outdoor temperature inside an urban canyon, as a vicious cycle.

Moreover, since climate change is expected to determine an increase of air temperature, exacerbating UHI at the local scale, the energy demand peak expected in winter season in some locations is reduced, while during summer seasons the power load expected is increased and alarming, leading to system vulnerability.

In order to study the local temperature increase, the urban factors involved, and the consequent energy demand of buildings of a specific urban area, assessments at the local scale are needed.
Several studies have aimed at mapping the energy consumption of urban texture at a local level; however, the lack of temperature mapping at the same scale for the overall urban area prevents showing the local responsibility of UHI. Effectiveness of local UHI mitigation measures on reducing the energy demand, are therefore assessed with urban canopy estimates (Kikegawa, Genchi, Kondo, and Hanaki, 2006), or building-scale estimate (Kolokotroni, Ren, Davies, and Mavrogianni, 2012). Based on building-energy models, a study based in Tokyo (Ihara, Kikegawa, Asahi, Genchi, and Kondo, 2008), found that improving local humidification and increasing albedo with recent technologies reduced the summer energy consumption by 3% and 1% respectively. Detailed mapping of

anthropogenic heat in Tokyo was drawn by another study (Ichinose, Shimodozono, and Hanaki, 1999) with data coming from energy statistics, discussing how reductions in energy consumption could mitigate UHI.
However, a lack of knowledge of UHI in its temporal and spatial variation in the city, can lead to the selection of measures that are not appropriate and can cause the contrary effect of energy consumption increase. Hirano and Fujita (2012, pp. 381–382), for example, confirmed Ihara's results, but quantified that the total energy consumption for residential areas and commercial areas are different, suggesting local-context city block-scale and building-scale UHI mitigation measures (e.g. high albedo coating and rooftop gardening) instead of measures generally applied to overall urban areas..

In order to define local-context measures, as suggested by the aforementioned study, mapping local urban climate and collecting local data from energy system service companies would be useful, and it will improve the accuracy of UHI impact and of mitigation estimates.

- - -

Most of the considerations about urban climate presented here, relate to the heat concentration in certain urban areas, worsening the temperature and condition of the air at the pedestrian level. In some way, urban heat can be therefore considered as a significant air "pollutant"; in fact, in the same way as pollutants like particulates do, extreme concentration of heat above defined thresholds have a harmful impact on the urban environment and on human health. To this regard, there have been proposals to include heat as a regulated pollutant by governmental air-quality management laws (Stone, 2005, p. 23).

The next section specifically deals with air pollution concentration in cities, with the same approach focused on urban planning role, and on the potential of mapping harmful air phenomena at the local level.

1.2. AIR QUALITY AND AIR POLLUTION

What does air quality refer to in the context of this work?

This section introduces air quality problems and definitions, the pollutant concentration within the urban environment, and its impact on the urban environment and on health, analogously to the previous § 1.1 for heat concentration. The scale considered in this work is herein defined, according to the pollutants' lifetime. The air quality index (AQI) is introduced, as it will be extensively used in this work.

1.2.A - AIR QUALITY AND AIR POLLUTION IN THE URBAN ENVIRONMENT

The purpose of this section is to show the basics of air quality, enough to understand how urban planning can map air pollutant concentration in urban environments.

It is therefore not meant as a comprehensive introduction to air quality environmental science. As done in the previous section about urban climate, where climatology basics were introduced to understand the responsibility and role of urban planning, in the same way that the brief information here is related to urban planners' concerns.

- *Air Quality and Air Pollution*
- *Scale definition*
- *Air pollution standard and air quality index*

Air Quality and Air Pollution

The term "air quality" usually refers to the state of the outdoor air typically near ground level, surrounding people's environment. Different levels of air quality are defined according to different studies and regulations. Poor quality of air refers to certain concentration of pollutants in the air ("air pollution") enough to endanger human health and the environment, wildlife, water, soil, vegetation. To some extent, urban heat can be equally considered an air "pollutant", whereas heat intensity is seen as concentration (Stone, 2005, p. 23).

Indoor air quality, such as enclosed spaces, homes, schools or workplaces, is also a critical aspect, according to local urban structure, weather, habits, which all might determine an higher exposure because of high percentage of time spent in indoor environment.

Air pollutants are distinguished between primary, secondary and greenhouse gases. Primary pollutants which are directly emitted into the atmosphere, include: sulfur dioxide (SO_2), oxides of nitrogen (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), and carbonaceous and non-carbonaceous primary particles. Secondary pollutants are formed within the atmosphere itself,

arising from chemical reactions of primary pollutants, and include: ozone (O3), oxides of nitrogen (NOx) and secondary PM. Greenhouse gases (GHG) include carbon dioxide (CO_2), nitrous oxide (N2O) and methane (CH4).
See the Glossary for more information about their specific characteristic and harmful effects.

Scale definition

In the same way as presented for urban climate, different scales can be considered in studying and mapping air pollution.
However, while for urban climate the physical and mechanic air fluxes were defined by several atmospheric layers, air pollution scale can be distinguished depending on the atmospheric lifetime of specific air components (Seinfeld and Pandis, 2012, pp. 18–19).

<u>Global scale.</u> GHG pollutants, having atmospheric lifetimes of years, are capable of distribution throughout a hemisphere and ultimately globally. Unless local source emissions are very large, GHG concentrations at the local level are marginal, compared to the regional background.
<u>Regional scale.</u> Fine particles (such as PM2.5) and some gas-phase pollutants such as O3 have atmospheric lifetimes of days/weeks, and they are therefore transported on a <u>regional</u> scale. Long-range transport, even crossing national boundaries, can be monitored for pollutants such as sulfate particles and O3, as well as black carbon arising from fossil fuels and biomass combustion.

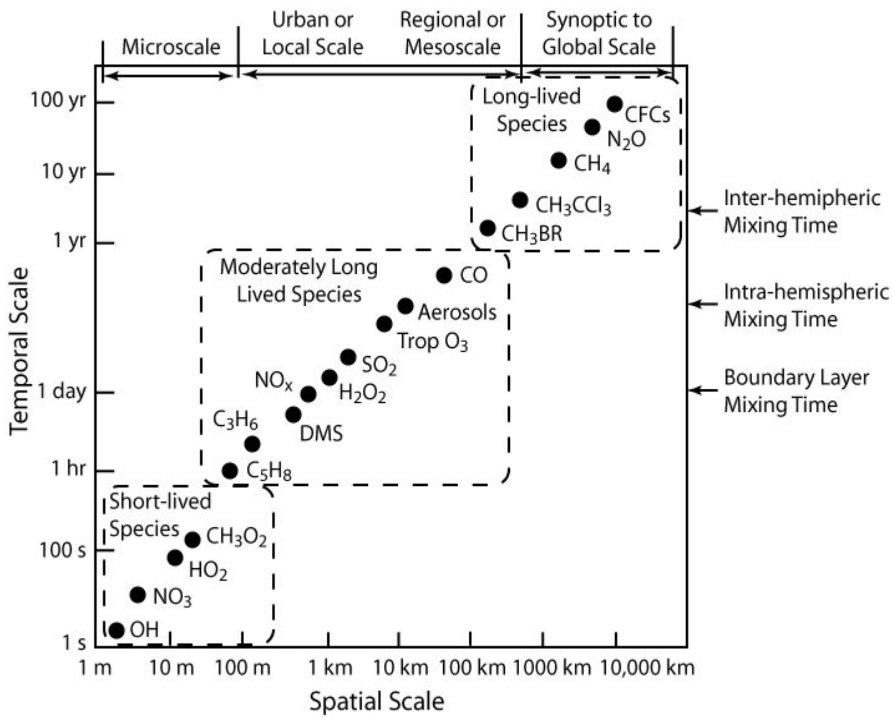


Figure 1-8
The space and time scales of trace gases in the atmosphere. The lifetime of pollutants influence their permanence on the air, traveling and affecting different scales. While moderately long-lived species contribute to urban air pollution, the long-lived species contribute to the ozone hole and greenhouse warming (Seinfeld and Pandis, 2012, sec. 2.1).

Local scale. Pollutants from urban sources, such as traffic related emissions of NOx are encountered at high concentrations within the city, according to their local emission patterns. Because of their atmospheric lifetimes of some hours, they tend to travel within the urban environment, according to the city morphology and weather condition, while their concentrations in the remote background atmosphere tend to be very low.
Finally, some pollutants tend to be only present in appreciable concentrations close to where they are emitted, because of their short atmospheric lifetime. For example, biomass fuels burned from household and neighborhood sources often cause serious local air pollution (Seinfeld and Pandis, 2012; World Health Organization, 2006).

As for urban climate, the focus of this study is on the people's level, at the pedestrian scale, the micro-scale, or as already discussed in § 1.1.A, the neighborhood scale, the intra-urban scale.

Air pollution standard and air quality index

"Air quality index" (AQI), also referred to as Air quality health Index, or Air pollution index or pollutant standards index, is a number used by used by government agencies to communicate the level of pollution in the air (current or forecasted), and is proportional to the percentage of the population likely to experience increasingly severe adverse health effects.
AQIs correspond to "Air quality standards", defined and enforced differently by different government agencies, as the maximum acceptable levels of air pollution, in terms of potential impacts on public health and the environment. While in Canada and the EU they are referred to as limit values, in China, India and in the United States they are called "national ambient air quality standards". The WHO provide guidelines based on the current state of international scientific literature and evidence. After the first guidelines published in 1987, and the review in 1997, the WHO published in 2006 a global update, based on a review of accumulated scientific evidence coming from new studies on the health effects of air pollution, including new research from low-and middle-income countries where air pollution levels appear to be the highest.
Nevertheless, WHO recommends that local factors can affect the impact of air pollution on health, such as population health, lifestyle characteristics, exposure patterns and pollutant mixes; therefore local studies in determining effects and levels for standard setting are needed (World Health Organization, 2006).

Most air pollutants do not have an associated AQI. Many countries monitor ground-level ozone, particulates, sulfur dioxide, carbon monoxide and nitrogen dioxide, and calculate air quality indices for these pollutants. Table 1-1 shows a selected range of pollutants and their standards:

µg/m3	WHO	US	EU
PM 10	50 (24-hour mean) 20 (annual mean)	150 µg/m³ (24-hour)	50 (24 hours) 40 (1 year)
Allowed number of exceedences per year		1	35
PM 2.5	10 (annual mean) 25 (24-hour mean)	15 (annual, primary), 12 (Dec 2014) 35 (24-hour, secondary)	25 (1 year) 18 (based on 3 year mean*)
Allowed number of exceedences per year	-	none	none
O3	100 (8-hour mean)	150 (8-hour) 235 (1-hour)	120 (8 hour)
NO2	40 (annual mean) 200 (1-hour mean)	100 (annual)	40 (1 year) 200 (1 hour)
SO2	20 (24-hour mean) 500 (10-minute mean)	365 (24-hour) 1,300 (3-hour, secondary) 80 (annual)	125 (24 hours) 350 (1 hour)

Table 1-1 Pollutants concentrations and standards. Source: author's elaboration adapted from WHO (World Health Organization, 2006) and EPA NAAQS ("National Ambient Air Quality Standards (NAAQS) | Air and Radiation | US EPA," n.d.) and EU standards ("Air Quality Standards - Environment - European Commission," n.d.)

1.2.B - IMPACT OF AIR POLLUTANT CONCENTRATION

- *Causes of air pollution concentration: weather, emissions, city planning/design*
- *Impact of air pollution: health*
- *Impact of air pollution: various*

Causes of air pollution concentration: weather, emissions, city planning/design

Analogous with urban climate, urban air quality is also affected by internal and external factors beyond the city's control. Air pollution directly depends on the emissions quantity (emission factor), but also on the quantity of emitting sources in the same area (density emission). Additionally, it depends on the physical and chemical properties of pollutants.
However, the concentration of the pollutants above the air quality threshold is inevitably determined by dispersion and accumulation phenomena.
Analogous to the formation of UHI, considering urban planning and design its role, 3 groups of coexisting causes can be identified in the air pollution concentration.
Firstly, weather and climate condition (such as wind, temperature, air turbulence, air pressure, rainfall and cloud cover), which is somehow external to the city control. It has been demonstrated that the presence of stagnant warm air within areas of the city determines the formation urban smog, because both emissions of precursor pollutants and the atmospheric photochemical reaction rates increase (Sillman and Samson, 1995, p. 11506).

Secondly, topography and geographic location (such as the presence of mountains and valleys, and other natural environmental factors). As noted for UHI formation, air pollution concentration also depends on the air mix of the area considered, which is related to the specific location of the area within a region. In addition, natural factors, such as the presence of a forest, affect the emission and absorption of pollutants, ultimately playing a fundamental role in air quality studies.

The third group of factors influencing air quality within cities is more pertinent to urban planning and design.
City form comprises the urban geometry and morphology (sky view factor, distance between buildings), amount of vegetation in the urban area. Pollutants concentration is favored by relatively dense building materials and urban texture that prevents natural ventilation (as for UHI formation) (Stone, 2005).
City functions govern the output of pollutants into the urban atmosphere, mostly coming from industrial activities, and from fossil fuel combustion in energy usage: transportation, and building heating/cooling.

As briefly shown, and in perfect analogy with urban climate factors, urban planning and design have a large responsibility in air pollution concentration within urban areas. However, the complex dynamic of pollutants in the urban environment follows the turbulence flow studies, with the additional complexity generated by the chemical processes involved.

For an overall framework on urban planning role and responsibility in urban climate and air quality, see section. 1.3.A

Impact of air pollution: health

In new estimates released in 2014, the WHO reported that about 7 million people died in 2012 from air pollution exposure, 1/8 of total global deaths, and double of the previous estimates, confirming that air pollution is now the world's largest single environmental health risk (WHO, 2014). In the European Union, the biggest environmental cause of premature death toll comes from poor air quality, even worse than road traffic accidents (European Environment Agency, 2014).

Large epidemiological studies have been conducted to quantify the relationship between ambient air pollution and population exposure, and a great amount of literature shows evidence of the adverse effect associated with air pollution. Among the pollutants, PM2.5 shows a strong and consistent association with negative effects on human health, such as cardiopulmonary morbidity and mortality (Brook et al., 2010; Pope III and Dockery, 2006), and it is therefore the main pollutant considered in this work.

The spatial scale and the resolution are crucial for an exposure study linking air pollution to human health effects. However many research works are limited by a lack of high resolution data and have used measurements from a single source or from a small number of fixed-site monitor stations to assess air exposure, and air pollution mortality effect estimates may underestimate the true pollution-related health burden (Pope III and Dockery, 2006, p. 717).

In a recognized spatial analysis study by Jerret et al. (2005), the link between population exposure and health impact are explored in the Los Angeles basin, in an effort to use the smallest scale possible and a proper resolution. The health data was based on the 267 zip code data (22,5 km2 average per zip code), while air pollution data (PM2.5) came form the 23 state and local district monitoring stations, using different interpolation methods.

While results suggest that chronic health effects associated with intra-city gradients in exposure to PM2.5, for example more strongly associated with ischemic heart disease than with cardiopulmonary (Krewski et al., 2009), high spatio-temporal concentration of emissions suggests the need for improving scale and resolution, and to account for the population living and commuting within different areas of the city.

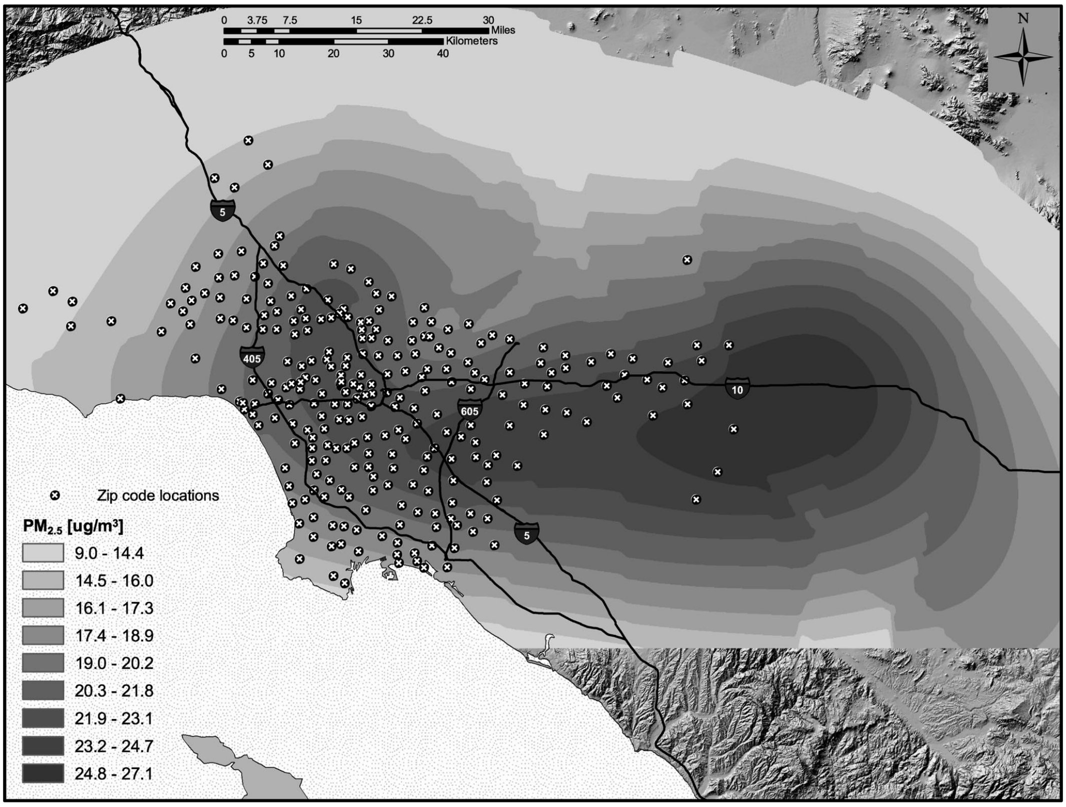


Figure 1-9
PM2.5 exposure surface for Los Angeles interpolated with a hybrid universal-multiquartic model (Jerrett et al., 2005, p. 729)

Impact of air pollution: various

The varied impacts of air pollution are diverse; besides human health, environmental, social, and economic aspects are all involved. For example, particles such as PM2.5 coming from the combustion of fossil fuels affect buildings facades, historical places, and make monuments / statues dirty, increasing cleaning and maintenance costs. Contribution of nitrogen oxides to the formation of acid rain, affects soils and vegetation, and surface waters (eutrophication).
Additionally, while air pollutants have a local effect on health and environment, some of them are also greenhouse gases (i.e. ozone) and have a global effect on the earth. Yet they both are linked and their impact may fuel each other, since climate changes due to greenhouse gases may increase air quality problems.

Comparable to heat stress but with a considerably stronger impact, air pollution causes lost working days, and high healthcare costs, with vulnerable groups such as children, asthmatics and the elderly the worst affected. The direct costs to society from air pollution, including damage to crops and buildings, amount to about €23 billion per year, and the external costs from health impacts alone are estimated at € 330-940 billion (3-9% of EU GDP) (European Environment Agency, 2014, p. 13).

Lack of environmental justice is often accentuated when the same degree of protection from environmental and health hazards is not guaranteed to everyone, and there is no equal right to have a healthy environment in which to live, learn, and work.
Ambient air pollution substantially contributes to social inequalities in health, in two major mechanisms, which may act independently or synergistically. Some studies found that people of a lower socio-economic status are recognized as being more often exposed to air pollution (differential exposure), while there is a general consensus that the poor are more susceptible to the resultant health effects (differential susceptibility) (Deguen and Zmirou-Navier, 2010, p. 28).

Together with these social aspects, the economic impact of air pollution is also relevant in the current debate. At a local scale, detrimental effects of air pollution on property values are still under research; first research on this topic reported a statistically significant negative relationship between common measure of sulfurous pollution, only data available at that time, and residential property values (Ridker and Henning, 1967, p. 253). Later studies disagreed, and confirmed the notion that even “nearly odorless, tasteless, and invisible pollutants” exert a negative influence on residential propriety prices (Anderson and Crocker, 1971, p. 179). More generally, hedonic estimations are generally questionable and need further research (Anselin and Lozano-Gracia, 2008; Chay and Greenstone, 2005; Smith and Huang, 1995).
Currently, agreed assessments of the socio-economic impact of air are not available; additionally, real estate market biases land use decisions in a way that the same group of people suffer from both a low socio-economic status and high exposure to air pollution, making the results questionable (Deguen and Zmirou-Navier, 2010, p. 33).

Nevertheless, there is stronger evidence that documents the impact of air quality at a higher scale than the local scale: more polluted cities and regions can feature overall lower home prices, considering local levels coming from economic activity emissions within the city, and also coming from cross-border pollution (Zheng, Cao, Kahn, and Sun, 2013).

Therefore, studies at the local scale are needed to connect pollution concentration to health and real estate, and research for dynamics at the local/neighborhood scale.

1.3. THE NEED FOR MAPPING URBAN CLIMATE AND AIR QUALITY

Why should we, as planners, need mapping urban climate and air quality?

This section introduces the role of urban planning in heat and pollutant concentration within the urban environment. Planners can be responsible for the deterioration of the urban climate and air quality, and local actions can be designed. In order to do so, mapping transfer sectorial outcomes into planning language, and increasing the base knowledge for urban studies and for urban planning and policy decisions.

In addition, considering climate change challenges, such as heatwaves, there is a need for planning to locally mitigate and adapt to its effect, and mapping urban climate and air quality is also helpful for this purpose (i.e. combination of UHI and heatwaves).

1.3.A - RESPONSIBILITY OF URBAN PLANNING, AND THE NEED FOR MAPPING LOCAL MEASURES

- Urban planning and design role in the urban climate and air quality
- Limiting responsibility by defining local measures
- The need for mapping for urban planning

Urban planning and design role in the urban climate and air quality

Changes in land use, such as urbanization and agriculture, and the emission of GHG are the most important anthropogenic influences; they both tend to increase the daily mean surface temperature (Kalnay and Cai, 2003). There is a growing body of evidence that processes of urbanization and land use effects are at least as important as climate change by GHG in altering weather patterns (Foley et al., 2005; Pielke, 2005; Stone, 2009).

The influence of land use on climate and air pollution is mostly pronounced at the scale of the city and urbanized regions. While considerable evidence is emerging on the important relationships between urban patterns, urban climate, and air quality, our understanding of these complex relationships is still rudimentary and no systematic studies have yet described how alternative spatial configuration impacts local sinks (Alberti, 2008, p. 195). In fact, these relationships are complex, and also mediated by decisions at different levels, from national strategies, to regional, to household behaviors about mobility, housing location, energy consumption and their impact on urban climate and air quality.

At the urban local level, the most important urban features responsible for climate and air modification can be grouped as (Oke, 2004):

- urban cover
- urban metabolism
- urban fabric
- urban structure

Urban cover, land use, sealing

Global "urbanization", or the land-use consumption and land cover transformation from natural open land into urban land is one of the major environmental impacts in most urbanized countries and regions, and the global adverse impact on climate and atmosphere related issues is widely acknowledged (Foley et al., 2005; Jalkanen, 2012; Kalnay and Cai, 2003; Pielke, 2005; Stone, 2009; Turner, Meyer, and Skole, 1994). At a regional level, a land use transition framework and impact assessment of land cover is missing, but recent monitoring and scaling down to the regional and city level has proven made strides in assessing the impact and in clarifying the spatially explicit implications (Nuissl, Haase, Lanzendorf, and Wittmer, 2009; Pileri and Maggi, 2010).

At a local level, the urban cover, or "urbanization", is related to the increase of built-up paved surfaces and the decrease of vegetated or bare soil. Considering urban climate, the albedo modification affects the radiant temperature, while the decrease of vegetation cause a reduction of evapotranspiration phenomena and a reduction of the latent heat, resulting in an increase in air temperature (see the surface energy balance model, § 2.1). Effects on plants on the environmental conditions are widely studied from an urban climate perspective (Taha, 1997), considering also different types of urban green cover, from large public parks to street trees. In fact, in addiction to its effect on the urban climate, and microclimate at the street scale, the decrease in vegetation causes vast effects on air pollution. Its presence, on the contrary, can contribute to improving air pollution and noise control. Air pollutant filtration and dry deposition processes occur, according to the capacity of the vegetation (leaf stomata and coverage per unit area of land). According to a renowned study (Nowak, Crane, and Stevens, 2006), urban trees in the Unites States have an estimated annual air pollutant removal of about 700.000 tons of 03, PM10, NO2, SO2, CO.

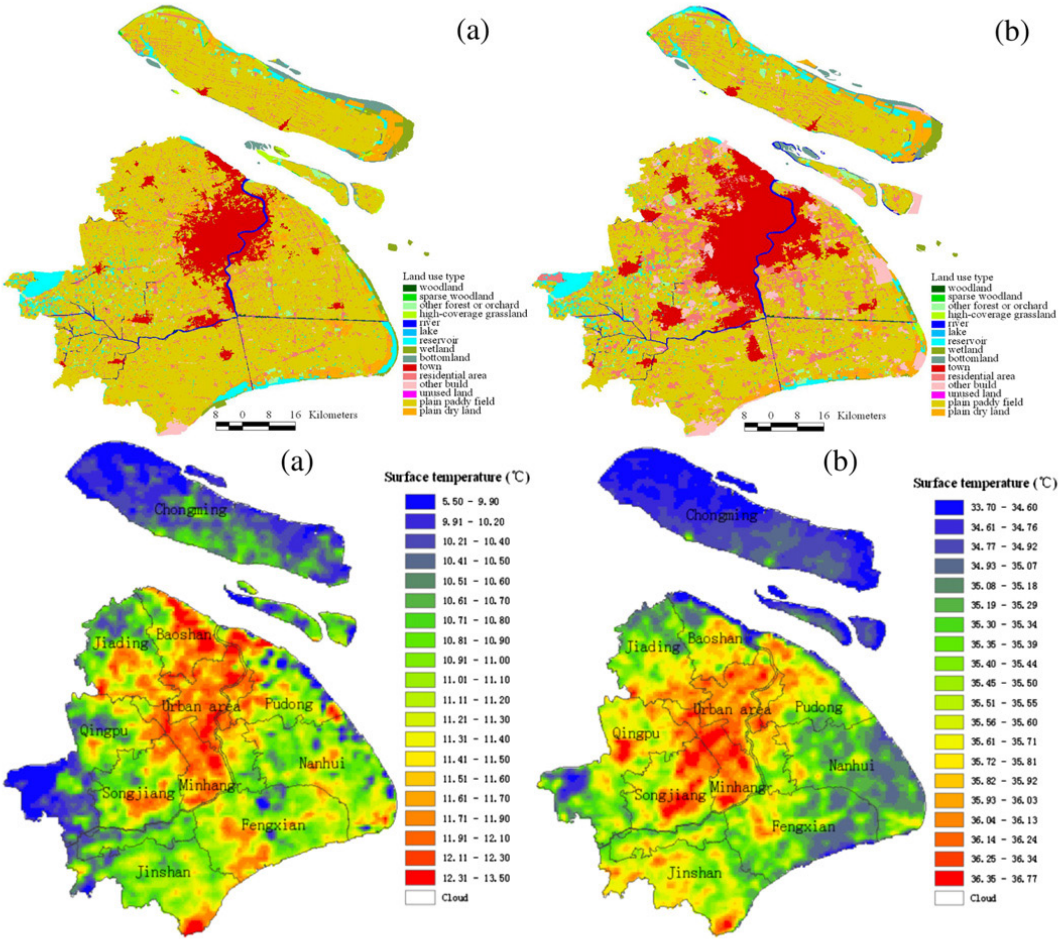


Figure 1-10
Pictured at top: land use types derived from Landsat remote sensing images (a: 1980, b: 2008). Pictured at bottom: spatial patter of land surface temperature in (a) winter and (b) summer retrieved from MODIS product in Shangai. See legends at cited source (Cui and Shi, 2012).

<u>Urban metabolism, urban service</u>
Flows of material and energy within urban environments, and exchanges with its surroundings determine air emissions and heat release in relation to the urban metabolism. Urban planning, energy planning, and mobility planning have a big role in altering the transfer of heat, water, pollutants due to human activity within cities. In particular, anthropogenic heat and air pollutants emission from fossil fuel combustions and energy for building heating/cooling and transportation, have their contribution and responsibility in UHI and air pollution. At the same time, cities are living, breathing ecosystems, and like all ecosystems are sensitive to the environmental strains imparted on them by air pollutant concentration.
A more comprehensive approach is currently being developed in recent urban planning literature (Blečić et al., 2014; Pincetl, Bunje, and Holmes, 2012; Steemers, 2003).

<u>Urban fabric, urban materials</u>
The construction materials of urban surfaces, as well as “natural” materials, have a role in within the urban air processes, mostly connected to their radiative and

thermal characteristics, such as solar reflectance (albedo) and thermal emissivity and heat capacity. While albedo affects the percentage of solar energy reflected by materials color (i.e. light color), and emissivity affects the surface ability to shed heat (i.e. materials), heat capacity, on its own, refers to the urban material ability to store heat (i.e. stone).
From an air pollution perspective, while urban fabric research is developing "self-cleaning" and pollution absorbent materials for building facades, such as the photo-catalytic cement, (Barbesta and Schaffer, 2009), green roofs and green surfaces integrated in buildings, may contribute to increase pollution removal.

Urban structure, urban geometry, urban morphology, urban sprawl and density, urban form

The effect of land consumption already mentioned, has even higher impact on urban climate and air quality when it is characterized by dispersed instead of compact developments.
Urban sprawl, with its typical features of mono-functional and low-density land uses --thus determining a reliance on private car ownership – is has demonstrated a direct effect, even in traditionally compact European cities (European Environment Agency, 2006; Kasanko et al., 2006). Generally, sprawling cities have higher emissions, such as CO2 emissions (Makido, Dhakal, and Yamagata, 2012), and are more vulnerable to climate change than compact cities (Stone et al., 2010); their different compactness or dispersion determines a variable impact on urban climate and air quality, ultimately affecting citizen's comfort and health (Martins, 2012; Schindler and Caruso, 2014). While a local densification may exacerbate UHI phenomena, because of the increase in build mass concentration, their thermal inertia and the storage of energy, synergies exist between strategies designed to control air pollution emission and strategies designed to improve urban climate, and urban containment strategies have been developed and studied (Gennaio, Hersperger, and Bürgi, 2009; Millward, 2006; Stone and Rodgers, 2001). For a detailed debate about the "compact city" as a sustainable urban form, see the work conducted by K. Williams E. Burton, M. Jenks (2003).

Urban density is therefore one of the main factors affecting urban climate and air quality, and at an urban design scale, is determined by urban morphology: surface fraction of land covered by buildings, the street widths and street spacing, the average and height of buildings.
Many features of urban structure can affect urban climate and air quality; just as the physical structure of a city can be controlled by urban planning and design, it is possible to modify urban climate and improve the comfort and health of the inhabitants outdoor and indoor with appropriate urban measures.
In fact, urban geometry affects solar radiation (Morello and Ratti, 2009b), and wind dispersion and ventilation (Di Sabatino, Leo, Cataldo, Ratti, and Britter, 2010; Carlo Ratti, Di Sabatino, and Britter, 2006), ultimately affecting urban climate and air quality. Two of the main parameters used in urban canopy models are "roughness" and the "sky view factor", usually interfered from 3D

models, LIDAR data and DEMs (Carneiro, Morello, Ratti, and Golay, 2009; L. Chen and Ng, 2009; Gal and Sumeghi, 2007; Svensson, 2004; Janos Unger, 2009). Figure 1-11 shows two studies comparing the impact of urban form on radiation and ventilation, ultimately affecting the modeled air temperature distribution. In the first one, each combined urban form is based on five LCZ, Local Climate Zones (Stewart and Oke, 2012) (see § 2.1) and three landscaping scenarios recreating three prevailing residential landscape types in the Phoenix metropolitan area: “mesic”, “oasis”, and “xeric” (Middel, Häb, Brazel, Martin, and Guhathakurta, 2014). In the second one, the potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE, is studied comparing a neighborhood structure to an “orthogonal” and a “volume orthogonal” model (Taleb and Abu-Hijleh, 2013).

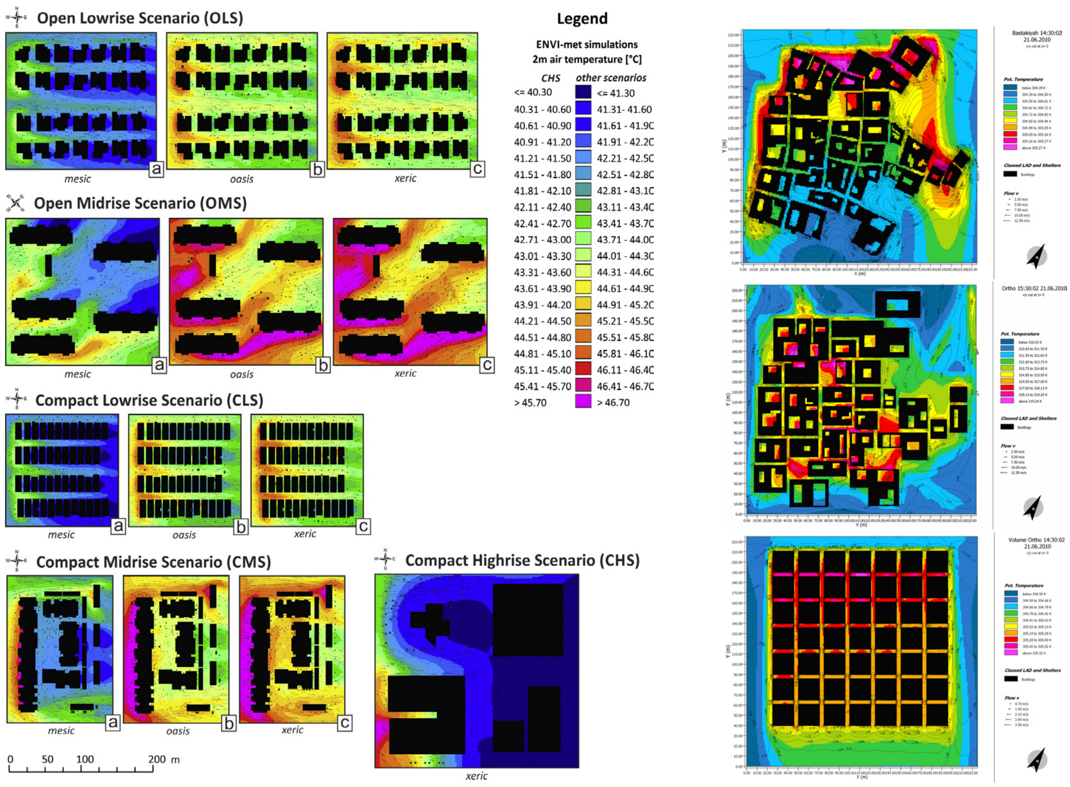


Figure 1-11
Pictured at left: snapshot of temperature gradient in three urban configurations (organic, volume orthogonal, and orthogonal) (Middel et al., 2014)*. Pictured at right: snapshot of temperature variation in Bastakiyah, in Dubai (top) and a “volume ortho model (middle) and a “ortho” model (bottom showing the distribution of temperature in one part of the configuration (Taleb and Abu-Hijleh, 2013). As can be qualitatively seen, the importance of a small-scale study for urban climate and air quality is essential because of both the people’s level and the local impact of urban morphology. In the example, the urban configurations are responsible for different local air temperature.*

Limiting responsibility by defining local measures

In the utopian town – let me call it Metutopia – we would postulate preservation of as many trees as possible. … reduce the need for surface space.. by reduced cars as a mode of transportation.. Pedestrian traffic will move through tunnels or under colonnades. Buildings will have open vegetated spaces between them…. Weak winds accompany synoptic stagnation situations when air pollutants accumulate and when any reduction in wind speed aggravates the problem. In Metutopia there will be no narrow thoroughfares, and distances between buildings and structures will be such to minimize solid wall of obstacles. .. In Metutopia, aside from electrification of transportation, pollutants of stationary origin are to the maximum feasible extent controlled at the source. If this is impracticable, they are ducted out of town where they are detoxified and dispersed under strict meteorological control.

(H. E. Landsberg, 1973, p. 87).

Since urban planning and design play a significant role in urban climate and air quality, as shown in the previous section, there is a large range of intervention limiting their responsibility. More specifically, urban climate can be achieved in two ways: by limiting its negative contribution and by acting on limiting the effects.

Both strategies can easily help prevent the increase in photochemical smog and its related health effects, and at the same time minimize UHI, by promoting synergies in urban strategies, including expanding green vegetation, minimizing impervious surface, and reducing emissions by designing patterns. In this regard, as Landsberg imagined (1973), a utopian city would include "bioclimatic" and air pollution consideration in its design. In fact, synergies exist between local measures designed to control emissions and measures designed to limit the UHI effect, even if they are currently underestimated (Stone, Vargo, and Habeeb, 2012).

There is an emerging role for planners in urban heat and air pollution debates (Stone, 2005), and urban literature and regulations on defining local measures are growing. The three main fields are:

- modifying urban ventilation and air movement through urban corridors,
- reducing thermal aspect and exhaust heat,
- reducing air pollutant emission.

Modifying the urban climate and comfort by urban design and altering ventilation and urban wind conditions offers perhaps the greatest potential (Givoni, 1998, pp. 256–266). Urban layout and orientation of streets with respect to wind direction, size, height and density of buildings, as discussed in the previous section, have a great impact on urban wind conditions, and can be controlled by urban planning design. For instance, reducing urban roughness will increase the wind speed and lower turbulence due to the friction between the buildings, ultimately resulting in alleviating heat and pollutant concentration within the urban canopy layer.

Thermal aspect can be reduced by several consolidated urban planning strategies, such as site layout: “road layout for passive solar design”, road layout to disperse pollutants” (Littlefair et al., 2000, pp. 50–53). Other measures “without altering city planning” (Che-Ani et al., 2009) are urban design interventions on the urban materials (i.e. albedo enhancements, such as cool pavements, cool roofs) (United States Environmental Protection Agency, 2008) and green roofs installation (United States Environmental Protection Agency, 2008, Chapter 3), tree planning and vegetation cover (Ng, Chen, Wang, and Yuan, 2012; Taha, 1997; United States Environmental Protection Agency, 2008, Chapter 2; Zhou and Shepherd, 2009), and on the urban geometry (i.e. increasing the sky view factor, modifying the H/W ratio). For instance, a combination of the above measures, and a reduction in the waste heat emission, has been proved to reduce citywide temperature by 1-7°C (Stone et al., 2012).
For an overall framework of measures to specifically mitigate UHI see Yamamoto’s paper (2006), and a recent paper review (Gago, Roldan, Pacheco-Torres, and Ordóñez, 2013).

Achieving a reduction of air pollutant emission is mostly connected to a decrease in energy use (i.e. building efficiency, site layout), and to the reduction of fossil fuel transportation, such as private car mobility (i.e. TOD development, relieving traffic congestion corners). However, strategies like achieving compactness and spreading activities within a city, may ultimately have unexpected counter effects, such as large area traffic generation or congestion (Fenger, 1999; Martins, 2012). Besides spatial planning, energy planning and transportation planning have a big role in improving urban climate and air quality within the urban environment.

Limiting responsibility by defining local measures		
Priority	**Objective**	**Measures**
1	Preservation	Measures for limiting, reducing the impact and consumptions (i.e. mobility)
2	Efficiency	Measures for increasing efficiency (i.e. energy)
3	Modification	Measures for modification of the urban structure (i.e. morphology)

Table 1-2
Local measured than urban planning can identify and implement in order to limit its responsibility in urban climate and air quality deterioration in cities. Source: author’s elaboration.

The complexity of the phenomena involved and of the urban structure, does not allow generic recommendations, but require a detailed spatial knowledge of heat and air pattern, only feasible through local scale mapping. See also Table 1-2 and Figure 1-12.

Causes	Effects	Mitigation strategies	Measures
Increased surface area Large vertical faces Reduced sky view factor 3-D geometry of buildings – canyon geometry	Increased absorption of shortwave (solar) radiation Decreased longwave (terrestrial) radiation loss Decreased total turbulent heat transport Reduced wind speeds	Modification of the urban form and fabric	High reflection building and road materials, high reflection paints for vehicles Spacing of buildings Variability of building heights Other urban morphology interventions: surface to volume ration, passive/non passive zones, orientation/ exposure, …
Surface materials Thermal characteristics	Higher heat capacities Higher conductivities Increased surface heat storage	Modification of the urban fabric	Reduce surface temperatures: changing albedo and emissivity (high reflecting roofing and paving material: cool roofs, cool pavements) Improved roof insulation
Moisture characteristics Urban areas have larger areas that are impervious	Shed water more rapidly – changes the hydrograph Increased runoff with a more rapid peak Decreased evapotranspiration (latent heat flux, QE)	Modification of the urban fabric	Porous pavement Neighbourhood detention ponds and wetlands which collect stormwater Increase greenspace fraction, urban trees managment Greenroofs, greenwalls
Additional supply of energy – anthropogenic heat flux – QF Electricity and combustion of fossil fuels: heating and cooling systems, machinery, vehicles. Air pollution Human activities lead to ejection of pollutants and dust into the atmosphere	anthropogenic emissions oh heat and pollutants in the local air (Increased longwave radiation from the sky Greater absorption and re-emission, 'greenhouse effect')	Preservation, Efficiency	Increase urban energy efficiency performances (increase buildings transmittance, minimum insulation values in building codes) Reduced solar loading internally, reduce need for active cooling (shades on windows, change materials) District heating and cooling systems Combined heat and power systems Increase renewables (requirements for wind, solar, geothermal sources) Decrease the use of private cars (ride sharing programs, transit investments, provision of pedestrian and cycling facilities)

Figure 1-12
Causes of urban warming and examples of mitigation strategies. Source: author's elaboration, adapted from cited source (C. S. B. Grimmond, 2007, p. 84) *inserting additional elements.*

The need for mapping for urban planning

Mapping urban climate and air quality, should be a base knowledge for urban planning: from the process of designing strategic plans to land use plans, to building codes. Since spatial planning has a big responsibility and also a big range of action, as shown in the previous section, it should improve the process of including more climatic and air quality arguments in the planning practices, and in the implementation of plans.

However, as briefly shown, while the strategies and measures are numerous, the relationship between the factors affecting urban climate and air quality is complex, and the effectiveness of the interventions tends to be different at different scales. At the same time, while several studies have focused their attention at the urban canyon level, few studies have estimated the contribution of those measures (on urban design, on land use) at the neighborhood level (C. S. B. Grimmond et al., 2010).

The complexity and interdisciplinary nature of the subject, and the scarceness of communication between urban climatology, environmental science, and urban planning, are likely among the causes of the lack of integration of the large body of knowledge concerning urban climate and air pollution into planning processes. However, there is an emerging role for planners in urban heat and air pollution debate, and urban literature and regulations on defining local measures is growing (Eliasson, 2000; Oke, 1984; Stone and Rodgers, 2001; Stone, 2005). Whilst this is probably confirmed at the building scale where these potential barriers have not prevented application of knowledge from climate, energy and environmental disciplines by planners, architects and engineers, this is not generally applied at the neighborhood scale.

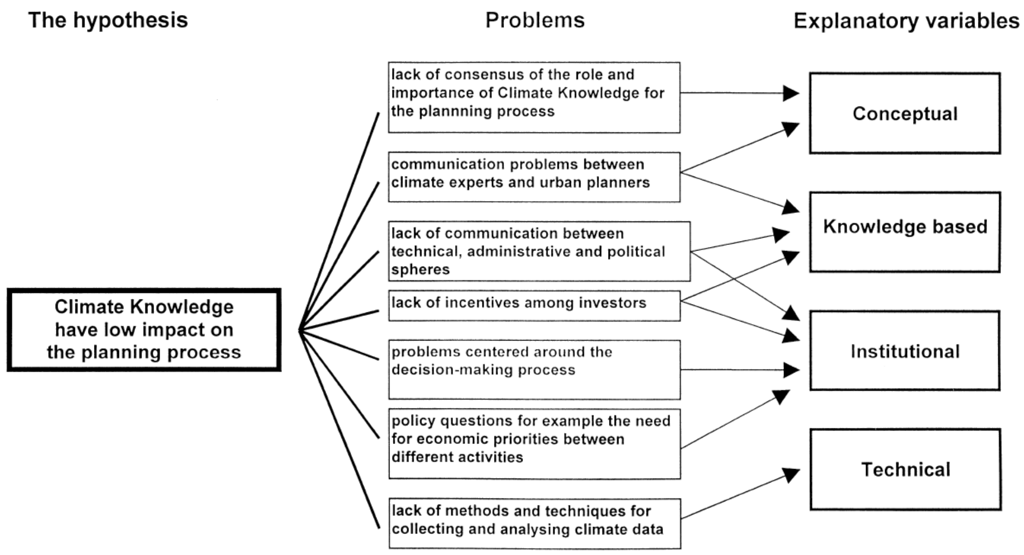


Table 1-3
Theoretical framework for explaining the low impact of climate knowledge on the planning processes (Eliasson, 2000, p. 35)

Mapping urban climate and air pollution at the neighborhood scale, helps understanding local inhabitants problems, such as UHI and air pollution concentration, and therefore facilitate the definition of specific addressed urban

planning and design measures. Mapping local phenomena at the pedestrian level, at the “people’s scale”, is the focus that need to be further developed in the research community, especially for urban climate and air quality, which affect people’s health.
It is important to emphasize that those phenomena are relevant at the local level and overlaid with people’s presence: exposure is what ultimately determines the health risk of citizens, and their movement and location in space and time need to be acknowledged in mapping UHI and air quality.
In addition, another underrated aspect requires underlining: in mapping urban climate and air quality, the more relevant aspect of an individual’s health is not simply heat or pollutants emitted but instead the surpassing of specific thresholds; mapping therefore needs to be addressed by identifying sensitive urban-climatic and environmental problem areas ("Hot-spots”, where heat or pollutants exceeds health limits, as defined by epidemiological and health studies).

The heat alert system implemented by the City of Toronto in 1999, considered a premiere example of heatwaves adaptation, and the recent mapping project. To ensure that municipal and community response services (such as heat-related services to isolated seniors, homeless, etc.) are delivered where they are mostly needed, the Toronto Public Health designed GIS maps liked to current epidemiology knowledge about heat-related factors; the project’s prototype maps characterize the spatial variation of factors that are likely to contribute (Figure 1-13).

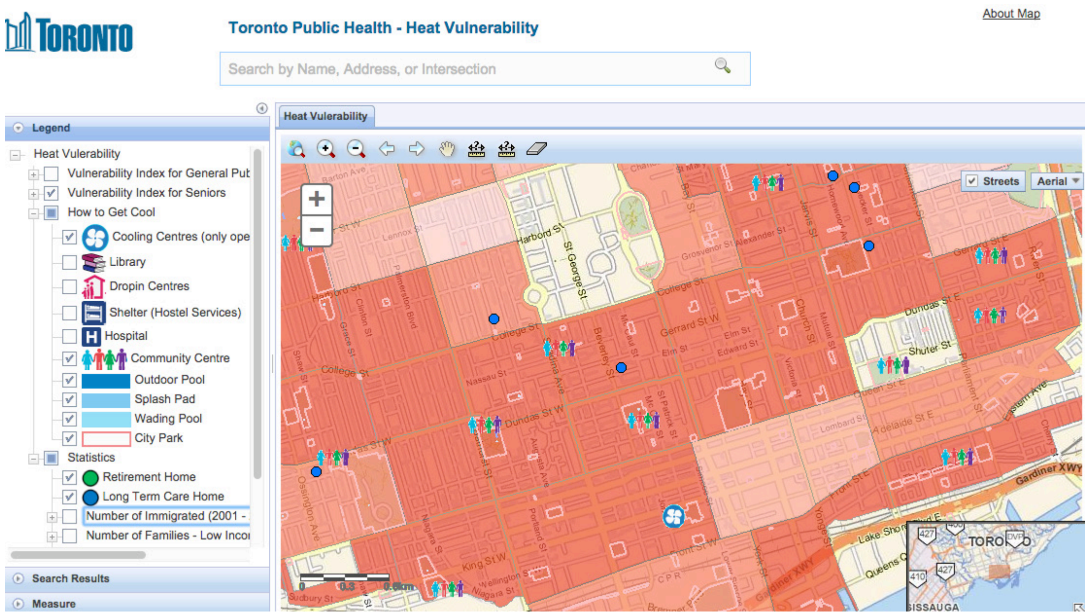


Figure 1-13
Maps help to target hot weather response where it is needed most (“Toronto Public Health - Heat Vulnerability,” n.d.).

Mapping environmental features at the pedestrian/neighborhood level, the main focus of this work, such as urban climate and air pollution, is the base knowledge for "sustainable" and "smart" planning. For instance, the New Urbanism movement stresses the attention to the neighborhood level, to the design of "compact, pedestrian-friendly and mixed-use" (Congress for the New Urbanism, 2013, pt. 11), and the sustainable urbanism concepts and design practices promoted, specifically fostering sustainable, walkable neighborhoods (Duany, Speck, and Lydon, 2009, Chapter 6; Farr, 2012, Chapter 7).
Additionally, recent protocols, such as the Ecodistricts protocol ("EcoDistricts | Revitalizing cities from the neighborhood up," n.d.), and rating systems, such as LEED-ND developed by the U.S. Green Building Council and the Congress for the New Urbanism (United States Green Building Council, 2014), have specifically addressed neighborhood health-wellbeing, and outdoor climate and air quality as one of their main components.
In addition, most of the spatial planning tools designed for improving urban quality and sustainability is multi-scalar but with a strong emphasis at the neighborhood level; for example, popular tools like INDEX ("Criterion Planners – Planning Support Tools," n.d.), Climate-Neighbor ("Climate Neighbor," n.d.) and I-PLACE3S ("I-PLACE3S," n.d.), are focused on mapping urban characteristics for neighborhood scenarios (Condon, Cavens, and Miller, 2009). However, while they include climate and environmental factors, such as air emissions from transportation or energy consumption from house cooling, their health and climate evaluations are limited (such as greenhouse gas and walkability), and do not currently assess local climate and air quality, such as heat and pollutant concentration and their consequences on discomfort and health.

For models and tools specifically designed for urban local climate and air quality, not commonly used for planning, but rather used for technical in-depth analysis, such as Envimet, see § 2.1.A.

1.3.B - EFFECT OF CLIMATE CHANGE, AND THE URGENCY FOR LOW CARBON AND RESILIENT CITIES

- Effects of climate change and heatwaves on urban climate and air quality
- Limiting effects by planning low carbon and resilient cities
- The need for mapping for environmental-climate planning

Effects of climate change and heatwaves on urban climate and air quality

According to the last IPCC report, the "Fifth Assessment Report" finalized in November 2014 (International Panel on Climate Change, 2014), climate change is happening with widespread impact on human and natural systems, and is projected to continue posing serious challenges for cities. Anthropogenic influence on climate is clear, and GHG emissions coming from urban activities are at their highest level in history. Extreme weather events resulting, such as heatwaves, floods, and droughts are expected to happen more frequently, if action is not taken. Continued GHG emissions will cause further atmospheric warming and climate changes in its components, increasing the likelihood of "severe, pervasive and irreversible impacts for people and ecosystems".
However, several complementary mitigation and adaptation strategies can be designed to help reduce and manage the risks of climate change with policies and cooperation at all scales.

Over half of the world's population live in urban areas, where climate change will be most apparent in everyday life, with stark impact on city economies and wealth. Climate change causes added stress on urban areas, through increased numbers of floods, droughts and increased numbers of heatwaves threatening the health of inhabitants, especially the elderly and the people whose health is already compromised. In the last report of the Urban Climate Change Research Network, UCCRN (Rosenzweig, Solecki, Hammer, and Mehrotra, 2011), twelve cities (Athens, Dakar, Delhi, Harare, Kingston, London, Melbourne, New York, São Paulo, Shanghai, Tokyo, and Toronto) were analyzed in their urban climate process, trends and projections. Results showed that:

- UHI is a challenge for most cities considered; they already tend to be warmer than the surrounding areas due to "urbanization" factors (concrete core and heat absorption, increase of soil sealing, removal of vegetation, etc.); (see also 1.1.B)
- Air pollution is exceeding WMO thresholds, and acute and chronic health hazards for urban residents are likely linked to pollutants concentration in urban; (see also 1.2.B)
- Climate extremes, besides determining floods and drought, will cause a projected temperature increase of between 1°C and 4°C by the 2050s. Most cities are likely to expect more frequent, more severe, and longer lasting heatwaves than they have experienced in the past. Climate change is likely to exacerbate health risks in cities and to create new ones, such as: respiratory illness due to worsening air quality related to temperature

increase, morbidity and mortality as a result of stress from UHI and heatwaves,

At the same time, cities are responsible for at least 40% of the global GHG emissions.
Given the current global trends in demographic increase and in the uninterrupted rural to urban shift, cities' responsibility is likely to increase over time.
In his recent work (Calthorpe, 2011), Calthorpe assesses the impact of urban strategies and conditions, or "urbanism", by comparing urban policies and 1950s-2000s change (in households, neighborhoods, urban transportation, and urban energy) with the environmental impact (carbon emission, carbon footprint). In the four urbanism scenarios for America 2050 ("trend sprawl urbanism" "simple urbanism", "green sprawl urbanism", "green urbanism"), impacts are estimated to be very different on land consumption, mix of housing, water consumption, building energy and infrastructure cost. Reaching carbon neutrality seems to be achievable, and altogether produces co-benefits for a sustainable future.

Nevertheless urgent action is needed, and urban planning has a big role in improving cities; in order to face the climate change challenges, urban planning and design need to urgently implement mitigation and adaptation strategies into their practice.

Limiting effects by planning low carbon and resilient cities

§ 1.3.A introduced the role of urban planning and the need for limiting its responsibility by mapping and defining local measures. The same approach is here presented in the context of climate change adaptation and mitigation, where strategies and measures are currently addressed at a higher scale (city scale, regional or global scale), but it would be desirable an integration of the two approaches (measures/ strategies/ plans/ policies for local urban climate modification and global climate change).

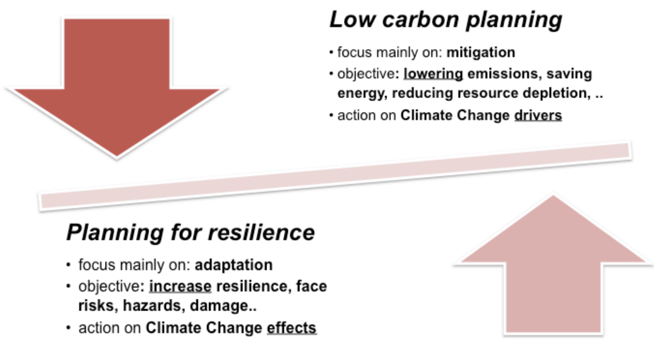
Several complementary mitigation and adaptation strategies can be designed and adopted by urban planning and design to help reduce and manage the risks of climate change. While promoting investments in innovation and technologies, urban planning and effective governance can enhance sustainable livelihoods, and behavioral and lifestyle choices.

Mitigation options addressed to climate change causes, are associated to the concept of "renewable city" (Droege, 2006); a "low carbon tomorrow" for cities and regions (Treville and Dosi, 2012) includes mitigation options such as: reducing GHG net emissions, reducing energy use, decarbonizing energy supply, reducing GHG intensity of end-use sectors, and increasing "carbon sinks." Hence, mitigation strategies are strongly connected to the urban energy transition (Droege, 2009, 2011), and many cities are setting carbon emission reduction targets (see for example in the Masterplan for Sonderborg, DK, with the ambitious objective of becoming carbon-neutral by 2029, starting with its "world best district heating system") ("ProjectZero," n.d.).

Adaptation options are addressed to climate change effects, and are sometimes related to the "resilient" ecological concept: "climate-resilient urban design" requires expanding traditional place-making urban design qualities to include principles such: resilience and adaptive, comfort and environmental permeability, resource efficiency and re-use synergy, biotic support and environmental diversity, health and pathological prevention (Raven, 2011). For instance, adapting to UHI harmful effects, especially in the case of heatwaves, is an adaptation strategy that increases urban resilience; climate action plans can enforce local-scale UHI management (Stone et al., 2012).
Examples of urban planning and design measures, for both mitigation and adaptation, can be found in Droege's work (2010), and international platforms such as European ADAPT platform ("Climate-ADAPT," n.d.) and ICLEI ("ICLEI," n.d.).

Potential synergies and conflicts between measures designed for mitigation and measures designed for adaptation may occur. Considering UHI air pollution concentration in urban environment, measures such as increasing green areas, reducing traffic congestion, and promoting a smart grid network have all made a synergic effect by reducing emissions through mitigation and increasing resilience through adaptation. Potential conflict might occur in the case of urban densification strategies: while limiting sprawl and mitigating emissions, potential impact on UHI can occur if urban design practice is not properly addressed to resilience and adaptation (see Figure 1-14)(Treville and Minucci, 2012).

			Examples of territorial planning interventions		
			Proactive	*Regulatory*	*Strategic coordination*
			Through plans, strategies, SPG; resource mobilisation	*Through development control*	*Through consultation / collaboration*
Mitigation Strategies	Power sector (Energy Supply)	Large renewables	Site allocation / identification	Infrastructure Planning Commission	Renewable energy industry / local communities etc
		Small renewables & micros	Specific requirements	Permitted development	Energy and insurance companies
		Carbon Sinks and Carbon Capture and Storage	Site allocation / identification	Infrastructure Planning Commission	Fuel industry (oil companies etc)
	Built Environment	Increasing energy efficiency (buildings)	incentives on refurbishment, retrofitting	local and regional regulations	Builging sector, Neighborhood associations
		Improving infrastructures integration and reducing emissions	low carbon wate and sewage systems, efficient waste systems, etc.	regional and local sectorial planning	Regional and local authorities, Public Services Agencies
	Transport	Reducing dependency upon private car	sustainable mobility incentives	public mobility plan (bikelanes, etc.)	mobility managers/ transport authorities
		Reducing travel and urban sprawl	Settlement size, density, mixed use location and accessibility, parking	traffic plans	Developers / transport authorities Etc
	Agriculture and Forestry	Reducing emissions	Low carbon agricultures	land use management	Farmers Associations
		increase of CO2 sequestration	green areas, woods, etc.	forest management	Regional Authorities
		Reducing albedo	natural and dead barriers/ mulching/cover crops	Desertification Plan/UNCCD Convention	Regional Authorities
	Water	Lowering energy implications of water systems	incentives for enhancing water consumption, sanitaritazion plans	Permitted development, water consumption monitoring and bills system	Local and Regional Authority, Developers
	Natural Disaster, NaTech and Climate Change	Lowering emissions connected to natural disasters	Studies on vulnerabilities/ Multi-hazards assessment, emergency plans	Planning conditions, Design standards	National, Regional and Local level



Adaptation Strategies	Power Sector	Diversification, diffusion of energy producers in the territory	Energy Efficient machinary , smart grids	Energy Adaptive Plans, Building Energetic Certification	Developers, Energy industry
	Built Environment	City/neighborhood scale	Avoiding urban heat islands, promoting green urban areas, flood risk systems (elevation from groundlevel, etc.)	Planning conditions, Code for Sustainable Homes	Developers
	Transportation	discouraging use of car	Protecting & enhancing green infrastructure	Mobility plan	Regional and local authorities, Transportation Associations
	Agriculture and Forestry	low input approach	organic agriculture	Organic Quality trademarks	Farmers Associations
		promoting urban and regional park	establishment of green area, natural park near to urban areas, artificial shelters	Masterplan, Landscape Plan, Climate Change Adaptation Plans	Local and Regional Authority
		promoting biofuels	biomass, biogas	Energy Plans, Forest Management Plan	Renewable energy industry / Local communities etc
	Water	flood risk prevention	irrigation and drainage improvements, infrastructure maintenance, water recycle systems, adaptive water resource management	Permitted development	River Basin Authorities, Water Associations, Local Communities
	Natural Disaster, NaTech and Climate Change	floods, landslides, etc. prevention	insurance converage, strategic development or land use plans	protocols for restoration or reconstruncions	River Basin Authorities, Water Associations, Local Communities, Stakeholders

Figure 1-14
Low Carbon Planning as an opportunity to build a more resilient city (extract from the poster presented for ICLEI Resilient Cities 2012, Bonn) (Treville and Minucci, 2012)

While hundreds of cities world are developing mitigation plans, less local governments have worked on adaptation plans. Among them, the following are noteworthy: London Climate Plan ("London Climate Plan," n.d.), an early model, and original in its partnership with political leadership, New York PlaNYC2030 ("PlaNYC," n.d.), as a successful model for integrated mitigation/adaptation planning, and Toronto Climate Plan ("Climate Change, Clean Air and Sustainable Energy Action Plan," 2007), as example of adaptation options developed for two areas of impact, such as heat and energy use (Rosenzweig et al., 2011, para. 8.6). However, they currently have little or no consideration of small-scale climate and measures, as intended in this work.

While some progress is being made, for the most part at the city and local level there is no standardized data and no established set of urban indicators that measure the effect of climate change and that assess its risks (Rosenzweig et al., 2011, para. 9.2.4). On the one hand, there is a need for comparable measurements and models, downscaling advanced global and national protocols. On the other hand, there is a need to standardize methodologies used to collect and monitor data at the local level, among them, urban climate and air quality data by air sensing.
It is important to stress the need for local urban climate and air quality studies in order to define standards and measures, with a focus on local scale effect, and its contribution to the larger, global, scale (see § 2.1.B, and § 2.2.B).

The need for mapping for environmental-climate planning

Recent plans are increasingly including mapping and regulation of environmentally sensitive, or critical areas, such as floodplains, watershed areas, or erodible soils and endangered species habitats (Rosenzweig et al., 2011, para. 8.6).
In the case of adaptation planning, climate and environmentally sensitive area mapping can help identify urban areas prone to climate change effects, such as "hot-spots" areas where heat and pollution concentrate. As discussed in the next chapter 2, such mapping should be based on local air sensing, integrated to (downscaled) climate models that incorporate urban conditions (fabric, form, functions).
In the case of mitigation planning, such as energy plans, mapping urban climate and air pollution can be a base knowledge from which the planning process can develop; urban blocks' energy consumption for heating and cooling is linked to the local outdoor temperature, and a better mapping of the outdoor climate will support designing appropriate measures.

Urban planners will need to contribute to and collaborate with interdisciplinary teams of climatologists and natural scientists in order to model impact and response, and develop adaptation plans with measures. Environmental planning challenges the urban planning profession to include a wider knowledge base of cities, people, nature, and of interdisciplinary modeling methods.
Climate Plans, for example, usually require assessing environmental parameters, such as CO2 balance, LCA analysis, and energy balance, which demand linking the local level to the global scale. After the scenario building, Climate Plans at the local and city level usually include the definition and evidence of detailed mitigation and adaptation measures, and their spatial and temporal scale. However, there is no doubt that mapping urban climate and air quality at the local level is essential for Climate Plans, in both building base data, and in predicting urban response.
In addition, mapping overtime helps to verify the effectiveness of the implementation of such measures: monitoring the implementation of measures, and verifying their effect is one of the main requirements of modern environmental planning. European Regional environmental plans, and all recent urban plans, such as territorial plans, for instance, always require a monitoring process, included in their Strategic Environmental Assessment (Treville, 2012). Monitoring effectiveness and efficiency is also one of the features of the "smart city" planning (see § 2.3)

Finally, considering the, exposure and vulnerability of a population to UHI or climate change hazards, such as heatwaves, or to air pollution emissions, such as fine particulates, planning tools specifically addressing health can benefit from mapping urban climate and air quality at the local level. For example Health Impact Assessment (HIA), that is likely to be used more frequently in planning processes, require fine grained data for both environmental pollutants stressors and vulnerable communities.

For the need for mapping at the "local scale", in order to improve air mapping, see § 2.3.B.

Conclusion

This chapter introduced urban climate and air quality as “urban” and “local” problems with harmful effects on which urban planning has a big role. Because the phenomena involved have a strong local urban component, urban planning can define local measures in order to limits its responsibility.
Mapping is therefore the planning tool to increase knowledge for both urban planning/design and climate/environmental planning.

The next chapter will explore “mapping” in order to increase knowledge of urban climate and air quality for urban planning interventions.

References

Air Quality Standards - Environment - European Commission. (n.d.). Retrieved December 28, 2014, from http://ec.europa.eu/environment/air/quality/standards.htm

Alberti, M. (2008). *Advances in urban ecology: integrating humans and ecological processes in urban ecosystems*. Boston, MA: Springer New York. doi:10.1007/978-0-387-75510-6

Anderson, R. J., & Crocker, T. D. (1971). Air Pollution and Residential Property Values. *Urban Studies*, *8*(3), 171–180. doi:10.1080/00420987120080391

Anselin, L., & Lozano-Gracia, N. (2008). Errors in variables and spatial effects in hedonic house price models of ambient air quality. *Empirical Economics*, *34*(1), 5–34.

Baccini, M., Biggeri, A., Accetta, G., Kosatsky, T., Katsouyanni, K., Analitis, A., … Michelozzi, P. (2008). Heat effects on mortality in 15 European cities. *Epidemiology (Cambridge, Mass.)*, *19*(5), 711–719. doi:10.1097/EDE.0b013e318176bfcd [doi]

Barbesta, M., & Schaffer, D. (2009). Concrete that Cleans Itself and the Air. *Concrete International*, *31*(2), 49–51.

Blečić, I., Cecchini, A., Falk, M., Marras, S., Pyles, D. R., Spano, D., & Trunfio, G. A. (2014). Urban metabolism and climate change: A planning support system. *International Journal of Applied Earth Observation and Geoinformation*, *26*, 447–457.

Brook, R. D., Rajagopalan, S., Pope III, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V, … American Heart Association Council on Epidemiology and Prevention and Council on Nutrition,Physical Activity and Metabolism, C. on the K. in C. D. (2010). Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation*, *121*(21), 2331–2378. doi:10.1161/CIR.0b013e3181dbece1 [doi]

Burton, E., Jenks, M., & Williams, K. (2003). *The compact city: a sustainable urban form?*. Routledge.

Calthorpe, P. (2011). *Urbanism in the age of climate change*. Washington, DC: Island Press.

Carneiro, C., Morello, E., Ratti, C., & Golay, F. (2009). Solar Radiation over the Urban Texture: LIDAR Data and Image Processing Techniques for Environmental Analysis at City Scale. In J. Lee & S. Zlatanova (Eds.), *3D Geo-Information Sciences* (Vol. 2009, pp. 319–435). Springer.

Chandler, T. (1965). *The climate of London* (p. 292). London, UK: Hutchinson & Co. Retrieved from http://books.google.com/books?hl=en&lr=&id=P2gFAAAAQAAJ&oi=fnd&pg=PA361&dq=The+Climate+Of+London&ots=4mzVvHXnTV&sig=nwHLJuY9SAwtd8eHkq7SovyIzXM

Chay, K. Y., & Greenstone, M. (2005). Does Air Quality Matter? Evidence from the Housing Market. *Journal of Political Economy*, *113*(2), 376–424. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=16477827&site=ehost-live

Che-Ani, A. I., Shahmohamadi, P., Sairi, A., Mohd-Nor, M. F. I., Zain, M. F. M., & Surat, M. (2009). Mitigating the urban heat island effect: some points without altering existing city planning. *European Journal of Scientific Research*, *35*(2), 204–216.

Chen, L., & Ng, E. (2009). Sky View Factor Analysis of Street Canyons And Its Implication For Urban Heat Island Intensity. *plea2009.arc.ulaval.ca*, *2*, 22–24. Retrieved from http://www.plea2009.arc.ulaval.ca/Papers/1.CHALLENGE/1.2 City/ORAL/1-2-07-PLEA2009Quebec.pdf

Climate Change, Clean Air and Sustainable Energy Action Plan. (2007). Retrieved December 29, 2014, from http://www1.toronto.ca/City Of Toronto/Environment and Energy/Programs for Residents/Files/pdf/C/clean_air_action_plan.pdf

Climate Neighbor. (n.d.). Retrieved December 29, 2014, from http://crit.com/portfolio/climate-neighbor/

Climate-ADAPT. (n.d.). Retrieved December 29, 2014, from http://climate-adapt.eea.europa.eu/

Condon, P. M., Cavens, D., & Miller, N. (2009). *Urban planning tools for climate change mitigation*. Lincoln Institute of Land Policy Cambridge, MA.

Congress for the New Urbanism. (2013). *Charter of the new urbanism*. (E. Talen, Ed.) (Vol. Second edi). McGraw-Hill Professional.

Criterion Planners – Planning Support Tools. (n.d.). Retrieved December 29, 2014, from http://crit.com/our-portfolio/planning-support-software/

Cui, L., & Shi, J. (2012). Urbanization and its environmental effects in Shanghai, China. *Urban Climate*, *2*(0), 1–15. doi:http://dx.doi.org/10.1016/j.uclim.2012.10.008

Deguen, S., & Zmirou-Navier, D. (2010). Social inequalities resulting from health risks related to ambient air quality--A European review. *European Journal of Public Health*, *20*(1), 27–35. doi:10.1093/eurpub/ckp220 [doi]

Di Sabatino, S., Leo, L. S., Cataldo, R., Ratti, C., & Britter, R. (2010). Construction of digital elevation models for a southern European city and a comparative morphological analysis with respect to Northern European and North American cities. *Journal of Applied Meteorology and Climatology*, *49*(7), 1377–1396. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77957727742&partnerID=40&md5=ed542b6e542f0ed060350be7138351dc

Droege, P. (2006). *The renewable city: a comprehensive guide to an urban revolution*. Wiley-Academy Chichester, UK.

Droege, P. (2009). *100% renewable: energy autonomy in action*. (P. Droege, Ed.) (p. 326). London, UK: Earthscan. Retrieved from http://books.google.com/books?hl=en&lr=&id=2ahMx9eh7m0C&oi=fnd&pg=PP2&dq=100%+Renawable.+Energy+autonomy+in+Action&ots=Xp4wo6bJQq&sig=6YpIvGHOPFCBOMo7QpKycbRkXcA

Droege, P. (2010). *Climate Design: Design and Planning for the Age of Climate Change*. ORO editions.

Droege, P. (2011). *Urban energy transition: from fossil fuels to renewable power*. Elsevier. Retrieved from http://books.google.com/books?hl=en&lr=&id=0bEecvixZRMC&oi=fnd&pg=PP2&dq=Urban+Energy+Transition.+From+Dossil+Fuels+to+Renawable+Power&ots=vOEggENude&sig=5unS6vSSqvkJr9wvsSkt0baUfvU

Duany, A., Speck, J., & Lydon, M. (2009). *The Smart Growth Manual* (Vol. 5, p. 240). McGraw Hill Professional. Retrieved from http://books.google.com/books?id=ESjbAgAAQBAJ&pgis=1

Dunne, J. P., Stouffer, R. J., & John, J. G. (2013). Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, *3*(6), 563–566.

EcoDistricts | Revitalizing cities from the neighborhood up. (n.d.). Retrieved December 29, 2014, from http://ecodistricts.org/

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*(1), 31–44. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204600000347

Emmanuel, M. R. (2005). *An Urban Approach to Climate-sensitive Design: Strategies for the Tropics*. Retrieved from http://books.google.com/books?hl=it&lr=&id=D7OJ23XA-18C&pgis=1

European Environment Agency. (2006). *Urban sprawl in Europe - The ignored challenge*. *EAA Report* (Vol. 10, p. 58). Copenhagen, DK. Retrieved from http://www.eea.europa.eu/publications/eea_report_2006_10/eea_report_10_2006.pdf

European Environment Agency. (2012). *Urban adaptation to climate change in Europe: Challenges and opportunities for cities together with supportive national and European policies* (Vol. 2/2012). Copenhagen: EEA.

European Environment Agency. (2014). *Air quality in Europe - 2014 Report* (p. 82). Copenhagen, DK: European Environment Agency. Retrieved from http://www.eea.europa.eu/publications/air-quality-in-europe-2014

Fanger, P. O. (1970). *Thermal comfort: analysis and applications in environmental engineering* (p. 244). McGraw-Hill. Retrieved from http://books.google.com/books?ei=ZuUOSsztFouqNpXHvbIJ&id=mUFSAAAAMAAJ&pgis=1

Farr, D. (2012). *Sustainable Urbanism: Urban Design With Nature* (p. 305). Hoboken, New Jersey: John Wiley & Sons. Retrieved from http://books.google.com/books?hl=it&lr=&id=6he0qcS3ZaUC&pgis=1

Fenger, J. (1999). Urban air quality. *Atmospheric Environment*, *33*(29), 4877–4900. doi:http://dx.doi.org.libproxy.mit.edu/10.1016/S1352-2310(99)00290-3

Foley, J. a, Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., … Snyder, P. K. (2005). Global consequences of land use. *Science (New York, N.Y.)*, *309*(5734), 570–574. doi:309/5734/570 [pii]

Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749–758. doi:10.1016/j.rser.2013.05.057

Gal, T., & Sumeghi, Z. (2007). Mapping the roughness parameters in a large urban area for urban climate applications. *Acta Climatologica ET Chorologica*, *40-41*, 27–36. Retrieved from http://www2.sci.u-szeged.hu/eghajlattan/akta07/027-036.pdf

Gennaio, M.-P., Hersperger, A. M., & Bürgi, M. (2009). Containing urban sprawl—Evaluating effectiveness of urban growth boundaries set by the Swiss Land Use Plan. *Land Use Policy*, *26*(2), 224–232.

Givoni, B. (1998). *Climate considerations in building and urban design*. *Building* (pp. 241–300). Retrieved from http://books.google.com/books?id=MGkArZ_berAC&pgis=1

Grimmond, C. S. B. (2007). Urbanization and global environmental change: local effects of urban warming. *Geographical Journal*, *173*(1), 83–88. doi:10.1111/j.1475-4959.2007.232_3.x

Grimmond, C. S. B., Blackett, M., Best, M. J., Barlow, J., Baik, J. J., Belcher, S. E., … Zhang, N. (2010). The international urban energy balance models comparison project: First results from phase 1. *Journal of Applied Meteorology and Climatology*, *49*(6), 1268–1292. Retrieved from http://journals.ametsoc.org/doi/abs/10.1175/2010JAMC2354.1

Hirano, Y., & Fujita, T. (2012). Evaluation of the impact of the urban heat island on residential and commercial energy consumption in Tokyo. *Energy*, *37*(1), 371–383.

Howard, L. (1818). *The climate of London* (p. 221). Retrieved from http://books.google.com/books?hl=en&lr=&id=P2gFAAAAQAAJ&oi=fnd&pg=PA361&dq=The+cliamte+of+London&ots=4mzVvHWsXT&sig=Z0k_EPGU85wB0yQNNhWw6TlsHSc

I-PLACE3S. (n.d.). Retrieved December 29, 2014, from http://www.sacog.org/services/scenario-planning/

Ichinose, T., Shimodozono, K., & Hanaki, K. (1999). Impact of anthropogenic heat on urban climate in Tokyo. *Atmospheric Environment*, *33*(24-25), 3897–3909. doi:10.1016/S1352-2310(99)00132-6

ICLEI. (n.d.). Retrieved December 29, 2014, from http://www.iclei.org/

Ihara, T., Kikegawa, Y., Asahi, K., Genchi, Y., & Kondo, H. (2008). Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures. *Applied Energy*, *85*(1), 12–25. doi:10.1016/j.apenergy.2007.06.012

International Panel on Climate Change. (2014). *Fifth Assessment Report - Synthesis Report* (p. 43). Retrieved from http://www.ipcc.ch/report/ar5/syr/

Jalkanen, L. (2012). WMO/IGAC impacts of megacities on air pollution and climate. *Urban Climate*, *1*(0), 67–68. doi:http://dx.doi.org/10.1016/j.uclim.2012.10.004

Jankovic, V. (2013). A historical review of urban climatology and the atmospheres of the industrialized world. *WIREs: Climate Change*, *4*(6), 539. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=90674342&site=eds-live

Jerrett, M., Burnett, R. T., Ma, R., Pope, C. A., Krewski, D., Newbold, K. B., … Thun, M. J. (2005). Spatial Analysis of Air Pollution and Mortality in Los Angeles. *Epidemiology*, *16*(6), 727–736. doi:10.1097/01.ede.0000181630.15826.7d

Kalnay, E., & Cai, M. (2003). Impact of urbanization and land-use change on climate. *Nature*, *423*(May). doi:10.1038/nature01649.1.

Kasanko, M., Barredo, J. I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V., & Brezger, A. (2006). Are European cities becoming dispersed?: A comparative analysis of 15 European urban areas. *Landscape and Urban Planning*, *77*(1), 111–130.

Kikegawa, Y., Genchi, Y., Kondo, H., & Hanaki, K. (2006). Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning. *Applied Energy*, *83*(6), 649–668.

Kolokotroni, M., Ren, X., Davies, M., & Mavrogianni, A. (2012). London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and Buildings*, *47*(0), 302–311. doi:10.1016/j.enbuild.2011.12.019

Kratzer, A. (1956). *The climate of cities*. *Scientific American*. Bedford, Massachusetts: Air Force Cambridge Research Laboratories. Retrieved from http://adsabs.harvard.edu/abs/1967SciAm.217b..15L

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., … Calle, E. E. (2009). *Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality*. Health Effects Institute Boston, MA.

Landsberg, H. (1981). *The urban climate* (p. 275). New York: Academic Press. Retrieved from http://books.google.com/books?hl=en&lr=&id=zkKHiEXZGBIC&oi=fnd&pg=PP2&dq=The+Urban+Climate&ots=-jZeXArFLb&sig=RGGCnEokQ_OcWVImDDISGwqMC04

Landsberg, H. E. (1973). The meteorologically utopian city. *Bulletin of the American Meteorological Society*, *54*(2), 86–89.

Littlefair, P., Santamouris, M., Alvarez, S., Dupagne, A., Hall, D., Teller, J., … Papanikolaou, N. (2000). *Environmental site layout planning: solar access, microclimate and passive cooling in urban areas*. *BRE Report BR* (p. 151). London, UK: CRC. Retrieved from http://orbi.ulg.ac.be/handle/2268/28963

London Climate Plan. (n.d.). Retrieved December 29, 2014, from http://www.london.gov.uk/thelondonplan/climate/

Makido, Y., Dhakal, S., & Yamagata, Y. (2012). Relationship between urban form and CO 2 emissions: Evidence from fifty Japanese cities. *Urban Climate*, *2*, 55–67.

Martins, H. (2012). Urban compaction or dispersion? An air quality modelling study. *Atmospheric Environment*, *54*(0), 60–72. doi:http://dx.doi.org.libproxy.mit.edu/10.1016/j.atmosenv.2012.02.075

Middel, A., Häb, K., Brazel, A. J. A., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, *122*, 16–28. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204613002120

Millward, H. (2006). Urban containment strategies: A case-study appraisal of plans and policies in Japanese, British, and Canadian cities. *Land Use Policy*, *23*(4), 473–485.

Morello, E., & Ratti, C. (2009). Sunscapes: "Solar envelopes" and the analysis of urban DEMs. *Computers, Environment and Urban Systems*, *33*(1), 26–34. doi:10.1016/j.compenvurbsys.2008.09.005

Narumi, D., Kondo, A., & Shimoda, Y. (2009). Effects of anthropogenic heat release upon the urban climate in a Japanese megacity. *Environmental Research*, *109*(4), 421–431.

National Ambient Air Quality Standards (NAAQS) | Air and Radiation | US EPA. (n.d.). Retrieved December 28, 2014, from http://www.epa.gov/air/criteria.html

Ng, E., Chen, L., Wang, Y., & Yuan, C. (2012). A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. *Building and Environment*, *47*, 256–271.

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, *4*(3), 115–123.

Nuissl, H., Haase, D., Lanzendorf, M., & Wittmer, H. (2009). Environmental impact assessment of urban land use transitions—A context-sensitive approach. *Land Use Policy*, *26*(2), 414–424. doi:http://dx.doi.org/10.1016/j.landusepol.2008.05.006

Oke, T. R. (1976). The distinction between canopy and boundary-layer urban heat islands. *Atmosphere*, *14*(4), 268–277. doi:10.1080/00046973.1976.9648422

Oke, T. R. (1981). Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations. *Journal of Climatology*, *1*(3), 237–254. doi:10.1002/joc.3370010304

Oke, T. R. (1984). Towards a prescription for the greater use of climatic principles in settlement planning. *Energy and Buildings*, *7*(1), 1–10.

Oke, T. R. (1987). *Boundary layer climates* (Second., Vol. Routledge, p. 435). London and New York: Routledge. Retrieved from http://books.google.com/books?hl=en&lr=&id=K_2dW7crfVIC&oi=fnd&pg=PP1&dq=Boundary+Layer+Climates&ots=112YqtIAbW&sig=OpORoBqDxjfdojOonDHY-OjpGzk

Oke, T. R. (1997). Urban climates and global change. In A. Perry & R. Thomson (Eds.), *Applied climatology: principles and practice* (pp. 273–287). London, UK: Routledge.

Oke, T. R. (2004). *Initial guidance to obtain representative meteorological observations at urban sites*. *geog.ubc.ca* (Vol. 81). World Meteorological Organization Geneva. Retrieved from http://www.geog.ubc.ca/~toke/IOM-81-UrbanMetObs.pdf

Oke, T. R. (2006). Towards better scientific communication in urban climate. *Theoretical and Applied Climatology*, *84*(1-3), 179–190.

Pielke, R. A. (2005). Land use and climate change. *Science (New York, N.Y.)*, *310*(5754), 1625–1626. doi:310/5754/1625 [pii]

Pileri, P., & Maggi, M. (2010). Sustainable planning? First results in land uptakes in rural, natural and protected areas: the Lombardia case study (Italy). *Journal of Land Use Science*, *5*(2), 105–122.

Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and Urban Planning*, *107*(3), 193–202. doi:10.1016/j.landurbplan.2012.06.006

PlaNYC. (n.d.). Retrieved December 29, 2014, from http://www.nyc.gov/html/planyc/html/home/home.shtml

Pope III, C. A., & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association*, *56*(6), 709–742. doi:10.1080/10473289.2006.10464485

ProjectZero. (n.d.). Retrieved December 29, 2014, from http://www.projectzero.dk/

Ratti, C., Di Sabatino, S., & Britter, R. (2006). Urban texture analysis with image processing techniques: Winds and dispersion. *Theoretical and Applied Climatology*, *84*(1-3), 77–90. doi:10.1007/s00704-005-0146-z

Raven, J. (2011). Cooling the Public Realm: Climate-Resilient Urban Design. In *Resilient Cities* (pp. 451–463). Springer.

Ridker, R. G., & Henning, J. A. (1967). The determinants of residential property values with special reference to air pollution. *The Review of Economics and Statistics*, 246–257. Retrieved from http://www.jstor.org/stable/1928231

Rosenzweig, C., Solecki, W. D. W., Hammer, S. A. S., & Mehrotra, S. (2011). *Climate change and cities: first assessment report of the Urban Climate Change Research Network*. Cambridge University Press. Retrieved from http://books.google.com/books?hl=en&lr=&id=9GHW24KCuBYC&oi=fnd&pg=PR7&dq=Climate+Change+and+Cities.+First+Assessment+Report+of+the+Urban+Climate+Change+Research+Network&ots=_2rzZWs1QD&sig=T36sbMPIw0uDhlWBVb-7pulOsYo

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., & Assimakopoulos, D. N. (2001). On the impact of urban climate on the energy consumption of buildings. *Solar Energy*, *70*(3), 201–216.

Schindler, M., & Caruso, G. (2014). Urban compactness and the trade-off between air pollution emission and exposure: Lessons from a spatially explicit theoretical model. *Computers, Environment and Urban Systems*, *45*, 13–23. doi:10.1016/j.compenvurbsys.2014.01.004

Seinfeld, J. H., & Pandis, S. N. (2012). *Atmospheric chemistry and physics: from air pollution to climate change*. John Wiley & Sons.

Shahmohamadi, P., Che-Ani, A. I., Maulud, K. N. A., Tawil, N. M., & Abdullah, N. A. G. (2011). The Impact of Anthropogenic Heat on Formation of Urban Heat Island and Energy Consumption Balance. *Urban Studies Research*, *2011*.

Sherwood, S. C., & Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(21), 9552–9555. doi:10.1073/pnas.0913352107 [doi]

Sillman, S., & Samson, P. J. P. (1995). Impact of temperature on oxidant photochemistry in urban, polluted rural and remote environments. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *100*(D6), 11497–11508. Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/94JD02146/full

Smith, V. K., & Huang, J. C. (1995). Can Markets Value Air-Quality - a Metaanalysis of Hedonic Property Value Models. *Journal of Political Economy*, *103*(1), 209–227. doi:10.1086/261981

Steemers, K. (2003). Energy and the city: Density, buildings and transport. *Energy and Buildings*, *35*(1), 3–14. doi:10.1016/S0378-7788(02)00075-0

Stewart, I. D. (2013). Local Climates of the City. *Architectural Design*. doi:10.1002/ad.1625

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. doi:10.1175/BAMS-D-11-00019.1

Stone, B. (2005). Urban heat and air pollution: An emerging role for planners in the climate change debate. *Journal of the American Planning Association*, *71*(1), 13–25. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360508976402

Stone, B. (2009). Land Use as Climate Change Mitigation. *Environmental Science & Technology*, *43*(24), 9052–9056. doi:10.1021/es902150g

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives*, *118*(10), 1425–1428. doi:10.1289/ehp.0901879 [doi]

Stone, B., & Rodgers, M. O. M. (2001). Urban form and thermal efficiency: How the design of cities influences the urban heat island effect. *Journal of the American Planning Association*, *67*(2), 186–198. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360108976228

Stone, B., Vargo, J., & Habeeb, D. (2012). Managing climate change in cities: Will climate action plans work? *Landscape and Urban Planning*, *107*(3), 263–271. doi:10.1016/j.landurbplan.2012.05.014

Svensson, M. K. (2004). Sky view factor analysis – implications for urban air temperature differences. *Meteorological Applications*, *11*, 201–211. doi:10.1017/S1350482704001288

Taha, H. (1997). Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, *25*(2), 99–103. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0031097861&partnerID=40&md5=7569bfa46642e949dafcd06c85a84018

Taleb, D., & Abu-Hijleh, B. (2013). Urban heat islands: Potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE. *Renewable Energy*, *50*, 747–762.

Toronto Public Health - Heat Vulnerability. (n.d.). Retrieved December 29, 2014, from http://map.toronto.ca/maps/map.jsp?app=TPH_HVMAP

Treville, A. (2012). Effectiveness of Strategic Environmental Assessment of urban and regional planning in Northern Italy: limitation of risks and impact of land consumption. *PLANUM*, *25*, 1–7.

Treville, A., & Dosi, M. P. (2012). New Climate Analysis Regions moving towards a low carbon economy, 1–100.

Treville, A., & Minucci, G. (2012). Low Carbon Planning as an opportunity to build a more resilient city (and regions). *3rd Global Forum on Urban Resilience and Adaptation*, 1. Retrieved from http://resilient-cities.iclei.org/fileadmin/sites/resilient-cities/files/Images_and_logos/Resilience_Resource_Point/RC2012__Congress_report.pdf

Turner, B. L., Meyer, W. B., & Skole, D. L. (1994). Global land-use/land-cover change: towards an integrated study. *AMBIO-STOCKHOLM-*, *23*, 91.

Unger, J. (2009). Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *International Journal of Environment and Pollution*. doi:10.1504/IJEP.2009.021817

United States Environmental Protection Agency. (2008). *Reducing Urban Heat Islands: Compendium of Strategies*. *Environmental Protection Agency, retrieved May* (Vol. 12, p. 39p). Washington, DC: United States Environmental Protection Agency. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Reducing+Urban+Heat+Islands+:+Compendium+of+Strategies#0

United States Green Building Council. (2014). *Green Neighborhood Development: LEED reference guide for neighborhood development* (Vol. v. 4). US Green Building Council.

Voogt, J. (2004). Urban heat islands: hotter cities. *America Institute of Biological Sciences*.

Voogt, J. (2007). How researchers measure urban heat islands. In *United States Environmental Protection Agency (EPA), State and Local Climate and Energy Program, Heat Island Effect, Urban Heat Island Webcasts and Conference Calls*.

Wolf, T., & McGregor, G. (2013). The development of a heat wave vulnerability index for London, United Kingdom. *Weather and Climate Extremes*, *1*, 59–68.

World Health Organization. (2006). *Air Quality Guidelines. Global Update 2005* (p. 485global). Copenhagen, DK: World Health Organization. Retrieved from http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/

Yamamoto, Y. (2006). Measures to mitigate urban heat islands. *Science and Technology Trends Quarterly Review*, *18*(1), 65–83. Retrieved from http://www.nistep.go.jp/achiev/ftx/eng/stfc/stt018e/qr18pdf/STTqr1806.pdf

Zheng, S., Cao, J., Kahn, M. E., & Sun, C. (2013). Real Estate Valuation and Cross-Boundary Air Pollution Externalities: Evidence from Chinese Cities. *The Journal of Real Estate Finance and Economics*, *48*(3), 398–414. doi:10.1007/s11146-013-9405-4

Zhou, Y., & Shepherd, J. M. (2009). Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards*, *52*(3), 639–668. doi:10.1007/s11069-009-9406-z

CHAPTER 2

2. MAPPING URBAN CLIMATE AND AIR QUALITY | LITERATURE REVIEW

Introduction

How to map urban climate and air quality? Can sensing improve mapping?

This chapter tackles with "mapping" urban climate and air quality, exploring literature examples in theoretical studies and practical examples. Mapping is done by "modeling" and "sensing", and this chapter emphasizes their differences. Because recent enhancement in sensor technology is shifting mapping from modeling to sensing, this chapter put an emphasis on the need for use and improving sensing in mapping urban climate and air quality.

What does mapping refer to in the context of this work?

"Mapping", as in other visual language techniques in urban studies research, is used for its rich potential in investigation and exploration, observation and interpretation, analysis and communication of small scale and large-scale urban contexts. Different uses of mapping, such as image processing, are suitable tools to work with perceptual aspects and environmental issues, in order to contribute to cross-reading the complex relationships between urban design and physical context. In the case of climate studies, for example, visualization and simulation are fundamental elements to analyze the data (i.e. GIS and DEM digital urban model), to be input in urban models, and to communicate the climate effect on the city, such as UHI and pollutant emissions (Treville, Vandini, and Cegna, 2014). See also Fig. 1-13 (Toronto heat map).

In fact, traditionally, mapping urban climate and air conditions of an urban area requires three methodological steps. Firstly, preliminary analysis of sensing station data and mobile spatial fieldworks, such as traverse surveys, are conducted, in order to detect where the anomaly resides ("sensing" step). Secondly, modeling the general patterns is pursued, by applying existing models developed by research communities ("modeling" step). The final step is mapping the urban area, for instance, by dividing it into local zones classified on the basis of their similar behavior (Oke, 2004).

Both sensing and modeling require appropriate compromises between approaches to achieve the goal (e.g. practical constraints, costs), and discussions between researchers focused on sensing and modeling "must be encouraged so that both groups are aware of limitations and what would provide complementary information" (F. Chen et al., 2012, p. 1728).

However, as evident from this short introduction, modeling heavily relies on sensing, on local observation and monitoring sensor networks. The more sensing data that is available, the better modeling performs in simulating real world phenomena.

However, the lack of sensing is mostly due to the cost of the surveys, their limited spatial-temporal validity, and the cost of the sensing infrastructure networks, including their maintenance and their limitation in representativeness.

While there have been many generated modeling studies in the past few decades, sensing studies are still relatively recent.

However, recent enhancement and innovation in sensor technology is shifting this paradigm: from urban modeling to urban sensing. This chapter introduces mapping by modeling and mapping by sensing, underlining some advantages and disadvantages in the two approaches, and concludes with a general theoretical debate on this paradigm shift, and the consequences for urban planning. (§ 2.3).

2.1. URBAN CLIMATE MAPPING

How mapping urban climate is currently done?
This section explores the two approaches used to map urban climate and heat concentration within the urban environment: “modeling” and “sensing”.

2.1.A - Modeling for urban climate mapping
2.1.B - Sensing for urban climate mapping

2.1.A - MODELING FOR URBAN CLIMATE MAPPING

In an effort to “manipulate” urban factors for improving climate such as mitigating UHI (ch. 1), urban planners and designers need to map the temperature differences, and to understand the impact of each factor. In fact, any observed temperature (“sensing”) reflects the combined effect of all factors, and mathematical predictive tools (“modeling”) are used to estimate their contribution.

The purpose of this section is to show basics of climate modeling, enough to understand how it helps the urban planning research in studying and mapping UHI and microclimate in the urban environment.
It is therefore not to be meant as a comprehensive literature review of urban climatology modeling research studies; it is instead intended as a brief premise for comprehending how sensing, the focus of the next section and of the overall thesis, is essential and useful to integrate air modeling in urban climate mapping.

- *Multi-scale models for Urban Climate: focus on the local scale*
- *The Surface Energy balance: a model for studying microclimate and UHI*
- *Urban Climate Mapping by Modeling*

Multi-scale models for Urban Climate: focus on the local scale
Mapping and studying urban climate requires improving the understanding of urban physical processes and the knowledge in urban meteorology and climatology.
In the last decades the number of models aimed at representing the urban climate processes, and the air exchange in and over urban areas has increased significantly (F. Chen et al., 2012, pp. 1726–1727). While many models share the

same purposes, they highly differ in their configurations and degrees of complexity, and widely vary in scale focus and in resources used.
Considering the resource base, three different groups of modeling can be arranged: empirically-base methods, physical models, and numerical models (Oke, 1984).
Empirically-based modeling is founded on empirical "real world" data, usually restricting their validity to the specific location where the data is collected.
Physical modeling refers to the traditional simulation using wind tunnels, aimed at studying the airflow around buildings, in a reproduction of an urban canyon or an urban area.
Numerical modeling, the most common especially for UHI studies, includes sets of mathematical equations designed to reproduce urban climate for any number of urban characteristics. The surface energy balance model, or town energy balance, described later in this section, is one of them. While they hold great potential for predicting urban climate and urban effects, the lack of a validated procedure determined the diffusion of hundreds of models.

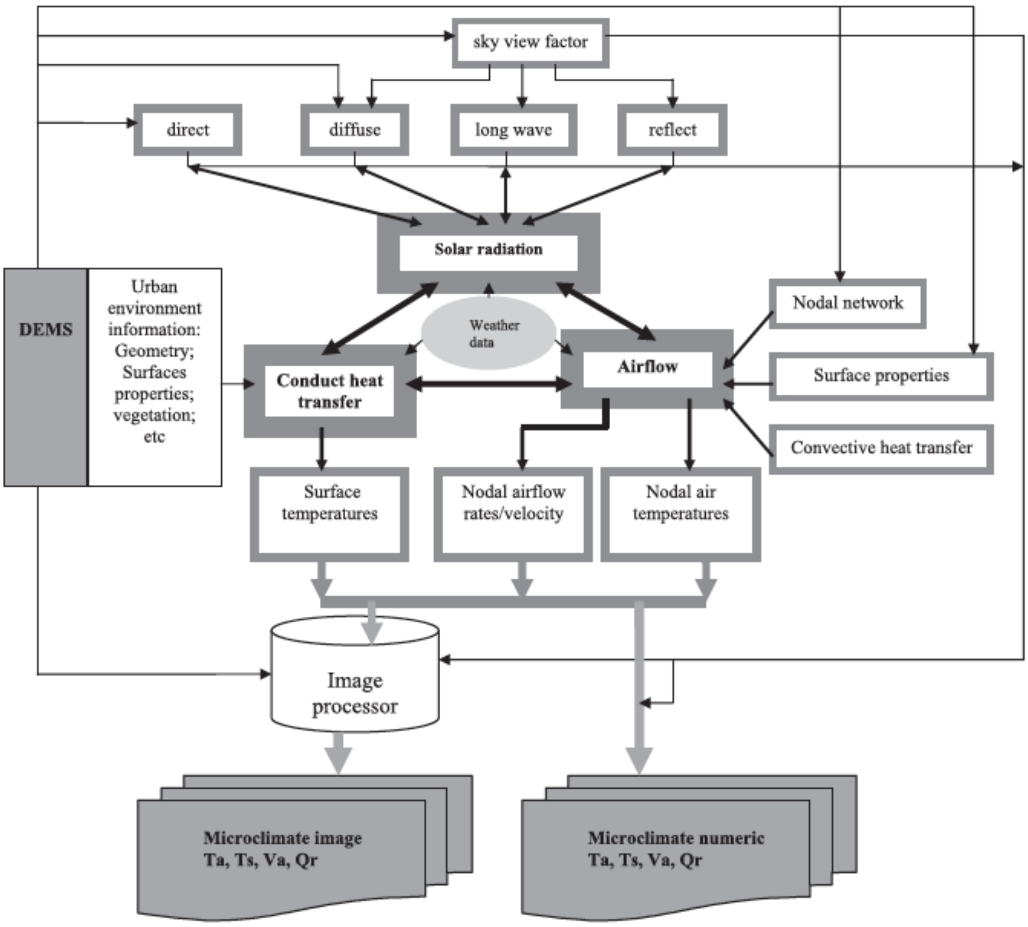


Figure 2-1
A example of a thermal urban model with the factors considered, and the outcome in terms of urban climate mapping (image) and numerical quantities (fluxes) (Yao, Luo, and Li, 2011, p. 255).

Weather and city model data feed the modeling process made up of the thermal and airflow components, giving as results the microclimate quantities and mapping (Yao et al., 2011).

Considering the scale of modeling, three main groups of climate modeling can be distinguished:

Urban boundary layer, macroscale and meso-scale modeling

Boundary layer modeling is important for determining urban/rural air dynamic, and vertical air exchange. They usually are unidimensional, and do not include the urban 3D structure.

The sensing component refers to thermal remote sensing, and surface sensing stations. While the former has problems in scale and resolution (see next section), the latter has the main problem of spatial representativeness in order to perform meaningful comparisons with model outputs.

Physical modeling and computational fluid dynamics (CFD) microscale models usually couple macro-scale to mesoscale models, as well as other techniques developed to coupling between mesoscale and microscale models (F. Chen et al., 2012, pp. 1726–1727).

Meteorological models at this level seem to be mainly of interest in understanding meteorological mechanisms, such as the ones promoting UHI, but have limited application in urban planning and design, since they are not under control of urban planners.

Considering the parameters of wind speed, while in a meteorological station in an open area the measured average speed is representative of the wind condition of that area, the situation is not replicable within a city. In an urban environment, wind speed often changes by a factor of three to five times over distances of few meters (Givoni, 1998, p. 266). Therefore, mathematical models predicting average climate conditions near the ground level, such as urban wind speed, are not useful for urban design as a tool mapping and understanding urban climate.

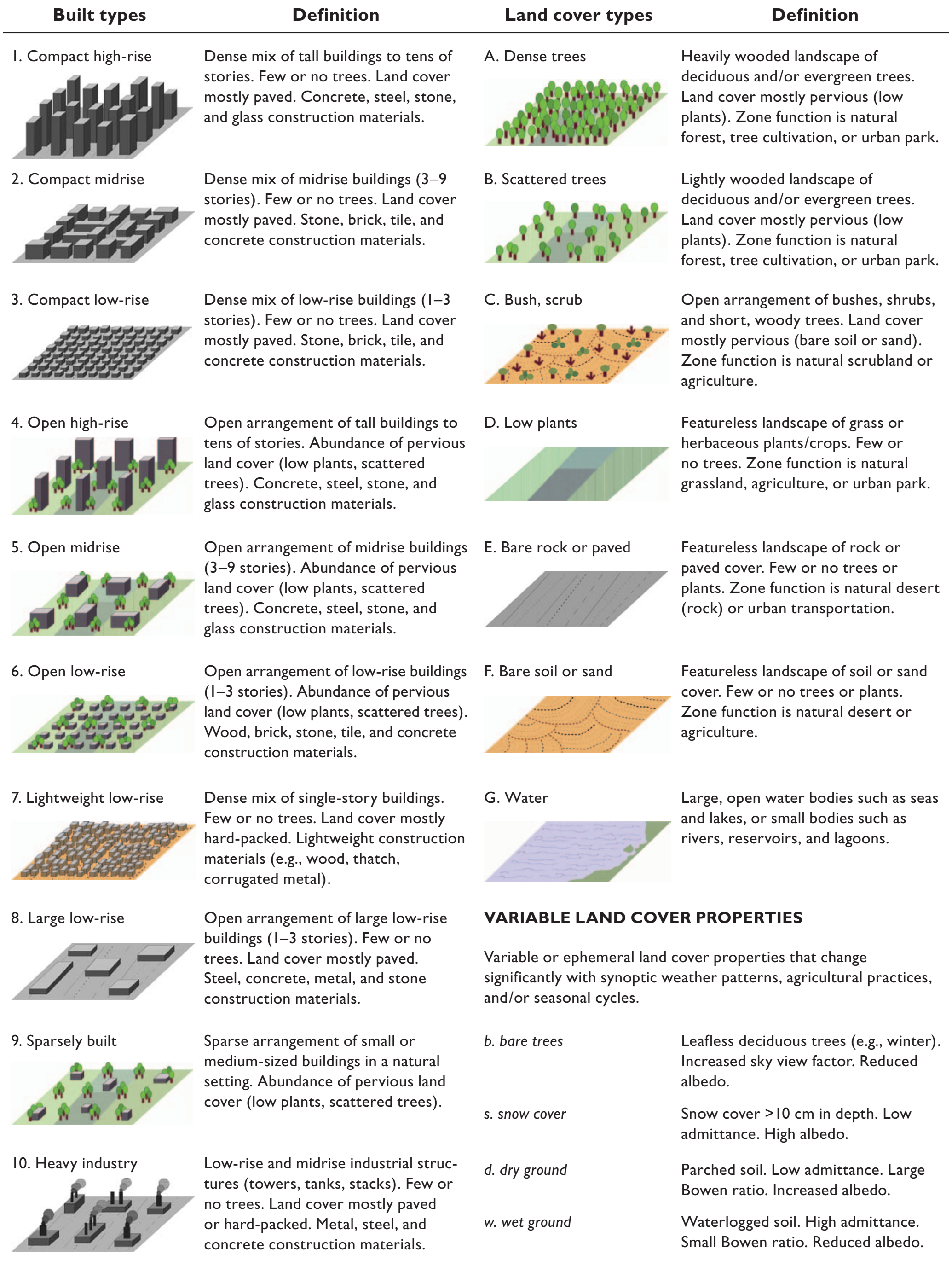
Urban canopy layer: micro-scale modeling

The urban canopy layer modeling refers to those models aimed at estimating the urban climate for the entire urban area scale, at an appropriate resolution. The resolution and the details of the modeling involved (such as vegetation or 3D building shape) is a compromise between the type of information simulated and the computational constraints (CPU time and requirements might undermine the modeling).

The sensing component is usually a combination between existing sensor networks, such as governmental weather stations, and field measurements with fixed or mobile sensors.

Required datasets include land use cover, digital elevation models (DEM) and other geographic and environmental parameters, such as anthropogenic heat and pollutant emissions.

Several studies classify urban land use as an input for meteorological and air-quality modeling, such as the land cover categories proposed for Salt Lake City, Utah (Akbari and Rose, 2001) and the climate local zones proposed by Stewart and Oke (2012). In this recognized work (Stewart and Oke, 2012), based on a previous study (Oke, 2004), the authors propose a modeling process based on a standard set of reference “climatopes”, called “local climate zones” (LCZ); they are classified based on areas with uniform surface cover, structure, material, and human activity (see Figure 2-2).



Built types	Definition	Land cover types	Definition
1. Compact high-rise	Dense mix of tall buildings to tens of stories. Few or no trees. Land cover mostly paved. Concrete, steel, stone, and glass construction materials.	A. Dense trees	Heavily wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
2. Compact midrise	Dense mix of midrise buildings (3–9 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	B. Scattered trees	Lightly wooded landscape of deciduous and/or evergreen trees. Land cover mostly pervious (low plants). Zone function is natural forest, tree cultivation, or urban park.
3. Compact low-rise	Dense mix of low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Stone, brick, tile, and concrete construction materials.	C. Bush, scrub	Open arrangement of bushes, shrubs, and short, woody trees. Land cover mostly pervious (bare soil or sand). Zone function is natural scrubland or agriculture.
4. Open high-rise	Open arrangement of tall buildings to tens of stories. Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	D. Low plants	Featureless landscape of grass or herbaceous plants/crops. Few or no trees. Zone function is natural grassland, agriculture, or urban park.
5. Open midrise	Open arrangement of midrise buildings (3–9 stories). Abundance of pervious land cover (low plants, scattered trees). Concrete, steel, stone, and glass construction materials.	E. Bare rock or paved	Featureless landscape of rock or paved cover. Few or no trees or plants. Zone function is natural desert (rock) or urban transportation.
6. Open low-rise	Open arrangement of low-rise buildings (1–3 stories). Abundance of pervious land cover (low plants, scattered trees). Wood, brick, stone, tile, and concrete construction materials.	F. Bare soil or sand	Featureless landscape of soil or sand cover. Few or no trees or plants. Zone function is natural desert or agriculture.
7. Lightweight low-rise	Dense mix of single-story buildings. Few or no trees. Land cover mostly hard-packed. Lightweight construction materials (e.g., wood, thatch, corrugated metal).	G. Water	Large, open water bodies such as seas and lakes, or small bodies such as rivers, reservoirs, and lagoons.
8. Large low-rise	Open arrangement of large low-rise buildings (1–3 stories). Few or no trees. Land cover mostly paved. Steel, concrete, metal, and stone construction materials.	**VARIABLE LAND COVER PROPERTIES** Variable or ephemeral land cover properties that change significantly with synoptic weather patterns, agricultural practices, and/or seasonal cycles.	
9. Sparsely built	Sparse arrangement of small or medium-sized buildings in a natural setting. Abundance of pervious land cover (low plants, scattered trees).	*b. bare trees*	Leafless deciduous trees (e.g., winter). Increased sky view factor. Reduced albedo.
		s. snow cover	Snow cover >10 cm in depth. Low admittance. High albedo.
10. Heavy industry	Low-rise and midrise industrial structures (towers, tanks, stacks). Few or no trees. Land cover mostly paved or hard-packed. Metal, steel, and concrete construction materials.	*d. dry ground*	Parched soil. Low admittance. Large Bowen ratio. Increased albedo.
		w. wet ground	Waterlogged soil. High admittance. Small Bowen ratio. Reduced albedo.

Figure 2-2
Abridged definition of Local Climate Zones (LCZs). LCZs 1-9 correspong to Oke’s (2004, p. 11) urban climate zones (UCZs) (Stewart and Oke, 2012, p. 1885).

By combining ten building types and five land cover types, the authors aim at identifying LCZ classes as a reference research framework and standardization for urban climate and UHI modeling studies.

DEMS are extensively used to assess urban morphology (Morello and Ratti, 2009a; Carlo Ratti and Richens, 2004), the urban texture and its energy consumption (Carlo Ratti, Baker, and Steemers, 2005; Carlo Ratti, Robinson, Baker, and Steemers, 2000), solar radiation (Morello and Ratti, 2009b), and wind and dispersion modeling (Di Sabatino et al., 2010; Carlo Ratti et al., 2006). In fact, urban parameters essential to urban canopy models, such as roughness or the "sky view factor", can be interfered from 3D models, LIDAR data, and used for urban climate studies (Carneiro et al., 2009; L. Chen and Ng, 2009; Gal and Sumeghi, 2007; Svensson, 2004; Janos Unger, 2009).

GIS datasets can also be a component of urban canopy models, such as the US National Urban Database with Access Portal Tool, which is a GIS tool designed to facilitate implementation of the latest advanced urban meteorological, air quality and climate modeling systems, such as NUDAPT (Ching et al., 2009). Another example is the GIS-based LUCID project, "Local Urban Climate model and its application in the Intelligent Development of Cities" (Evans, 2009).

The challenge for modeling is to represent the dynamic and thermodynamic effects in the spatially averaged turbulent fluxes and mean flow (F. Chen et al., 2012, pp. 1726–1727). Considering the models based on the surface energy balance (described later on in this section), vegetation and anthropogenic heat play several roles and tend to be included in the models at a proper scale (for instance, trees in the urban canopy level determine latent heat, modify the ventilation and produce shadows).
However, according to a documented modeling review of the last two decades of urban climate research, the validation of those models "lags behind their creation and, when performed, is often weak, relying more on plausibility of outputs than direct comparison with process variables" (Arnfield, 2003).

Building scale modeling
Models at the building scale, or at the urban canyon scale, can be bi-dimensional, such as the ones modeling the section of a parametric street, or tri-dimensional, such as the ones modeling a 3D portion of a limited urban area. The main objective is usually estimating the local impact of UHI and the local effectiveness of a proposed local measure, such as albedo modification in facades. The sensing component usually comes from field measurements at the urban canyon level.
Among the models at the building level, and its connection to the urban canopy level, many studies analyze the interaction between urban climate and the energy performance of buildings, such as the impact of UHI on the energy consumption for cooling, and the waste heat influence on outdoor temperature (Bueno, Norford, Pigeon, and Britter, 2012).

Combined models, such as the ones coupling building energy models to urban canopy models and town energy balance (Bueno, Norford, Pigeon, and Britter, 2011), or using building level software such as EnergyPlus for energy simulations (Toppi, Zangheri, and Paolini, 2009), or developing their own software for simulating building flows in the urban climate (D. Robinson et al., 2009), all aim at predicting urban climate effect with increased simplicity and computational efficiency.
Other models and tools designed for environmental sustainability of urban planning, such as LEED-ND, INDEX; I-PLACE3s (see § 1.3), and also LCA-based models (Treville, 2011a, 2011b), include some limited climatic considerations for urban planning.

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The two main challenges of modeling are: finding low-computational models that still provide an adequate representation of the urban climate complexity, and improving the sensing techniques, since only a few meteorological stations are available and monitor site-specific microclimates conditions.
While sub-models with a specific component designed at transferring data from different locations are being developed, such a rural-to-urban weather transformation in estimating temperatures inside an urban canyon from measurements taken from an operational weather station located in an open area outside a city (Bueno, Hidalgo, Pigeon, Norford, and Masson, 2013), calibrating models are still potentially limited, and statistical error might be significant (Street, Reinhart, Norford, and Ochsendorf, 2013).
Sensing is therefore the component that needs to be improved in order to get more site-specific climate data, and to map the spatial variation of urban climate. Nevertheless, modeling and sensing both work in a mutual process. For example, in order to plan an effective representative urban-climate sensing network, it is necessary to choose locations that optimize "representativeness" (see §2.3), and climate modeling can be used to this specific purpose (János Unger, Savić, and Gál, 2011). In fact, modeling can also inform sensing, for instance by providing answers to questions such as: "Where would be the best place to locate instruments? Where are places of little or large change in variables being observed? What areas will/will not be spatially representative? How can microscale measurements be used for mesoscale model evaluation? How does the spatial representativeness vary with wind direction?" (F. Chen et al., 2012, p. 1728).
See next section for more information about air sensing and its current research status.

The Surface Energy balance: a model for studying microclimate and UHI

The "urban surface energy balance", sometimes referred to as town energy balance (TEB), or "energy balance" models, is a most common urban canopy model to study microclimate and UHI effect. It is based on the first law of thermodynamics (conservation of energy), and it expresses the balance among flux densities within an urban portion. According to this model (Oke, 1987, Chapter 8.3):, urban climate, its air temperature and UHI, can be studied as result of the following equations based at ABCD level (see Figure 2-3)

$Q^* + Q_F = Q_H + Q_E + \Delta Q_S + \Delta Q_A$

where: Q^* = Rn (net wave radiation), comes from the "radiation balance" of longwave (L) and shortwave (K) radiation:

$Rn = Q^* = K\downarrow - K\uparrow + L\downarrow - L$

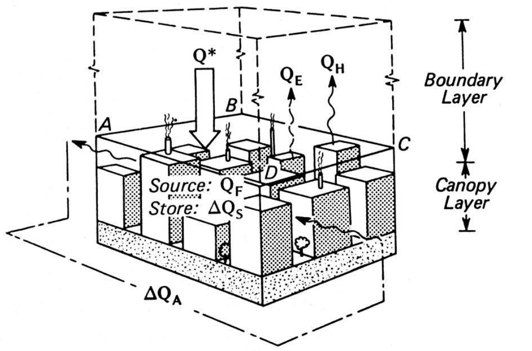

Figure 2-3
Schematic depiction of the fluxes involved in the energy balance of an urban air volume (Oke, 1987, p. 275).

The surface energy balance model is the fundamental base modeling for urban climate studies, as it tries to include most of the factors involved in determining UHI at the local level. It is therefore particularly valuable for a theoretical systematic understanding of the interrelationships among the factors involved in urban climate at the neighborhood level.
In fact, the temperature within an urban "frame" is function of a complex relationship among factors involved in the two equations. It can be noted that:

- urban morphology (sky view factor, etc.) acts on radiation (Rn), energy consumption (anthropogenic heat, Q_F), advection heat (ΔQ_A)
- climatic data (cloud cover, wind, etc.) acts on net radiation (Rn) and on sensible heat (Q_H)
- urban material proprieties (thermal and radiation: albedo, emissivity) act on heat storage (ΔQ_S) and on net radiation (Rn)
- land use (green and blue areas) acts on latent heat (Q_E)
- urban mobility and urban energy consumption (emissions, combustion and waste heat) act on anthropogenic heat (Q_F)

Additionally, besides urban energy balance, some factors affect other "climate change-related" aspects, such as water scarcity, air pollution, CO_2 emissions. For example, energy consumption from summer air conditioning during heat waves can significantly contribute to urban temperature increase (anthropogenic heat, Q_F), though generating a vicious cycle.
Figure 2-4 show a tentative map explaining the complex relationship a selection of indicators selected to describe the model: drivers, outcomes, input and output, and urban balances involved (Treville, 2013).

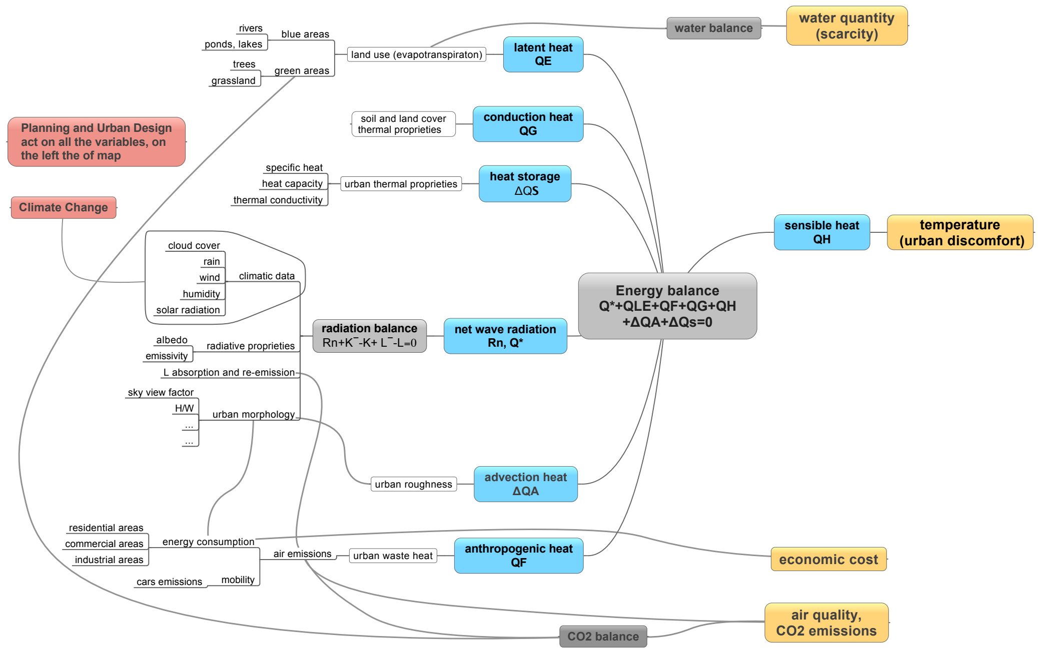

Figure 2-4
Indicators involved in explaining the complex relationship between the factors in the model: drivers, outcomes, input and output, and urban balances involved (Treville, 2013, p. 114). See chapter 3 for its application for the case of Milan.

While the urban energy balance model is widespread and used in hundreds of studies (C. S. B. Grimmond et al., 2010), several limitations affect its results. First of all, because the complexity of the urban surface makes the energy balance equation not realistically solvable for every point of the surface, large approximation is required (Harman, 2003). Each application model aimed at solving the equation, therefore frames its assumptions around the important features of the surface and the exchange process that needs to be incorporated
In addition, many applications of the urban energy balance model exist in several forms of modeling experiences, all aimed at better definition of the theoretical framework, in improving the equation components (Harman, 2003; Mariani and Pangallo, 2005), and from an empirical perspective, in testing the validity of the models (Masson, Grimmond, and Oke, 2002; Nunez and Oke, 1977; Ross and Oke, 1988). Some models integrate water balance to the energy balance, because of the inter-relationships between vegetation, moisture, latent heat in the surface balance (Järvi, Grimmond, and Christen, 2011); other models use the energy balance to predict climate change impact ((House-Peters and Chang, 2011).

Because of the large number of un-validated urban surface energy balance models, a first large-scale systematic evaluation and comparison project was launched, involving more than thirty research centers and models. According to the first phase of this project (C. S. B. Grimmond et al., 2010), there is high variability among the existing models in simulating the fluxes of the energy balance. In general, it was proved that the simpler models had the same performance of more complex models based on all statistical measures.

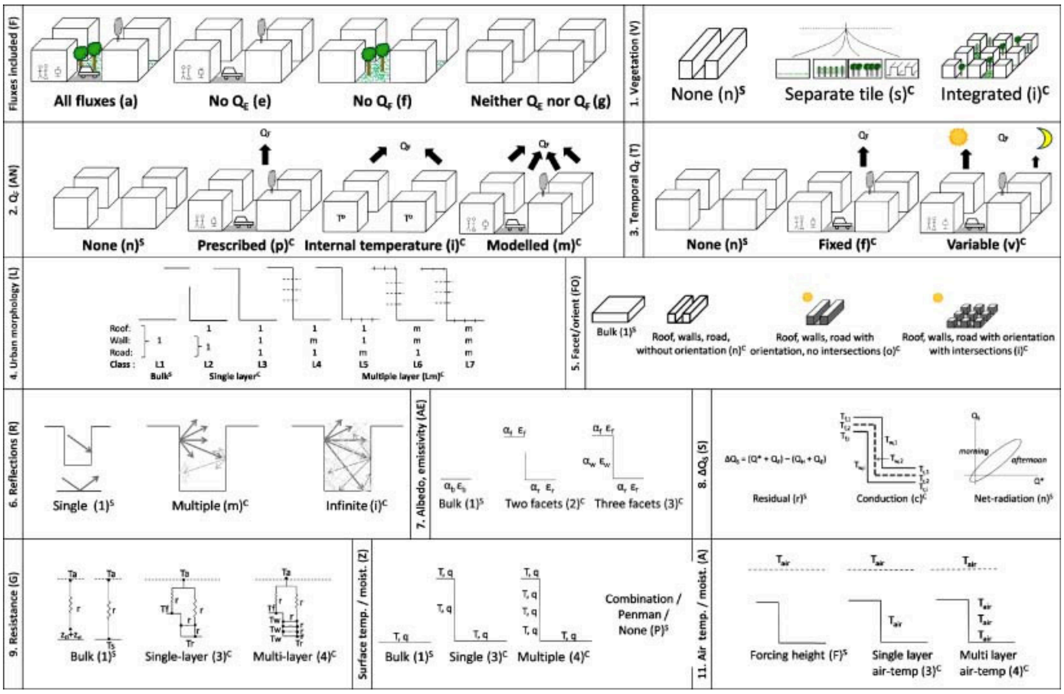

Figure 2-5
Several models exists, each considering different energy fluxes and indicators (C. S. B. Grimmond et al., 2010, p. 1270).

According to the results of the second phase (C. S. B. Grimmond et al., 2011), based on the calculated fluxes for a specific location (suburban Preston, Melbourne, Australia), wide performance variation was evident while no individual model performed the best for all fluxes.

The final message of this project suggests that while most of the models performs well across all heat fluxes, there is need for caution in their application, and planner and decision makers should be aware of the approximation and their implications for practical applications (C. S. B. Grimmond et al., 2011, p. 244).

Urban Climate Mapping by Modeling

As mentioned before introducing urban climate modeling, the main aim here is to explore what knowledge from urban climatology can be transferred to urban planning, and how plans can benefit from applied results.

Urban climatic mapping can present climatic phenomena in two-dimensional spatial maps, therefore providing a useful evaluation tool to urban planning. In fact, from urban climatic mapping, specific spatial recommendation can be generated.

Theoretically, different layers and datasets (see Figure 2-6), such as energy mapping (van den Dobbelsteen, Broersma, and Stremke, 2011) can be spatially overlaid and used in order to “close” the surface energy balance. Once the fluxes are calculated, such as the sensible heat, the resulting urban climate can be mapped at the proper spatial scale. However, as seen in the previous section, though decades of research explored the relationship between the factors involved in urban climate, most of the models still only consider few factors, and there is no universal agreed mapping process suggested.

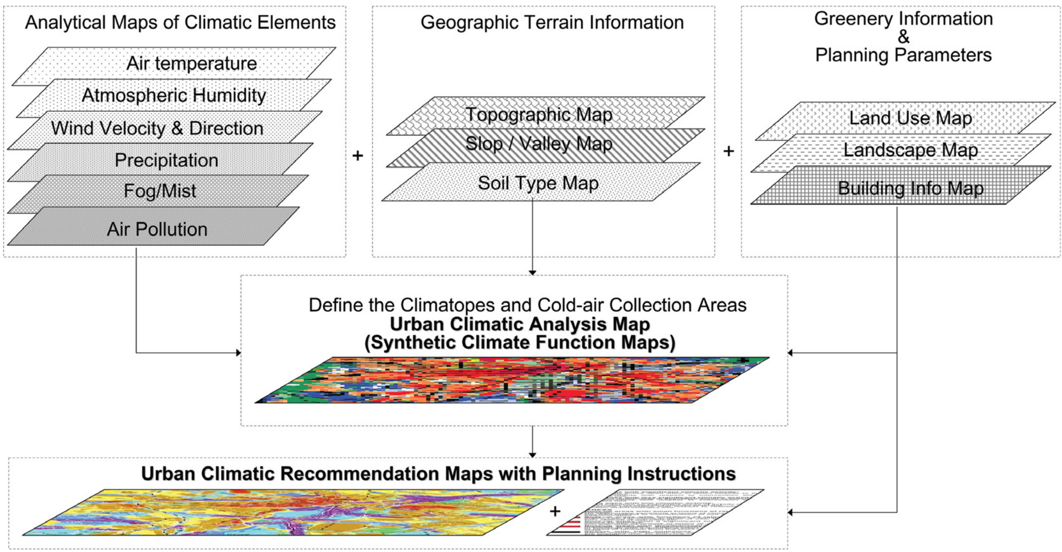

Figure 2-6
Structure of a model for urban climate mapping (Ren et al., 2011).

Guidelines and tools for including climate aspect in urban planning, such as climatic maps, have been developed in the last decades, and examples where climatic aspects were successfully incorporated in the planning process are present in literature, showing the challenging impact of climatic information in urban planning (Eliasson, 2000, p. 33).

In particular, “Climatopes” were firstly mapped in the 1980s, in a project aimed at controlling heavy metal pollution in the old industrial areas of the Ruhr, Germany, and urban climatic factors were connected to spatial information and land use information (Ren et al., 2011).

Austrian and German urban climatology pioneered the field; the Stuttgart is a good example of one of the first urban climate maps planned. In that example, the 11 categories of climatopes were developed in a process relying on expert knowledge and qualitative and subjective assessment (Figure 2-7).

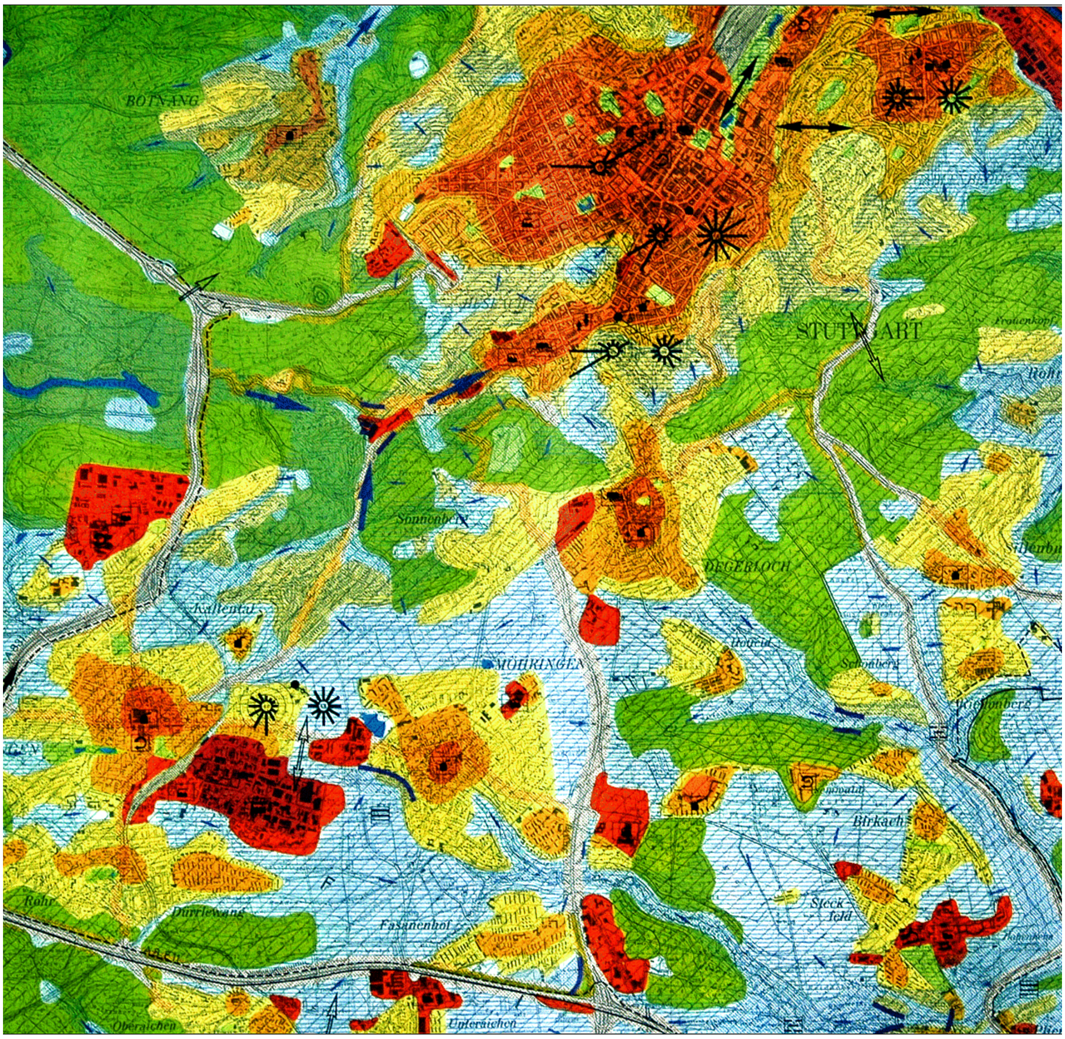

Figure 2-7
A partial urban climate map for Stuttgart, Germany (Ren et al., 2011). See also Figure 6-3.

In recent cases, calibration and verifications studies have been conducted for a better understanding of the climatopes, in order to be able to define them in a quantitative way, rather than relying on qualitative evaluations. For example, in the case of Hong Kong, besides using simulation modeling, wind tunnel studies, and a GIS-based building database, extensive sensing was necessary to be implemented, and spot field measurements were conducted (L. Chen and Ng, 2011). Eight climatic analysis classes of climatopes were defined (see Figure 2-8), and thanks to the sensing component, the field measurements provided a useful data reference for calibrating and verifying the climatopes, obtaining a good agreement with the real urban climate condition of the city (CUHK, 2009; Ren et al., 2011).

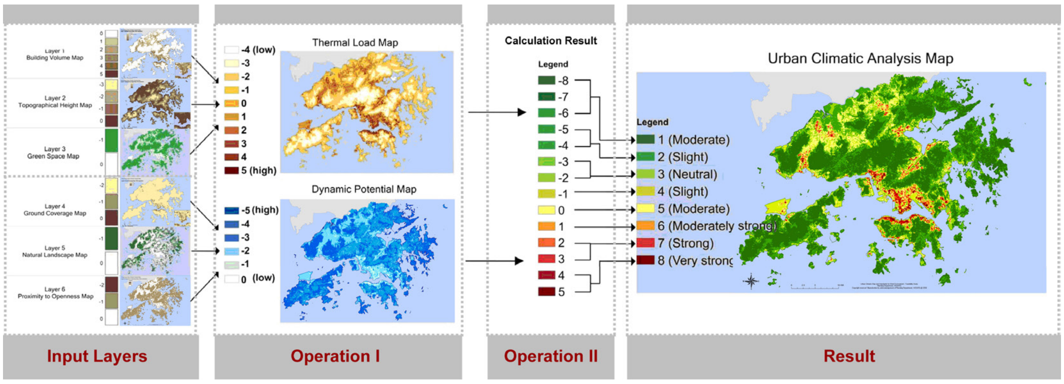

Figure 2-8
The working process of the urban climate map of Hong Kong, combining six layers of input data ("building volume", "topographical height", "green space", "ground coverage", natural landscape", "proximity to openness"), a "thermal load" map and a "dynamic potential" map (CUHK, 2009).

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From a modeling/software perspective, the most commonly used tools for modeling and mapping urban climate at the local scale are: Rayman, Solweig and Envi-met. Other software tools are more focused on single aspects, such as solar radiation using Solene (by Cerma, Centre de recherche méthodologique d'architecture, Nantes) ("Solene - Software for simulating of sunshine, lighting and thermal radiation | Cerma," n.d.) or turbulence flow and dispersion of gases, using Fluent ("ANSYS Fluent," n.d.).

Rayman model, developed by prof. Matzarakis at the Department of Meteorology and Climatology of University of Freiburg, is used for the calculation of short- and long-wave radiation fluxes on the human body (Matzarakis, Rutz, and Mayer, 2007). The final output of the model is the mean radiant temperature, MRT, connected to human energy balance model, PMV and PET. Although user-friendly and popular in the research community, it is a stationary model very limited in mapping results, compared to the two following models (i.e. in 3D radiation fluxes).
The Solweig model, developed by the Göteborg Urban Climate Group and released in 2010 in successive upgraded versions, is targeted to urban climate researchers, urban designer and planners. It allows modeling and mapping the simulates spatial variations of mean radiant temperature and long-wave and short-wave radiation in complex urban settings, ("The SOLWEIG-model," n.d.) (Lindberg, Holmer, and Thorsson, 2008). It is an open-source tool, and its user-friendly mask is helpful for researchers with little experience with MatLab environment.
The Envi-met model, developed by the Environmental Modelling Group at the University of Mainz, is 3D microclimate model designed to simulate the surface-plant-air interactions in urban environment with a typical resolution of 0.5 to 10 m in space and 10 sec in time (Bruse, 2004). Although it is not open-source as Solweig, it is a comprehensive freeware tool, since it includes the possibility to control several thermal parameters and environmental factors (such as CO2, and particles). However, compared to Solweig, because of its complexity, it requires

more steps in the data input, and has high limitations for the processing, such as the maximum domain size of the mapping area (250x250x25 m).

In Figure 2-9, an example of mapping by modeling using Solweig and Envimet (Katzschner and Thorsson, 2009).

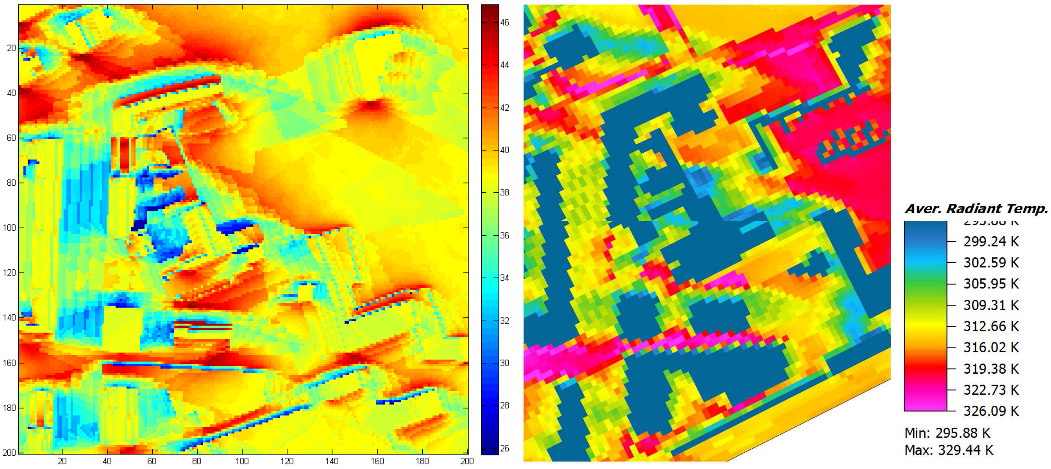


Figure 2-9
Mean value of the mean radiant temperature from Solweig calculation (left) and Envimet (right) (Katzschner and Thorsson, 2009, p. 4).

2.1.B - SENSING FOR URBAN CLIMATE MAPPING

- Sensing Networks for Urban Climate
- Mobile Sensing for Urban Climate
- Urban Climate Mapping by Sensing

Sensing Networks for Urban Climate

Remote Sensing is valid source of information that is used in urban climate studies, considering that sensors mounted on satellites can be seen as sensor networks providing data available for government and private studies, with inventories that are vast and growing. Thanks to multispectral imaging coming from space-borne sensors, different temperatures of urban objects can be directly related from the energy emitted according to the spectral bands. NASA Landsat data has been available since the 1970's, and the MODIS sensor (moderate resolution spectroradiometer) mounted on board the Terra satellite, is able to detect surface temperatures over large areas (Sandifer and Mountain, 2014). In fact, since the 1970s many studies have used thermal remote sensing to investigate the spatial variation of thermal patterns in urban areas, and the relation to their surface characteristics (Voogt and Oke, 2003).

However, its spatial resolution (usually 1000 m) does not allow studying urban climate at a small-scale level. Other satellite sensing studies have higher resolution, but the availability of coverage and time series (day to weeks) can be highly limited. Furthermore, data is often impacted by weather and atmosphere conditions (such as clouds), making this platform useful for thermal studies only if coupled with other sensing systems providing the proper range of parameters required for modeling urban climate (Seto and Christensen, 2013, p. 2).

Sensing networks specifically built for climate and meteorological studies are traditionally global or national networks, and are essential to monitor atmospheric processes, and to assess both long-term climate modification and short-term weather events. They can be coupled with air pollution monitoring sensors, and are designed to collect data for studies at a global/ macroscale/ regional/ mesoscale level (see Table 2-1).

They collect standardized data, representative of climatological observations of wide regions, and are usually not present in urban areas, but rather in airports. Being also costly to deploy and maintain, they ultimately result in sparse coverage, and are not suitable for urban climate research (Muller and Chapman, 2013).
Additionally, monitoring stations in cities can provide observations that are severely compromised, due to obstruction of air-flow and radiation exchange by buildings and trees, unnatural surface cover and waste heat and water vapor from human activities (World Meteorological Organization, 2008, para. 11.1).
Thus, only dense sensing networks at the local/micro scale can appropriately monitor urban environments. A number of these have been implemented in

several urban areas worldwide in recent years. For references and general information about sensors currently used in measuring climate parameters, such as temperature and humidity, and here below mentioned within the sensor networks, see § 4.2.

Spatial scale areal extent	**Description**	**Atmospheric processes and applications**
Global > 10^8 m	Global network of networks, internationally facilitated	global climate change, satellite calibration/validation
Macroscale/Synoptic 10^5–10^7 m	Networks of national monitoring stations located around countries, usually in rural areas.	Used for examining regional and national synoptic events, national weather forecasting, modeling
Regional/Mesoscale 10^4–10^6 m	Monitor regional meso-scale events. Urban, peri-urban and rural areas covered.	Thunderstorms, downbursts, squall lines, temperature variations over urban and rural areas, sea circulations
City-scale 10^4–10^5 m	Monitoring weather and climate at the scale of the whole city.	Air pollution urban heat island studies, urban climate studies,
Local scale/ Neighborhood 10^2–10^4 m	Effects of minor landscape, neighborhoods with similar types of urban development. Monitoring equipment is sited to be representative of neighborhood (i.e. a set height, representative surface cover, little obstructions, to avoid micro-climate effects)	Air pollution Urban heat island, variations with land use, surface cover, tornadoes
Micro-scale 10-10^2 m	Microclimate phenomena. Influenced by urban areas the dimensions of component elements: buildings, trees, roads, streets, courtyards, and gardens. Equipment located to be representative of the micro-climate	Air pollution, human comfort and exposure, urban canyon studies, IHU studies, turbulence and dispersion studies, impact of buildings, agricultural meteorology

Table 2-1
Spatial scale and atmospheric processes and applications, from the largest to the smallest. Adapted from cited source (Muller and Chapman, 2013, p. 1587).

Oklahoma City Micronet is one of the first successful examples of sensor networks for urban climate. Made of 40 automated environmental monitoring stations across the Oklahoma City metropolitan area, it is functioning with stationary monitoring stations and 36 sensors mounted on traffic signals (Basara et al., 2011). However, due to budget constraints, the daily operations have been suspended. Considering the average station spacing of approximately 3 km, the scale of this project is metropolitan and not local, as are all the following networks.

LUCE is the sensor network implemented by the Ecole Polytechnique Federale de Lausanne in Lausanne. Its main purpose is monitoring temperature and humidity, air and surface, and other weather parameters, using 92 sensors covering an area of 750x500m. It allows studies of estimate sensible heat flux using low-cost sensors such as Sensirion SHT75 for temperature and humidity. It can be considered the real first full experiment on microclimate, though its maintenance cost limited its activity from October 2006 to April 2007. The results show a good estimate of the sensible heat over the campus compared to independent thermal measurement, and overall, illustrates how an extensive network of sensors can be a useful tool in complex urban environments (Nadeau et al., 2009).

UScan is the sensor network implemented by the Tokyo Denki University in Tokyo. Its main purpose is monitoring temperature, vibration, illumination, using 200 sensors, covering an area of 100.000 mq (250x450m). It allows studies of fine-scale temperature variations using low-cost sensors such as uParts (TC1047A for temperature) The network was only active for 2 months (July - August 2007) and was able to discover the correlation between temperature change and the amount of sunshine (Thepvilojanapong, Ono, and Tobe, 2010).

In the same city of Tokyo, AiryNotes is the sensor network implemented by the Graduate School of Media and Governance, Keio University in the Shinjuku Garden. Its main purpose is monitoring temperature using 165 sensors, covering an area of 580.000 mq. It allows studies of info about temperature in the park, showing UHI and latent heat using low-cost sensors such as uParts. The network was active for a limited time (August 2006) but was able to monitor temperature change within the area, and make park visitors understand the role of the park in lowering the temperature of the surrounding urban areas (Ito, Katagiri, Ishikawa, and Tokuda, 2007).

Another academic research sharing the same aim is the sensor network implemented by Princeton University, SNOP (Sensor Network Over Princeton, by Elie Bou-Zeid) in Princeton. Its main purpose is monitoring temperature, radiation, and other parameters using 7 sensors covering an area of 300x300m. A second network is the WHSN implemented in Baltimore with the main purpose of monitoring temperature, radiation, and other parameters using 7 covering an area of 400x400. They allow detailed studies of microclimate using eddy-covariance stations. While they represent a unique microclimate permanent sensor network, SNOP in particular, their scale provides information limited to urban canyon analysis inside the campus (Wang, Bou-Zeid, and Smith, 2010).

Accurate air temperature observations in urban areas are indispensable to study urban climate and UHI, though the cost of deploying and maintenance of dense sensing network limits its use. However, the recent advancement in sensor technology is leading to a new approach for high-resolution air temperature studies in urban areas, in two ways. A first way is by increasing the resolution of sensors deployed, which simply means by using a larger number of low-cost sensors connected in a network. Since air quality network usually includes temperature measurement, this is later described in § 2.2.B.

The second way of increasing spatial resolution using sensors, is deploying them in a mobile installation rather than in a fixed monitoring place. Examples of pioneering sensors installed in moving vehicles are more and more common, and used by governmental authorities to collect granular information (such as the ones used by the US National Weather Service on commercial trucks and buses between New York City and Montreal). Examples of sensors installed on urban vehicles are more significant for the purpose of studying urban climate and UHI, and they started in the 1920s with mobile measurements using cars equipped with meteorological instruments (Buttstädt, Sachsen, Ketzler, Merbitz, and Schneider, 2011). Various studies followed in Europe, using mobile carriers such as pedestrians and bicycles, though usually for only fieldwork research.(See later on this section)

A final sensing network approach, in a wider sense, is the use of weather data coming from un-calibrated personal weather stations connected to a network, or from uncalibrated sensors installed in smartphones.
Wunderground and Weather Signal, are examples of a network of weather stations and sensors gathering temperature and humidity data coming from crowd-sourced observations. Recent smartphones models integrate temperature sensors (such as Samsung Galaxy 4S using sensor Sensirion SHTC1) and using specific Apps, a number of un-calibrated measurements are aggregated in order to improve weather forecasting.
This approach has been proved to be so successful that The Weather Company, one of the most recognized weather service in the US and worldwide, in 2012 bought Wunderground in order to include its data for their daily weather service.
Projects like mPING (Meteorological Phenomena Identification Near the Ground), developed through a partnership between research centers (the National Severe Storms Laboratory, the University of Oklahoma and the Cooperative Institute for Mesoscale Meteorological Studies), follow the same approach: a collection of qualitative or un-calibrated quantitative weather data coming from a mobile phone App, collected in order to improve traditional forecasting and temperature studies.

Within the same field of air temperatures and smartphones, but with another approach, an interesting research study shows how it is possible to gather information without the need of an air sensor, and only using the sensor measuring the internal battery temperature of the phone itself (Overeem and Robinson, 2013). This approach confirms the promising use and applications of city sensing with numerous and un-calibrated sensors; however, while low-cost and diffusion are encouraging factors, accuracy of sensors is still a factor to be further developed.
Temporary and non fixed-networks, and specific fieldwork studies can better emphasize this aspect. The next section introduces this aspect.

Mobile Sensing for Urban Climate

Using sensors to measure urban climate factors, such as temperature and humidity, in a specific spatial and temporal situation, and without the need for being networked and for providing real-time data, is the most common example of air sensing.

Recent innovative observing technologies and assimilation approaches, such as motes, lidars, sodars, and fiber optical temperature measurements, provide the opportunity to get a high and temporal resolution of air data, both horizontally and vertically (F. Chen et al., 2012).

As for sensing network, remote sensing can be used to obtain atmospheric variables in greater spatial and temporal detail, using aircraft or ground-based fixed and mobile thermal investigations, they usually require a high cost for the measurements, and provide irregular coverage, and non-standardized observations (i.e. for natural and agricultural surfaces). Additionally they provide information about the surface condition, such as the surface UHI (SUHI) (see § 1.1), and their data is not directly linked to the air temperature above the surface, which is the main focus of UHI and heat stress effects on urban health. Therefore, in contrast to the direct on-site measurements made with air sensors, the remotely sensed SUHI requires extra considerations for the intervening atmosphere, the surface orientation and radiative properties. For these reasons, while remote sensing proved to be useful in studies at a regional level, it is still not suitable in handling canopy—radiation processes in the short-wave region (Voogt and Oke, 2003).

Small scale studies using sensors installed on cars for mobile measurements are a common practice, usually to conduct transect studies running from the rural to the urban area and integrating data to fixed meteorological stations data. In the case of the recent Padua UHI study (Busato, Lazzarin, and Noro, 2014), low-cost temperature and humidity sensors were used (LSI Lastem DMA672.1), and their accuracy, as in many UHI studies, was considered to be enough to detect UHI at a reliable definition (6°C for Padua), since the main interest is differences rather than absolute values of observed temperature, and values are also compared to accurate governmental monitoring station data.
While this approach is quite traditional, it is still being used to accurately quantify the UHI effect on urban areas, sometimes in combination with some climate modeling. In the case of Goteborg, automobile measurements were conducted (2003-2006) in order to obtain a fine resolution of 57 evenly spread measurement points throughout the study area of the city historical center. Integration of sensing to modeling is a good example of such a process: DEM and sky-view factor calculation, GIS geo-database and vegetation influence, anthropogenic heat estimation and the artificial pedestrian street heating contribution, thermal infrared sensing and mobile temperature measurements, all beneficially combine to describe the spatial variation of urban climate (Lindberg, 2007).

Essentially the same approach, but using bicycles instead of cars, is less traditional and used to study urban climate and heat stress in several cities since 1996, when it was introduced to observe UHI in Reading, UK (Melhuish and Pedder, 1998). Issues such as the heating of instrumentation and the cooling needed through ventilation were solved with the use of shielded sensors in recent studies; in Rotterdam a mobile “bio-meteorological station” was mounted on a cargo bicycle and allowed a UHI assessment of 7°C, and the contribution of green areas in cooling the local temperature by 3°C (Heusinkveld et al., 2010). In order to validate the results coming from the mobile sensing fieldwork, a comparison with urban fixed weather stations was conducted, and a UHI map of Rotterdam was derived showing that high density urban configurations lacking in green areas and close to water bodies are vulnerable to heat waves, especially during nighttime (Heusinkveld et al., 2014). A similar approach is used to explore UHI in Utrecht, where bike sensing data provided temperatures and humidity measurements useful for estimates of the spatial and temporal variation of UHI within the city, in combination with SVF modeling and weather statistical modeling (Brandsma and Wolters, 2012).

As mentioned for sensing networks, smaller sensing fieldworks limited in space and time, can also benefit from the contribution of crowd-sourced temperature data; new methods that apply participatory sensing need to be further explored (Sun, Du, and Zhou, 2013).

Urban Climate Mapping by Sensing

Analogous with the mapping process described for urban modeling, further urban climate mapping is presented here as a result of sensing approaches. Mapping helps displaying sensing data in their spatial distribution, therefore becoming the convergence point for cooperation between climate experts and planner. In addition, in the case of real-time sensing data streamed directly to a common platform, digital mapping is certainly a good communication tool between climatologists, planners, investors, decision-makers and the public (see § 2.3.A).

As already mentioned, sensing is often used to integrate modeling with fieldwork data; however the stress here is on urban climate mapping examples with the main use of sensing rather than modeling data coming from land use covers and other assumptions (see § 2.1.A).
Mapping by remote sensing, as introduced in the previous section, is often a valid process at a large scale, and urban thermal mapping and SUHI mapping can be obtained at a 20m resolution (Figure 2-10). Additionally, also the temporal scale is limited for UHI studies, given the lack of available data at different hours of the day. However, the availability of large time-series make remote sensing more suitable for UHI variations over several years, and comparing it with the urbanization process (T. W. Lee, Lee, and Wang, 2012).

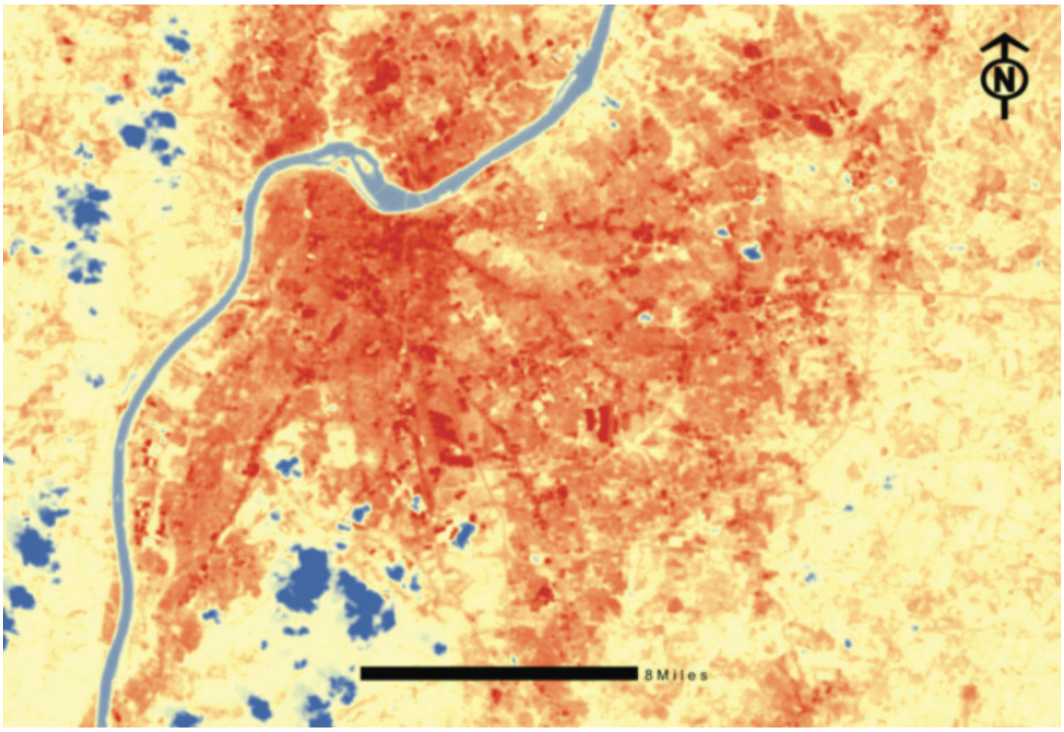


Figure 2-10 Landsat 8's Thermal Infrared Sensor (TIRS) detects energy emitted in the infrared band as a result of surface heating. In this false color image the blue areas are clouds which are cooler than the surface and, therefore, radiate less energy in the IR spectrum. This image of the greater Louisville Metropolitan area was recovered on June 6, 2013 (Sandifer and Mountain, 2014, p. 11)

Mapping urban climate by sensing, requires the translation of data gathered from fixed or mobile sensors into a static or dynamic map; according to the scale and resolution of the data, different mapping strategies can be applied to represent urban climate, for example, to represent air temperature in streets at the pedestrian level. In the case of data coming from a mobile sensor, the "logging" process and the speed of the sensor will determine the resolution of data points to be represented and aggregated for mapping purposes. Representation of the raw data might be sufficient if the resolution is comparable with the map scale (see Figure 2-11).

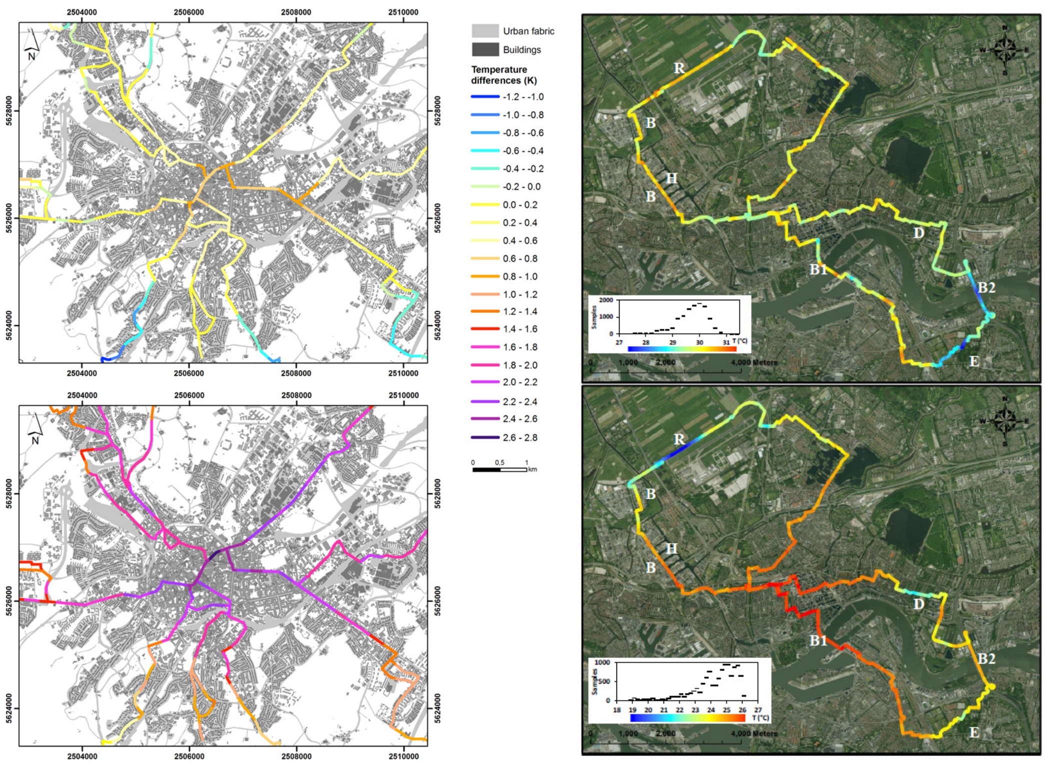


Figure 2-11
Pictured at left: Average temperature differences between mobile measurements and suburban weather station in Aachen-Horn during (top) the period of maximum temperature (12:30p.m.–05:30p.m.) and (bottom) the evening cooling phase (05:30 p.m.–10:30 p.m.). Source: (Buttstädt et al., 2011, p. 1019).
Pictured at right: Air temperatures along the measurement track. Histogram inserts show the distribution of the measured air temperatures, trend removed. Top: midday (from blue: 27.4 to red 31.3°C). Bottom: evening (from blue 18.9 to red 26.1°C) Source: (Heusinkveld et al., 2014)

These mapping strategies are similar in every case where discrete information, such as scattered data points, need to be represented in linear or a real way; interpolation and kriging techniques are applied to distribute the information on larger areas surrounding the data points, according to a set level of representativeness. See § 2.3.B and 2.2.B for more about this.
Many more examples of mapping by sensing are described in the next section about air pollution; in most of air quality sensing, in fact, temperature and humidity are essential parameters and therefore air quality mapping by sensing often includes heat-related information (see § 2.2.B)

See also **Annex 1** for a comparative table with mapping by sensing examples.

2.2. AIR QUALITY MAPPING

How mapping air quality is currently done?
This section explores the two approaches used to map air quality and pollutant concentration within the urban environment, similarly to the previous section about urban climate and heat concentration: "modeling" and "sensing".

2.2.A - Modeling for air quality mapping
2.2.B - Sensing for air quality mapping

2.2.A - MODELING FOR AIR QUALITY MAPPING

As briefly introduced in § 1.2, air pollution concentration has harmful effects on human health, and its spatial variation within the city requires a proper scale mapping in order to let urban planning intervene. In fact, pollutants concentration depends on emission source location, and on dispersion processes. Therefore, numerous numerical models help understanding the distribution and concentration of pollutants in the urban environment.

The purpose of this sub-section is to show basics of air modeling, enough to understand how it helps the urban planning research in studying and mapping of air pollution concentration in urban environments.
It is therefore not to be meant as a comprehensive technical literature review of physics and mechanics modeling research studies; as for climate modeling (§ 2.1.A), it is instead intended as a brief premise for comprehending how sensing, focus of the next section and of the overall thesis, is essential and useful to integrate air modeling.

- Multi-scale modeling for Air Pollution
- Spatial and local scale pattern of air pollution concentration
- Air Quality Mapping by modeling

Multi-scale modeling for Air Pollution
Anthropogenic air pollutants are mainly emitted on the lower urban scale and formed, distributed, and communicated to regional, global and smaller scales via transport and turbulence processes. Pollution concentration in urban areas is therefore determined by two factors: the amount of pollutant locally emitted and the airflow patterns that can contribute to pollutants dispersion or reduce air mixing. Figure 2-12 shows the complex airflow in the two major scales: regional perturbation level and diurnal ground level, with the typical logarithmic wind velocity profile.

Looking at the process, there are two traditional broad categories of air modeling:
- dispersion modeling
- receptor-based modeling.

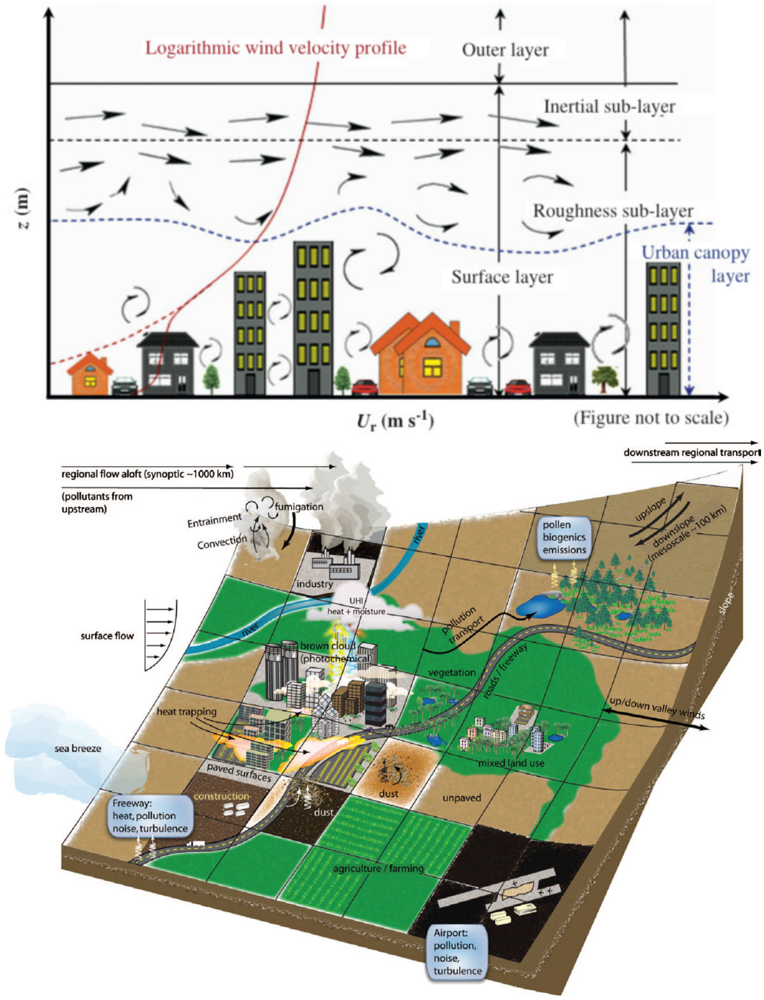


Figure 2-12
Pictured at the top: typical logarithmic wind velocity profile within the urban boundary layer, modified after cited source (C. Grimmond and Oke, 2002, p. 793).
Pictured at the bottom: A schematic of flow and turbulence related phenomena typical of urban environments. Roadways, water bodies, buildings, facilities, industries, and land-use variations all influence urban flow patterns. Overlain the schematic is a typical mesoscale model grid, and all processes within need to be parameterized (Fernando et al., 2010, pp. 051301–2).

While dispersion models are aimed at studying how pollutants move in the air and at predicting their concentrations, receptor models uses database air quality measurements itself, often in combination with meteorological data, in order to determine the sources and quantify their contributions.
They vary on many aspects, such as: the spatial (microscale, local, regional, global) and temporal scale (episodic or long-term models), the inputs (i.e., meteorological data, building and land contours); the numeric equations (simple box models, Lagrangian or Eulerian models), the complexity of the approach and processes included in the modeling.
For example, taking into consideration dispersion modeling of pollutants from road traffic in the urban environment, which are usually the dominant source in cities, broad differences can be highlighted. Besides different treatment processes included, nanoparticle size ranges, the scale focus and their consequent performance vary.

Within the "urban scale", five key scales can be considered, each one with its flow, mixing and air pollution dispersion dynamic: vehicles wake, street canyons, neighborhoods, city and road tunnels (Kumar et al., 2011).

For a detailed overview of existing air modeling, see recognized literature (Arya, 1999; Britter and Hanna, 2003a), and the recent advancement included in the "Air Pollution Modeling and its Application XXIII" proceedings in Complexity (Steyn and Mathur, 2014).

Spatial and local scale pattern of air pollution concentration

The particular structure of the urban environment affects the atmospheric circulation (i.e. UHI) and the air mixing and dispersion of the pollutants. Unlike surface energy balance models for urban climate, which solve equations considering single urban portions (see § 2.1), air models cannot consider portion of a city as individually polluted "boxes". A local scale concentration, such as particulate matter in a street canyon, is a result of a scale interaction with the city and regional level atmospheric airflows. For example, PM2.5 concentration inside an urban canyon can be caused up to 40% by emissions in surrounding street (Mensink, De Ridder, Deutsch, Lefebre, and Van de Vel, 2008).

In order to study the spatial variability of air pollution concentration within cities, and to describe and map the intra-urban spatial pattern, specific models have been developed and used, such as: dispersion models, proximity-based assessments, GIS geo-statistical interpolation and kriging, and land use regression, integrated meteorological emission and hybrids. A review of air modeling studies (Briggs et al., 1997; Jerrett et al., 2004) showed there is no better modeling method, as their theory concept, data requirements, cost and performance highly vary among them. This is due to the complexity of the phenomena involved (such as turbulence and chemical reactions) and to the desired level of scale and parameters involved.

In order to model and map air quality at a local scale, most of the existing air modeling studies use emission grid datasets coming from national scale inventories, spatially distributed over a smaller grid; a small scale distribution of pollutants, like the urban and local scale, is therefore reached by down-scaling. Additionally, further datasets can be available in some cases, like in several large European cities and urban conglomerations, where dedicated "bottom-up" inventories coming from local estimates, provide more accurate fine scale modeling (Timmermans et al., 2013).
However, only a dense spatially distributed network of information, emission or concentration, can provide accuracy in estimating local scale air quality.
Moreover, since numerous thermodynamic and chemical processes (i.e. secondary air pollutants formation) can interact in nonlinear, complex ways,

holistic models are necessary to include all dominant forcing and feedbacks, emission and concentration at the local scale.
Given this complexity, "reduced-models" are commonly used in environmental studies with the aim of studying selected processes and interactions. Similar to modeling for urban climate, air models traditionally investigate few physical mechanisms in isolation using controlled laboratory, mathematical and theoretical techniques (from computational fluid dynamics CFD to micrometeorological models mentioned in § 2.1.A).

Although they have contributed to the current knowledge, those models preclude identification of mutual interactions among processes, and therefore their results should be viewed circumspectly in decision making and planning context (Fernando et al., 2010, para. 051301–18). Additionally, as the review by Jerret et al. showed (2004), there is the need for more research in integrating sensing for air pollution exposure modeling: remote sensing, mobility analysis, and personal monitoring to cross validate estimates and improve understanding of the role that measurement errors play in risk assessment models.

In this regard, a new generation of instrumentations and the diffusion of field measurements by sensing will increase the environmental complexity through a better holistic approach. The contribution of pervasive sensing in improving modeling will be further discussed in § 2.3.

Air Quality Mapping by modeling

As mentioned before introducing air quality modeling, the main aim here is to show what knowledge from environmental and fluid mechanic studies can be transferred to urban planning, in order to map air pollution concentration in cities, and to provide urban planning with the spatial knowledge to intervene. In fact, air quality mapping can present air pollution concentration in two-dimensional spatial maps, therefore providing base knowledge of the city for urban planning processes. Starting from air quality mapping, specific environmental and urban measures can be put in force, and spatial recommendation can be individuated (see § 1.3.1).

As already anticipated, and similarly to urban climate mapping, there is no universal mapping process in the research community, and several air maps correspond to the different models applied. In addition, while in climate mapping, most of the studies use three software tools (Rayman, Envimet, Solveig), in air pollution mapping the tools used are uncountable.

Four heterogeneous examples are therefore shown here, selected in order to underline the potential and limits of mapping by modeling at a local scale.
In the first example, a local-scale modeling applied to a city quarter of Ghent, Belgium, shows predicted PM2.5 concentration inside street canyons (numbers) and outside background contribution (colors), based on a traffic simulation software (Mensink et al., 2008). While results appear to need further investigations, the map easily highlights how the background contributes to the air pollution at the local level (about 40% contribution.)

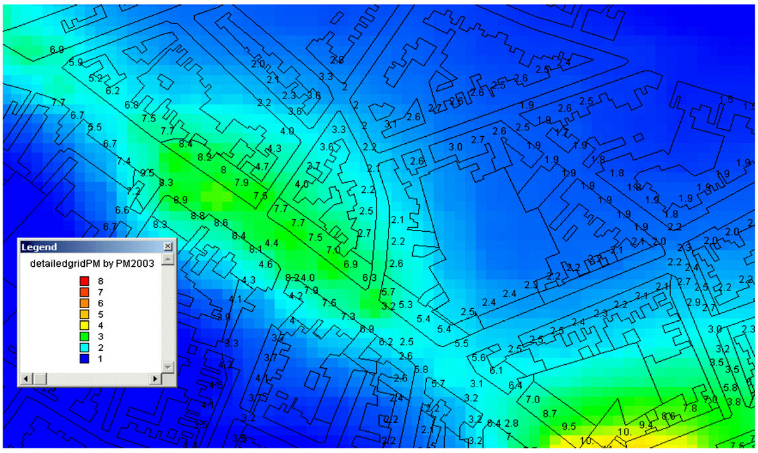


Figure 2-13
Predicted concentrations of PM2.5 (2003) in µg m-3 in the city quarter of Gentbrugge. Numbers show the PM2.5 concentrations inside street canyons. Colors show the PM2.5 concentrations outside street canyons (Mensink et al., 2008)

In a second example at the same scale, air modeling is brought to a high level of simulations, using a building model and a wind model combined to a Langrangian random-walk model that together compute the 3D flow around buildings (Fernando et al., 2010). The map, showing the airflow streamlines at 1 m, and the PM10 concentration in the morning and at noon of a selected day, is able to display the relation between high pollution concentration and slow circulation.

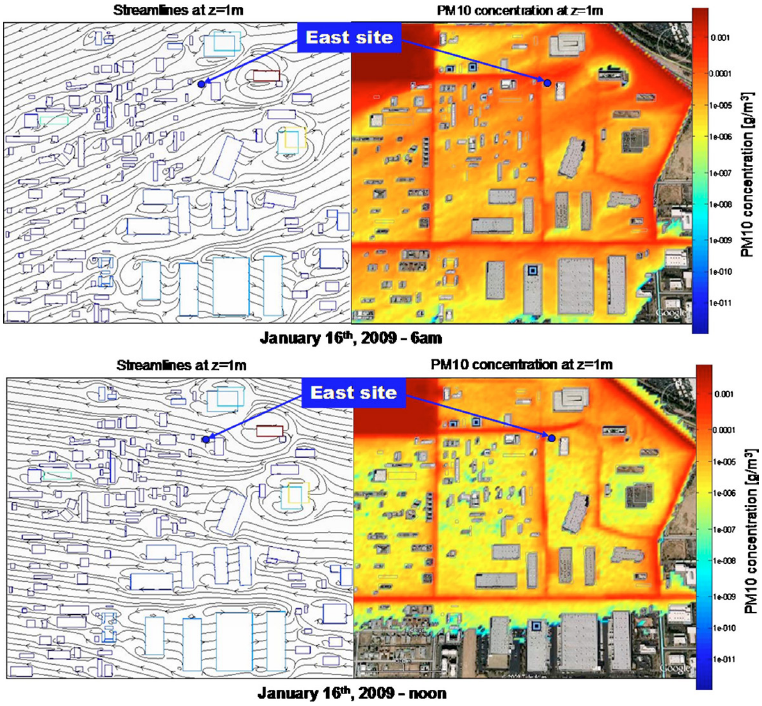


Figure 2-14
Color online: Streamlines of the airflow at 1 m agl (left) and PM10 concentration (right) in the morning and noon time on a selected day, calculated using a model. Only local emissions from the domain are included in this calculation (Fernando et al., 2010, pp. 051301–17).

The third example focuses on mapping by modeling, when modeling relies on national/local inventories, as described in the previous section. Emissions of nitrogen oxides from road transport are mapped for the city of London, using a resolution grid of 1x1 km (World Health Organization, 2006, p. 23).

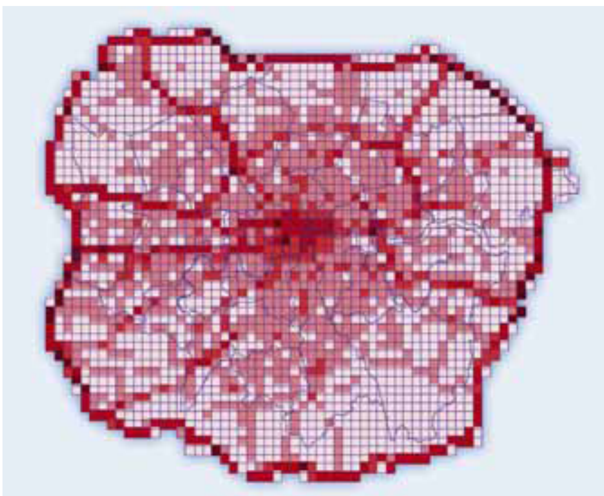


Figure 2-15
Emissions of nitrogen oxides from road transport in London, 1999 (0–10 tonnes 10–30 tonnes 30–50 tonnes 50–100 tonnes 100–200 tonnes) (World Health Organization, 2006, p. 23).

The map clearly shows the influence of road traffic in terms of a gradient increase in emissions from central areas to less trafficked suburban areas of the city. Additionally, the map has clear delineation of major arterial routes, which are visible despite the fact that they correspond to objects smaller than the 1x1 km resolution.

In the last example, at a higher city scale, two scenarios for the development of the German Ruhr are considered: an urban sprawl scenario and a satellite city scenario. Using land use, traffic and atmospheric modeling, a 3-week simulation, period was calculated. The maps provides immediate insight into the modeled situations, different for ozone and PM10: in the case of ozone, there is an evident increased plume according to a southeast wind direction for the urban sprawl scenario, and a better situation for the satellite city scenario (Mensink et al., 2008). In the case of PM10, the maps are able to show unexpected results: while emissions might be increased, the concentration, and consequently the exposure, is reduced for the sprawl scenario, while the satellite scenario determine local spots of increased concentration and an overall higher global exposure.

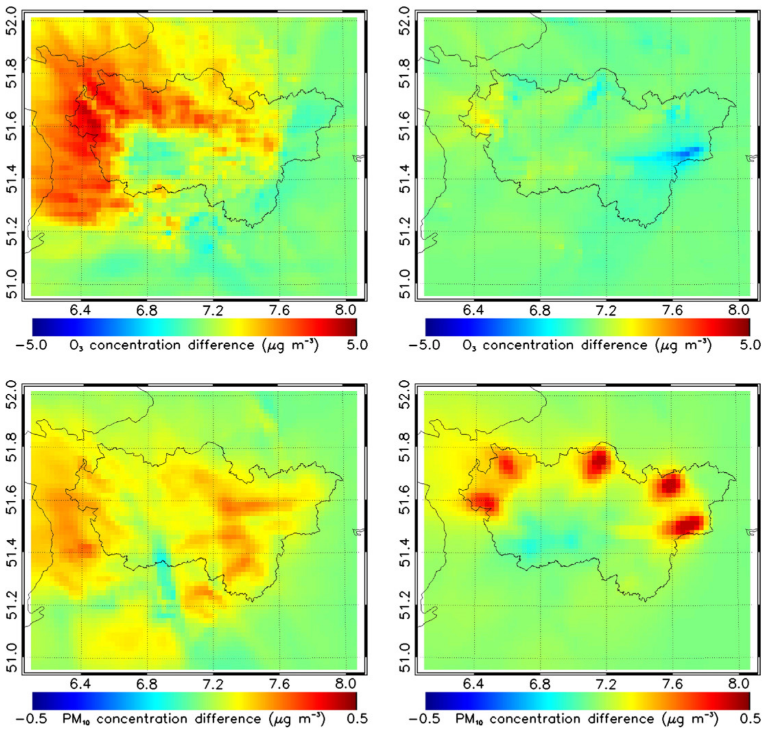


Figure 2-16
Concentration change (µg/m3) of ozone (upper panels) and PM10 (lower panels) for scenario 1 (left panels) and scenario 2 (right panels). Positive values indicate an increase in the considered scenario as compared to the reference situation (Mensink et al., 2008).

2.2.B - SENSING FOR AIR QUALITY MAPPING

Sensing networks specifically built for air quality studies coincide in most cases with traditional climate and meteorological global and national networks (see table 1-1, § 1.2), or with environmental stations usually designed to collect data for studies at a global/ macroscale/ regional/ mesoscale level.
In addition, even if governmental monitoring stations measure air pollution at the city level, the specific measurement protocols and standard instrumentations, are costly to deploy and maintain, ultimately resulting in very sparse coverage.

Increasing the spatial resolution of air quality within urban environments is a priority in current research and traditional approaches are being improved as new technologies are emerging.
Biomagnetic monitoring, for instance, uses living organisms as "sensors" by monitoring their response to changes in their environment; in a study done collecting ivy leaves in 100 locations in Antwerp, NO2 intra-urban maps showed a variation with a reliable accuracy (Hofman, Lefebvre, and Janssen, 2014). Because of the high uncertainty in processes determining leaf particulate deposition, and the incorporation of multiple emission sources with diverging magnetic composition, air quality modeling through "direct" air sensing remains the most prosperous field of research, thanks to the advance in the sensor technology.

- *Sensing networks for air quality: intra-urban scale*
- *Mobile Sensing for air quality*
- *Air Quality Mapping by sensing*

Sensing networks for air quality: intra-urban scale

There are few examples of city-scale dense sensor networks for air quality studies. Considering all existing networks worldwide, the following urban air sensor networks appear to be the most noteworthy. For references and general information about the sensors currently used within the sensor networks in measuring air parameters mentioned here below, such as different optical, electrochemical sensors, see § 4.2 and the Annexes 1-2.

Citysense is the sensor network implemented by Harvard University in Cambridge, USA. Its main purpose is monitoring temperature, wind, humidity, CO2, noise, using 25 sensors (100 proposed) covering an area of 18.000.000mq. The sensors used in the network are Vaisala, WXT510, Weather Sensor (humidity/temperature with sensor Humicap180). It allows studies of weather, air and water pollution, biochemical agents (Murty et al., 2008). It was the first real network at a micro scale covering a whole city; however, technology constraints, and lack of management over time, determined a decline in its momentum and the network was never further developed and it is currently offline.

SmartSantander is the recent sensor network implemented by a European project (companies and institutions including Telefonica I+D and the University of Cantabria in Santander, Spain). Its main purpose is monitoring temperature, CO, noise, light and car presence, using 2000 sensors installed at streetlights, facades, and 150 in public vehicles. The sensors used in the network are Libelium Waspmote (MCP9700 for temperature). It represents the most ambitious project about smart networks: "a unique in the world city-scale experimental research for a smart city" (Hernández-Muñoz and Vercher, 2011; Sanchez et al., 2011). While it includes a variety of features, a web platform and a mobile App for public participation, the project is still not completely developed and fully implemented to its potential.

OpenSense is the sensor network implemented by ETH Zurich (and EPF Lausanne) in Zurich and Lousanne. Its main purpose is monitoring temperature, humidity, CO, CO2, NO2, O3, UFPs, using a combination of mixed and mobile sensors; in Lausanne: 3 stationary stations, 2 mobile on buses, 1 mobile on electric car; in Zurich: 1 stationary station, 10 mobile on trams, 1 mobile on bus. The sensors used in the network are OpenSense stationary and mobile stations (Hasenfratz et al., 2014).
It could be the most successful case of a sensor network for air quality studies, thanks to its coverage, continuous maintenance, flexibility, and data dissemination. In fact, it allows studies of accurate location-dependent and real-time information on air pollution. However, due to the mobility factor (i.e. airflow direction) of the sensors, there are numerous extra challenges in interpreting the results.

A last example of city-scale sensor network for quality is the New York City Community Air Survey (NYCCAS), aimed at monitoring the intra-urban spatial variability of the following air pollutants related to combustion: PM2.5, BC, NO2, O3, SO2. It consists of 150 sensors installed on light poles at 10/12 feet height collecting samples in selected locations representing a wide range of traffic, building density and other neighborhood features (“NYC Community Air Survey,” n.d.) (Clougherty et al., 2013; Matte, Ross, and Kheirbek, 2013). Compared to the other examples cited before, NYCCAS is not a real-time sensing network: samples are systematically collected and brought to a laboratory for analysis.

The following two examples of sensing networks are not specifically designed for air quality as the previous ones, but they share some similar features and can be seen as references in sensing studies.
SensorCity is the sensor network implemented by Province of Drenthe and the municipality of Assen in Assen, NL. Its main purpose is monitoring sound and mobility, using 200 sound sensors and several tens of mobile sensors. The sensors used in the network are “On Board Unit” (a smart box) and tablet in cars. It allows studies on identification of “sound zones”, and it allows anticipating

instead of reacting to the current traffic situation. While the project does not include air quality sensors, it can be seen as a reference example of functioning networking technology, of development and application of knowledge related to sensors (“Sensor City,” n.d.).
SensingCity is the sensor network implemented by a social enterprise with the same name, Arup, and MIT Little Devices, in Christchurch, New Zeeland. Its main purpose is monitoring water quality but ongoing development includes air pollution and mobility. For the water sensing component, the project used sensor kits distributed to students who measured water quality, and proved to be successful involving public participation in environmental topics (“Sensing City,” n.d.).

Besides city scale sensing networks, smaller intra-urban air networks also exist, mainly for academic studies. Four leading universities have designed and deployed sensors within their campuses in order to collect real-time data and map air quality.

Clairity is a project aimed at monitoring air quality within the MIT campus with the use of 24 real-time low-cost sensors nodes (Alphasense and Dylos, monitoring CO, NO, NO2, O3, PM10, PM2.5) installed in the nodes of major activity. Because the existing governmental air sensing network is made up of 6 stations in the suburb of the Boston great area, and the closest official station to the campus is 6 km far, Clairity aimsto better reflect and monitor air quality within the campus (“Clairity: MIT’s Air Quality Network,” n.d.; Clairity, 2014). See more on next chapters.

Beacon shares the same concept of using a high-density sensing network of devices instead of using a small number of extremely sensitive instruments. Developed by University of California, Berkeley, and experimented in Oakland bay, the network measures CO2, and other data currently not available to the public (“BeACON - The BErkeley Atmospheric CO2 Observation Network,” n.d.).

Philadelphia air quality sensor network was a pioneer experience in the field, as a project of Drexel University in 200-2010. Twelve networked sensing nodes were installed, and data coming from their low-cost sensors, such as particulate matter concentration from Dylos, were compared to municipal governmental monitoring for validation (Arling, O’Connor, and Mercieca, 2010).

CamMobSens, developed by University of Cambridge, UK, conducted the first example of large scale deployment of low-cost electrochemical sensors (Alphasense) in the greater Cambridge area, in spring/summer of 2010 (Mead et al., 2013). While the project ended with successful and promising results, new research has now begun on a NERC funded project, aimed at deploying an improved version of the devices, incorporating a novel particulates/aerosol sensor, at about 60 locations around Heathrow airport.

As can be seen from this brief overview, while the research community is exploring the potential of sensing networks for air quality studies, as the examples show, governmental authorities and in particular urban planners have yet to discover its opportunities.
However, the US EPA, in the last two years, is strongly supporting the "Next Generation Air Measuring" (United States Environmental Protection Agency, n.d.), profiting from the rapid developments in technology that is leading to the production of small, low-cost air pollution sensors. An annual "Air sensors" workshop was established in 2013, and repeated in 2014 ("Air Sensors 2014," n.d.), in order to spark more discussions about advancing innovative air sensor technologies, by bringing together government, scientists, policy makers, technology developers, data analysts and community groups (see § 4.2).

Mobile Sensing for air quality

As seen in the previous section, sensing for air quality expresses its potential of integrating scarce monitoring stations data with high density measurements at a small scale, even between neighboring streets and over the course of a day. Besides the examples of structured sensing networks presented, other interesting experiences on air sensing exist, although with less spatial or time coverage. They all started within the last 5 years, and are still active with increasing emphasis.

With the aim of increasing awareness and participation on air pollution matters, two ongoing European projects are promoting monitoring air quality through networked mobile sensors.
The first, EveryAware in an ongoing European Project (2011-2014) based on citizen-science concept, in the field of air quality and noise pollution. Case studies were designed in order to make individuals participate in directly monitoring parameters of their environment (such as noise pollution or air-quality) during their normal activities. Thanks to a portable sensor (Air Probe), geo-localized data is continuously collected, together with personal perceptions (see: www.everyaware.eu). The international game challenge, held in 2013 in London, Turin, Antwerp and Kassel, and the development of smartphone Apps, engaged more than ten thousand people in experimenting monitoring air quality and noise in their cities.
The second, Citi-Sense (2012-2016) is one of the five "Citizens Observatories" projects funded by the European Union aimed at developing novel technologies, applications, and architecture platforms in the domain of air quality. By exploiting the capabilities offered by portable sensor devices, including smartphones, the main objective is to enable effective citizen participation in environmental monitoring and policy making ("CITI-SENSE," n.d.; J. Robinson, Kocman, Smolnikar, Mohorcic, and Horvat, 2014). Recognizing the

environmental, cultural and social differences between the several partners, each participating country is running its own citizen empowerment campaign adapting to local circumstances; however, this approach has prevented practice exchange and international relevance of the results.

With the same focus on increased citizen participation, but with a “bottom-up” design and implementation, two air sensing network projects are quickly developing and increasing attention worldwide.
The first, Air Quality Egg, is a network of air sensors created with a 2012 kickstarter project by designers and technologists working on urban social and environmental problems. It is a community-led sensing project based on about 1100 “AirEggs” (sensors monitoring air quality parameters, designed as a fixed base, although it’s portable) currently active and mapped worldwide (“Air Quality Egg,” n.d.). With the help of good design and fundraising campaign, the project has attracted media attention, and its implementation has addressed people’s desire to participate in the conversation about air quality.
The second, Air Casting developed by HabitatMap (a New York based NGO) and other partners (including Google Earth Outreach Developer Grant) is a sensing project based on the DYI (do-it-yourself) concept, which is an articulated sensor to be built based on simple instructions (“AirCasting,” n.d.). It includes optional features (such as an air casting luminescent vest), and health exposure data. Because of its wearability or portability, it has been extensively used since its launch in 2011, for fieldwork monitoring campaigns, and “community mapping” showing reliable results and a growing worldwide interest. A new version with an improved design and sensors, AirBeam, was launched in November 2014 with a kickstarter campaign, with the aim of “moving to mass production”(“AirBeam: Share & Improve Your Air by HabitatMap,” n.d.).

Back to the research community, three mobile air sensing projects from Universities in the USA showed its potential although they are still undeveloped.
Common Sense by UC Berkley is a sensing project aimed at developing mobile sensing technologies that help communities gather and analyze environmental data. The air sensing project, not yet implemented, will install sensor systems on street sweepers in San Francisco and deploy handheld device with a community action group in West Oakland (“Common Sense — Mobile sensing for community action,” n.d.).
Urban Sensing developed by CENS/UCLA is a sensing project based on a series of research sub-project under the topics of "embeddable sensors" (SES) and participatory sensing (PART-URB), such as the personal environmental impact report project (PIER) (“CENS: Center for Embedded Networked Sensing,” n.d.; Mun et al., 2009).
Common Scents (or better known as The Copenhagen Wheel) is a project developed by Senseable City Laboratory, MIT, which included a bike prototype capable of collecting air quality data while riding in the urban environment (“Copenhagen wheel project,” n.d.). During its launch, the bike sensors collected

data in December 2009, showing the potential of mobile sensing for fine-grained environmental information.

Several private companies' mobile air sensor projects are growing in recent years, and in particular in 2014: an emerging business has been discovered, thanks to the continuous increase of public interest and awareness on environmental matter, and in particular on air pollution exposure. Most relevant examples are Sensodrone ("Sensorcon | American Made Single Gas Meters and Environmental Sensors," n.d.), and Sensaris ("Sensaris - Wireless sensors," n.d.), both developing and selling low cost sensor devices but with different targets: personal sensing for the first company, and participatory sensing for the other.
For a thorough overview of air sensing devices, commercially availably or research prototypes (M-pod, Envboard, etc.) see the US EPA "Air sensor 2014" website ("Air Sensors 2014," n.d.) and § 4.2.

See **Annex 1** for more about "Sensor networks" and **Annex 2** for more about "Mobile sensing" devices.

Air Quality Mapping by sensing

In mapping air quality at the local level, sensing shows one of its main advantages: compared to modeling, sensing measures "real world" instead of predicting air pollutants concentration. As already mentioned in the previous sub-section, most of modeling relies on some sensing data, in an effort to transfer them into a finer grained resolution spatial scale (mapping) or into a future temporal scale (forecasting).
Compared to mapping by modeling (§ 2.2.3), mapping by sensing is therefore limited to only describing the current condition of air quality, with fixed time and space coordinates; however, continuous and extensive sensing can, in some cases, help forecasts with limited use of modeling, providing "real" data with less prediction errors. This is the case of recurrent areas with high pollutants concentrations, of time periods with recurrent patterns.

While fixed sensor networks usually provide data with little resolution and therefore useful for modeling, mobile sensing can use its raw data for mapping air quality following urban paths. As for sensing for urban climate (§ 2.1.B), it is a matter of visualization techniques in how to present on a 2D/3D map the data collected. Figure 2-17 shows the air quality mapping through sensing in Turin, at two different scales: while the data source is the same, the visualization tool aggregate the data spatially, according to the zoom level chosen. The high resolution of the map is permitted thanks to the mobile sensing conducted covering the most streets and multiple times (data shows a daily average of black carbon).

Figure 2-17 Screenshots of the mapping by sensing campaign in Turin. Black carbon concentration estimation based on data collected by mobile sensors (left). Pictured at bottom-right: CO output from a mobile CO sensor; the highest values are found along the main road, highlighted in red, especially at the intersections. The lowest gas levels are found inside a green pedestrian area ("Air-quality | EveryAware," n.d.).

Mapping from raw data is usually the case of real-time platforms, where data is shown as being collected without processing it (Figure 2-18). Machine learning techniques are frequently applied in cases where data above certain limits or data with low accuracy is calibrate in real-time with historical pattern or with official monitoring station data.

In most cases data processing is conducted at a second stage, using the raw sensing data integrated with other parameters, in order to create a spatially complete maps (see Figure 2-19 and Figure 2-20)

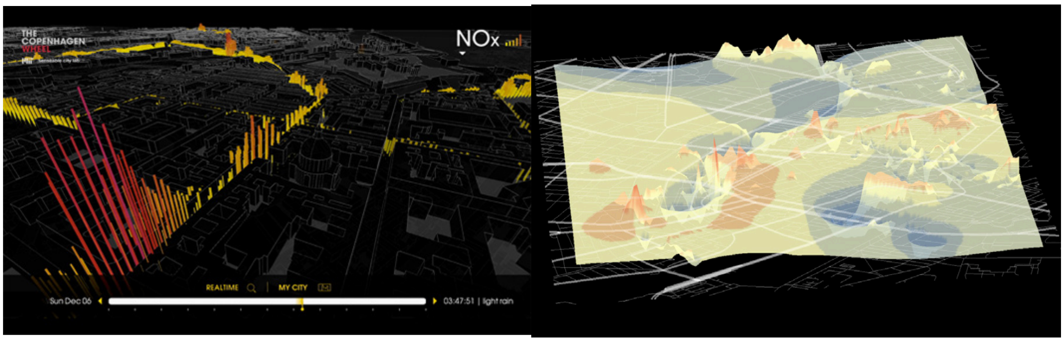


Figure 2-18
Pictured at left: raw data of NOx in the Copenhagen Wheel Project mapped on a 3D model. While the environmental sensors were originally intended to be placed within the hub of the bicycle wheel, due to logistical pressure they were placed on bicycles ridden by couriers in Copenhagen going about their normal daily routine (ten cycles).
Pictured at right: map generated from raw data. The analysis component, which processes the collected data, performs a spatial Inverse Distance Weighting (IDW) interpolation, used for correlation operations with emission distribution or traffic emergence, and for the detection of urban heat islands ("Copenhagen wheel project," n.d.; Resch, Britter, and Outram, 2011)("CamMobSens," n.d., "Copenhagen wheel project," n.d.).

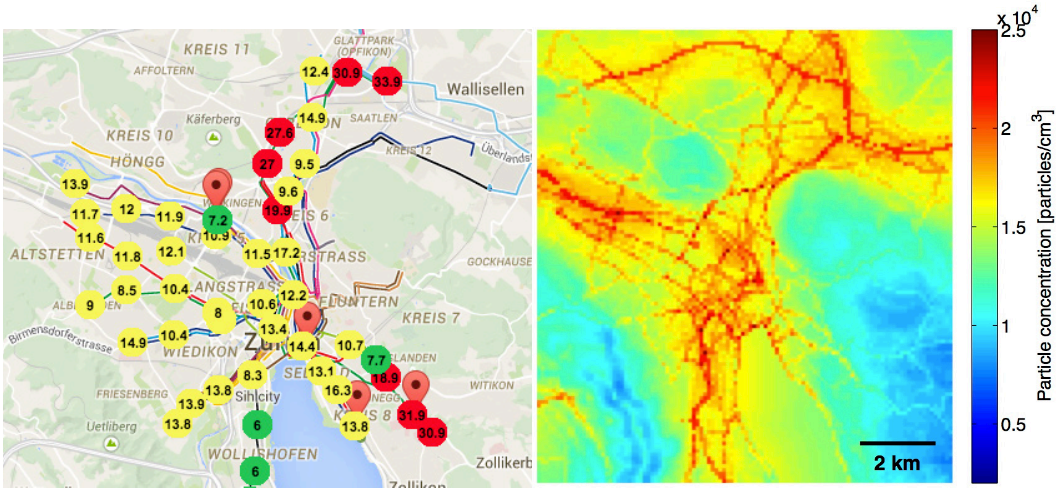


Figure 2-19
Data from Opensense project in Zurich.
Pictured at left: real-time data from sensors installed on 10 trams and 1 bus in Zurich, as displayed on the project website ("OpenSense Live Data Browser," n.d.).
Pictured at right: processed data in a heatmap showing particle concentration (yearly average), as elaborated by ETH Zurich research team ("OpenSense," n.d.).

Sensing can also be a temporary survey where data is collected for modeling air pollution prediction according to other conditions. Figure 2-21 shows the case of Montreal, where NO2 concentration was measured at 133 locations with passive diffusion samplers, and data was used for land use regression (Crouse, Goldberg, and Ross, 2009). On the basis of the same map, a web-based route planning tool was developed, calculating cyclists' potential exposures to traffic pollution on an A to B path with three conditions. The "cleanest" route is the calculated one based on the sensing campaign ("CycleApp | Air Quality of Cycling Routes in Montreal," n.d.; Hatzopoulou et al., 2013).

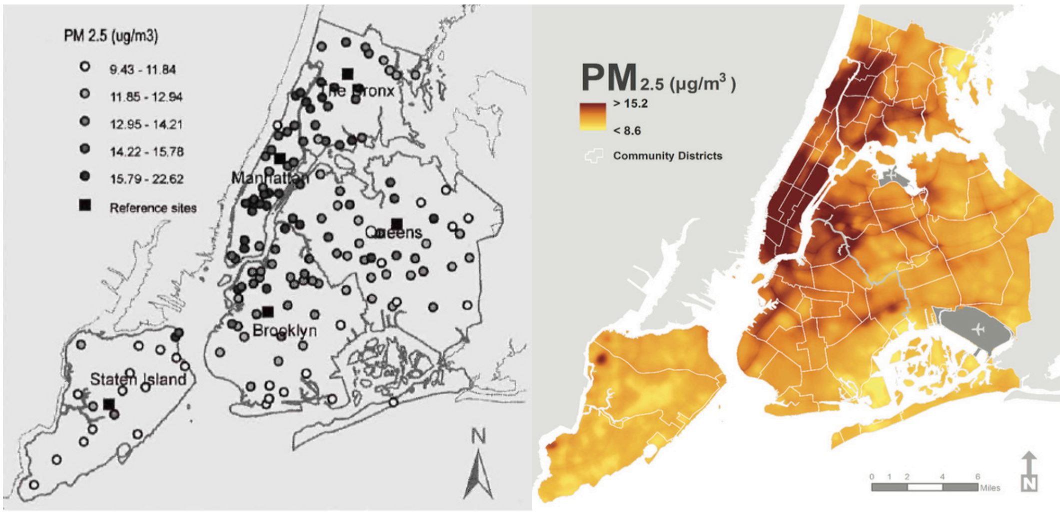


Figure 2-20
NYCCAS PM2.5 concentration map (right), generated using raw sensing data from 150 sensors installed throughout New York City (left), combined with land use regression modeling (Clougherty et al., 2013, p. 234,238)

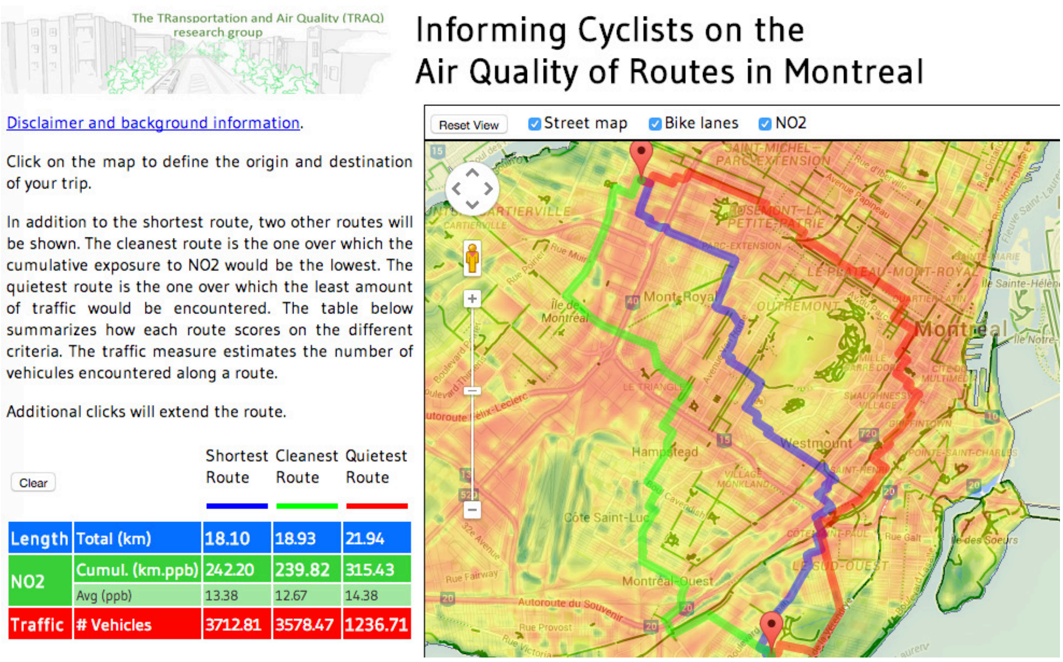


Figure 2-21
Surface map of predicted concentrations of NO2 based on the average of the three sampling periods, Montreal, 2005–2006 (Crouse et al., 2009; Hatzopoulou et al., 2013). *Pictured at right: three alternative routes from A to B provided by the "CycleApp", considering distance, air quality (NO2 level) and noise ("CycleApp | Air Quality of Cycling Routes in Montreal," n.d.).*

See also **Annex 1** for a comparative table among the mapping by sensing examples.

2.3. THE NEED FOR IMPROVING AIR SENSING TO MAP URBAN CLIMATE AND AIR QUALITY

This section introduces the potential of sensing in mapping urban climate and air quality. On the one hand, it is real-time and allows a better response and control of the urban phenomena. On the other hand, it allows a better scale and resolution, which is essential for the kind of phenomena involved. In addition, sensing can engage citizens increasing participation and awareness.

2.3.A - PROVIDING REAL-TIME INFORMATION, CITY RESPONSE AND MONITORING

§ 1.1 and 2.2 presented "modeling" and "sensing" in the process of mapping urban climate and air quality. From the evidence of their respective shortcomings, a better integration of the modeling and sensing approaches is needed "to make progress in our understanding and thus better parameterization with respect to applications" (F. Chen et al., 2012, p. 1728).
While some advantages and disadvantages in the two approaches were underlined, here they are put in a general theoretical debate within the context urban planning.

A paradigm shift: form urban modeling to city sensing

Continuing demand by planners for better tools to explore urban problems has helped to increase the relevance of urban modeling research. Its origins trace back to transportation studies in North America in the late 1950s; the objective of urban modeling was there aimed at forecasting the future trip generation and its spatial distribution in urban areas, usually using linear regression analysis and gravity models.
In the 1954 book "Urban traffic: a function of land use" by Mitchell and Rapkin, urban modeling, for traffic analyses, convinced for the time engineers and planners of the need for integrated spatial planning and transportation planning (Mitchell and Rapkin, 1954). During the same time, social sciences and related fields experienced a revolution that brought to the development of a more explicit approach. It was agreed that progress in social science knowledge needed rigorous theory-building rather than by loose speculation, leading to the so-called "quantitative revolution" and "system approach". Urban modeling therefore exploded as a prosperous field of research, defined as "an experimental design based on theory (Batty, 1976, pp. V–XXI,1–16).
As it can be deduced, modeling was, and still is today, addressed by the double use for urban planning; on one hand, in the search for a relevant understanding

of urban structure, and, on the other hand, for aiding conditional predictions, helping planners, politicians and the community to predict, describe and invent the urban future.

In both cases, urban modeling is connected to designing, building and implementing mathematical models of urban phenomena, typically at the city/neighborhood scale. Though urban modeling is truly interdisciplinary, mathematics is perhaps the most useful and applied skill in urban modeling, creating some sort of criticism because it favors those who have acquired skills not in the social but in the physical science (Batty, 1976, p. XX).

In fact, the criticism of modeling, and the rise of sensing, starts from this detachment between urban problems and the numerical modeled worlds, evolving in new evidences of the limits.

The first critique of urban modeling relates to the fact that “model builders are learning more and more about their models and less and less about the real world which they are attempting to model” (Batty, 1976, p. 4). In addition and in relation to this, models often keep adding complexity to their modeling processes, and consequently “if, in order to explain each new phenomenon we mush invent a new mechanism, then we have lost the game” (Simon and Chase, 1973, p. 396).

A second major critique regards the evidence of the limits of the classical tradition in making mathematical deduction for urban phenomena based on relatively little experimentations. In the last decades, a more conscious process of theory development has largely supplanted this tradition by manipulating a large number of observations (Batty, 1976, p. XXI). “Sensing” therefore became more and more essential to the process of describing urban phenomena, and model design started implementing large data coming from real-world experiments, what we today call “big data”, thanks also to the increase capacity of computers.

This argument leads to anther critique to urban modeling in favor of urban sensing. If one of the main rules of urban modeling is “parsimony”, where parsimony relates to the idea of “using Occam’s razor to prune unnecessary embellishments to theories and models which seek to mystify rather than explain” (Batty, 1976, p. XXII), the reality of data to be treated in today’s cities (big data with its inherent gaps and bias), makes it hard if not impossible to calibrate in their pure form.

This process is also connected to the so-called “geocomputation revolution”, where developments in IT, and new data gathering and earth observing technologies, has offered a new approach to analysis and description of territorial, socio-economic, behavioral and micro-spatial urban processes, giving planners new insights into how cities grow and evolve (Diappi, 2004).

More in detail, it can be noted that this paradigm shift from urban modeling to sensing was fostered by the increasing combined use of GIS and ICT in urban planning. From this point of view, in order to design a representation of urban scenarios, the evolution in this approach includes a gradual shift from the “virtual cities” (Dodge et al., 1998), based on the design of virtual realities and 3D simulation, to the “computable city” (Batty, 1997), where advanced models were

possible thanks to innovation in computer and ICT. In relation to the ICT developments, a further shift brought to the concept of the "ubiquitous city" (Jang and Suh, 2010; H. Lee et al., 2008), a model of interconnected city where every citizen can get services at any location, therefore spreading the computational load within the city. Ubiquitous computing, also defined as "Everyware", (Greenfield, 2006), is "a vision of processing power so distributed throughout the environment that computers per se effectively disappear….Although aspects of this vision have been called a variety of names – ubiquitous computing, pervasive computing, physical computing, tangible media, and so on - I think of each as a facet of one coherent paradigm of interaction that I call everyware" (Greenfield, 2006, p. 1).
Today, less than a decade after, this vision became reality, and from "ubiquitous computing" the research attention shifted to "pervasive sensing", given the spread of sensors, as technologies used in everyday urban life. From this step, considering also the further development in ICT and network studied (wireless networks, sensors, remote sensing, social networks), the sentient/real-time/responsive city concepts developed, finally leading to "city sensing" (Borga, 2014), as further described in the next section.

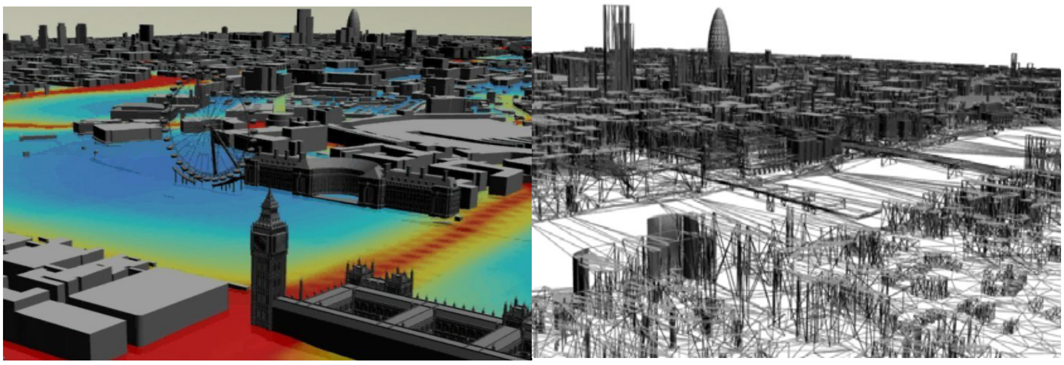


Figure 2-22
"Virtual London as a Mirror World": Layering an Air Pollution Map (NOx) on the digital block model (Hudson-Smith, Milton, Dearden, and Batty, 2007)

Sensing for mapping the real-time city, the sentient city, the responsive city

The previous section briefly introduced the advantages of urban sensing, in relation to urban modeling. In particular, in describing urban phenomena, urban sensing has the ability to create dynamic real-time mapping, instead of a virtually modeled condition.

Moving forward "everyware", as the digital technologies became increasingly pervasive (and networked online, as in the vision of "Internet of Things"), every individual and urban activity is creating a gigantic amount of data. Even though the data sets generated are still disconnected, they are slowly converging to common interfaces. The first scientific example of such data sets ICT for urban planning purposes is the Real Time Rome, a project developed in 2006 by Senseable City Laboratory at MIT. Taxi, bus and especially phone calls were mapped in real-time during a large event (final of the World Cup). Through an unprecedented sophistication in sensing data, the real-time map was able to display the spatial movements of people within the city, and the calls intensity in its spatial variation (Calabrese and Ratti, 2006), later evolved to the "wiki city" idea, a platform able to collect, manage and provide real time data (Calabrese, Kloeckl, and Ratti, 2008), and to "current city", with a stronger emphasis on a city as "layers of networks and digital information blanket our urban space" (ww.senseable.mit.edu).

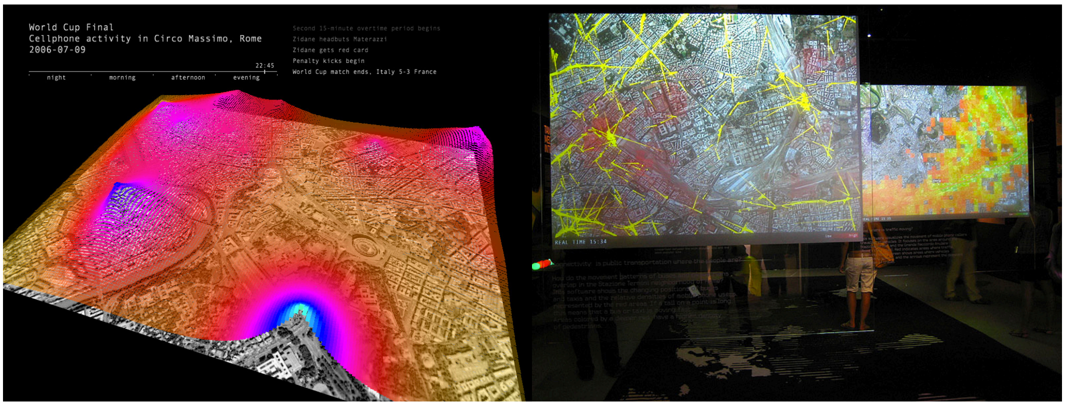


Figure 2-23
Real time Rome, a MIT SENSEable City Lab's contribution to the 2006 Venice Biennale. The project aggregated data from cell phones (obtained using Telecom Italia's innovative Lochness platform), buses and taxis in Rome to better understand urban dynamics in real time. By revealing the pulse of the city, the project aims to show how technology can help individuals make more informed decisions about their environment (Calabrese et al., 2011; "Real Time Rome," n.d.).
Pictured at left: screenshot of the movie showing the spatial distribution of the cellphone activity overtime during the world cup final match (Italy-France, July 9, 2006). Pictured at right: the yellow lines represent buses in real time and the red corresponds to density of people (Sep. 2006).

This early example of the usage of data sets for mapping urban phenomena is only one type of "sensing" in urban space. More generally, this category refers to "opportunistic sensing", where data is generated for other reasons (i.e. phone calls) and is used to get insights and reach other conclusions. Because many digital traces are geo-located, datasets are enhanced with multidimensional tags, and allow multiple cross-disciplinary studies (Martino et al., 2010).

A second category of sensing for mapping the "real-time city" (Kitchin, 2014), is "crowdsourcing sensing", where data is coming from people providing

information with or without their personal digital devices. This process is sometimes incentivized through monetary compensation, or voluntary, especially in the case of social matters (such as real-time traffic). In the case of air quality mapping, for instance, sensing becomes a deliberate civic action, and citizens take an active role in participatory sensing.
The third category is the more intuitive use of data coming from an array of sensors deployed with the specific intent of collecting spatial and temporal variation of urban phenomena. Because sensors are becoming smaller, more accurate and networked, they are leading to idea of “smart dust”.
The “sentient city” is therefore the idea of a city that “can remember, correlate, and anticipate”, thanks to the availability of smart dust, as “information processing capability is embedded throughout more and more of our urban infrastructure” (Shepard, 2011).
Finally, the “responsive city” concept develops from the above, and a recent book (Goldsmith and Crawford, 2014) emphasizes the use of city sensing for intelligent urban governance, capable of anticipating and predicting problems, and of reacting with prompt actions.

Sensing for managing and monitoring the city, the smart city

The idea of the "responsive city" presented in the previous section, can be connected to the conventional "smart city" vision, if this is considered in the traditional paradigm of top-down and technocratic approach.
In fact, just as Le Courbusier's Ville Radieuse was a reaction to the rise of mass production and cars, present-day smart city idea designed as "open air computers" is generated to address current efficiency and sustainability concerns (Carlo Ratti and Claudel, 2015). In classic examples, like Masdar City, smart cities systematically address maximum resource efficiency through design and top-down management, and almost leave citizens as an afterthought.

In relation to material introduced in the previous section, sensing lets city governments use real-time analytics for management, control and regulate city functions. For instance, mobility management through cameras and sensors that feed back to a central hub in order to monitor the traffic flow, adjust traffic light sequences, control speed limits and automatically order traffic violations penalties (Kitchin, 2014).
Similarly, data related to environmental conditions, such as urban climate and air quality, can be collected by a sensor network distributed throughout the city; local governments can therefore respond in real-time in case of emergency, generating a surveillance system. For example, the Centro De Operacoes Prefeitura Do Rio (Figure 2-24) in Rio de Janeiro, a partnership between the city government and IBM, have created a citywide system that draws together data streams from mobility agencies, utility and emergency services, into a single data analytics "surveillance" center, in order to manage ordinary city development and to manage environmental risks, such as flooding (Ruvolo, 2013).

Figure 2-24
Two images from the official webpage of the Rio surveillance center ("Centro de Operações Prefeitura do Rio de Janeiro | Acompanhe em tempo real tudo o que está acontecendo na cidade do Rio.," n.d.)

However, as Jane Jacobs anticipated in her 1961 seminal work "The death and life of great American cities", a natural surveillance is possible if cities are "places for people", and their "eyes upon the street" can create a safer environment, thanks to "an intricate, almost unconscious, network of voluntary controls and standards among the people themselves, and enforced by the people themselves" (Jacobs, 1961, pp. 32–35). Through the idea of improving connectivity, “urban activism” is an actuator for natural surveillance, and today’s social networks and digital media are enforcing this idea. Saskia Sassen emphasizes this concept of being able to “activate a citizenry”, with the bottom up and self-organizing energy that can be fostered and catalyzed by social networks: “Leak the knowledge of the neighborhood into codified systems – like a wikileak” (Sassen, 2014). A more modern vision of smart city, therefore, emphasizes sensing with public involvement in an integrated bottom-up and top-down approach of managing and monitoring a city. For example, the Smart Santander project includes a “participatory sensing app” (Pace of the City) (“Participatory Sensing Application,” n.d.) providing augmented reality information in real time for city functions (such as traffic, buses, bike-rental) and for city environment (such as urban temperature, air quality) together with the possibility for citizens to directly report geolocalized information about environment (temperature, noise), damages, traffic, and other anomalies to the municipality. See also § 2.2.B for more examples of participatory sensing for environmental data.

It can be noted that, besides the apparent stark opposition of these two approaches (top-down and bottom-up), sensing is the fundamental component oriented to reinforce and galvanize urban management.
However, some concerns can arise from the pervasive sensing for city management, such as “the corporatization of city governance and a technological lock-in” or the creation of a “panoptic city” (Kitchin, 2014). See § 5.2 a focused discussion about limits of sensing, in the field of urban environmental data (air quality and climate).

Figure 2-25
More than two thousands sensors installed at streetlights, facades, and 150 in public vehicles are networked in order to map Santander urban environment (“SmartSantander Maps,” n.d.).

2.3.B - PROVIDING FINE-GRAINED DATA, IMPROVING SCALE AND RESOLUTION

As mentioned several times, mapping urban phenomena requires a proper scale often only reachable with sensing. In the case of urban climate and air pollution, a diffused sensing network, or a mobile sensing, has the potential of helping the construction of fine-grained urban climate and air pollution maps.

- *Sensing for improving scale*
- *Sensing for improving resolution*
- *Sensing for engaging participation*

Sensing for improving scale

The issue of scale is one of the reasons of the unsuccessful integration of air studies known for city planning (Mills, 2006; Oke, 1984), and has brought models to use regional scale data for local studies (Bueno et al., 2013). In the field of air pollution it is even clearer how the minimum scale usually considered for air quality mapping is not compatible with individuals' exposure. In addition, models and inventories used at a smaller scale than the regional are limited, and provide estimations that can significantly differ (Timmermans et al., 2013). Likewise for climate change studies, the quantification of GHG emissions at an urban scale is a global effort, and new measurements tools such as mobile field spectometers, are seen as the solution for collecting real-time data with high precision and spatial-temporal resolution (Bellucci, Bogner, and Sturchio, 2012).
The current people's exposure estimation made by environmental and health agencies is generally based on air pollution maps with restricted spatial resolution, because they are generated from air sensor networks at a high scale, mostly regional. At the same time, people's location is generally considered with simplified estimates of population distributions (static residential population densities). Excluding single case studies, some mentioned in § 2.2, there is no systematic study on the impact of air pollution at the local scale (see § 1.1). However, a European study about health impact caused by air pollution explored the intra-urban air differences within cities, concluding that exposure for urban populations may be of the order of 20% greater than estimated by a simple urban average, because of scale averaging which gives misleading results (Barrett et al., 2008, p. 43).
Additionally, at a local scale, it is possible to assess the different exposure generated by people's mobility within the urban space, such as passing by highly polluted road corridors or by commuting from rural areas (generally accounted in the estimation made) to more polluted central areas.
Sensing (opportunistic sensing) is helpful also for this purpose, since aggregated local scale data of individuals' presence within the urban environment can be derived from mobility pattern from mobile phone data analysis (Calabrese et al., 2011; Manfredini, Pucci, and Tagliolato, 2012).

Thanks to recent availability of technology, and the diffusion of the pervasive sensing, a new paradigm in urban air quality studies can be leveraged; a number of sensors within the urban environment can unveil the spatial pattern of air pollutant and heat concentration, and improve scientific knowledge for urban planning and design (both spatial planning and environmental planning), ultimately posing urban planning as the reference platform for urban exposure studies, turbulence and mechanic studies, climatology, and environmental science.

SCALES OF SENSING	national/ regional	regional/ urban	local/micro (with high resolution)
(type)	remote	proximal	immersive
“by humans”	/	traditional survey	crowd-sourced sensing, mobile sensing
“no humans”	remote sensing	UAVs, Lidar, etc. governmental monitoring stations	sensing networks

Table 2-2
Scales of sensing. Adapted from cited source (Borga, 2014, p. 80)

Sensing for improving resolution

Besides scale, the spatial resolution and representativeness are fundamental aspects to be considered in improving mapping for air quality and urban climate studies.

In fact, urban context is characterized by large variations within continuous physical phenomena over small temporal and spatial scales, making point measurements less likely to be representative of the system as a whole.

In local scale studies, this high spatial variability of measured parameters and the rapid change of urban form can cause considerable bias. Therefore, an evolving argument for environmental regulations based on comprehensive sensing data rather than mathematical modeling is likely to grow (Resch, Mittleboeck, et al., 2011).

Traditional sensing, done with scarce stationary monitoring, had to deal with the concern of optimal location and representativeness. Both for weather and for pollution, air is sensed in selected locations and, since the measurement relates to a small portion of volume of air, the representativeness of the data is results from "joint appraisal of instrumentation, measurement interval and exposure against the requirements of some particular application" (World Meteorological Organization, 2008, pp. I–1–1). The low number of monitoring stations is attributable to the generally high cost of sensor networks and stations, and the logistic complexity of deploying the stations (Sullivan and Collins, 2009).

However, while a better spatial resolution is recommended in climate studies, such as UHI magnitude quantification (Stewart, 2011) and air pollution and exposure research (Stroh, Harrie, and Gustafsson, 2007), current mapping has both scale and resolution issues, due to the imitated number of data.

Representativeness can be therefore only be improved by increasing and averaging the number of measurements within the urban environment.

"In the next century, planet earth will don an electronic skin. It will use the Internet as a scaffold to support and transmit its sensations. This skin is already being stitched together. It consists of millions of embedded electronic measuring devices: thermostats, pressure gauges, pollution detectors, cameras, microphones, glucose sensors, EKGs, electroencephalographs. These will probe and monitor cities and endangered species, the atmosphere, our ships, highways and fleets of trucks, our conversations, our bodies--even our dreams".

(Gross, 1999)

Following the vision by Neil Gross (1999), and considering that pervasive sensing has recently become feasible and affordable, the knowledge about our environment can be enriched thanks to the availability diffused fine-grained and real-time information layers. In fact, with the development of new technologies, a wide range of new instruments and platforms, such as unmanned aerial vehicles (UAVs), smartphones, low-cost portable devices, and wearables have become available; they offer unprecedented opportunities to improve resolution of mapping urban climate and air pollution studies.

This is mainly due to great performance enhancement combined with drastic price reduction (Paulsen and Riegger, 2006).

§ 2.1.B mentioned the most noteworthy examples of mapping urban climate and air pollution at a fine-grained resolution, such as temperature mapping by internal phone battery temperature data streamed online and processed (Overeem and Robinson, 2013). Other examples showed how high spatial resolution is reached by mobile sensing: thanks to the use of mobile sensors, or stationary sensors installed in mobile vehicles, it is possible to cover larger areas with fine grained data, according to the logging settings. In addition, fine resolution sensing at a local level, such as a mobile sensing, can help identify urban heat/pollutant hotspots within the urban environment.
Issues about data accuracy are relevant, because of the low-cost technology involved, potential lack of calibration, and the varied measurement conditions that may occur.
However, “big data” can change urbanism (Offenhuber and Ratti, 2014), and decoding the city is a matter of big data usage. To this regard, the characteristics of data potentially coming from sensing devices and networks, are assailable to big data, and can be therefore used to “decode” urban climate and air quality.
In fact, in the case of the air sensing needed for urban climate and air quality, with a large diffused availability of climate-related and air pollutants measurements, with an appropriate temporal scale and fixed or random geolocation, the features of big data are recognizable. As recalled by Kitchin (2014), they are:

- “huge in volume, consisting of terabytes or petabytes of data;
- high in velocity, being created in or near real-time;
- diverse in variety, being structured and unstructured in nature, and often temporally and spatially referenced;
- exhaustive in scope, striving to capture entire populations or systems (n = all), or at least much larger sample sizes than would be employed in traditional, small data studies;
- fine-grained in resolution, aiming to be as detailed as possible, and uniquely indexical in identification;
- relational in nature, containing common fields that enable the conjoining of different data sets;
- flexible, holding the traits of extensionality (can add new fields easily) and scaleability (can expand in size rapidly)”

From this big data perspective, the limits of low-cost sensor measurements, such as data overload and great error in accuracy, can be therefore potentially reduced with big data analysis, with help of statistics and machine learning processes that detect patterns in data and adjust results accordingly.

Sensing for engaging participation

In the field of urban climate and climate, sensing can offer opportunities in increasing public participation in urban planning, and in increasing awareness in environmental matters.

§ 2.3.A anticipated crowd-sourced sensing, a form of participatory sensing where individuals share monitoring, air monitoring in this case, with the urban community.

Within the field of "Open source", "open data", "web 2.0", participatory sensing is a form of Volunteered Geographic Information (VGI), as effectively described by Goodchild:

"It is useful to distinguish three types of sensor networks. Most examples fit the first, a network of static, inert sensors designed to capture specific measurements of their local environments. Less commonly cited are sensors carried by humans, vehicles, or animals. For example, much useful research is emerging from projects that have equipped children with sensors of air pollution, in an effort to understand the factors affecting asthma. A third type of sensor network, and in many ways the most interesting, consists of humans themselves, each equipped with some working subset of the five senses and with the intelligence to compile and interpret what they sense, and each free to rove the surface of the planet.

This network of human sensors has over 6 billion components, each an intelligent synthesizer and interpreter of local information. One can see VGI as an effective use of this network, enabled by Web 2.0 and the technology of broadband communication."

(Goodchild, 2007)

A new view of people-centric urban sensing is emerging, where people are no longer just consumers of sensed data, rather they participate in the new role of producers of data about people sensed and collected (Campbell, Eisenman, Lane, Miluzzo, and Peterson, 2006).

In the field of air sensors, in some cases, sensing is personal, for instance coming from wearables, and the main purpose is to estimate the personal exposure. The interest on personal health and potential damage coming from air pollution is growing dramatically, and is the case of most of the home air quality measurements and mobile personal devices increasingly put on the market, such as AirEggs and AirBeams described in § 2.2.B. For an overview of all noteworthy devices for personal sensing, see § 4.2.A.

In other cases, sensing is specifically designed for collaborative sensing. A sensor network is generally designed in order to share the data collected. This is the case of some non-profit sensing projects such as Aircasting, described in § 2.2.B.

Sensing enhances participation, and participation increases scale and resolution, which ultimately improves sensing itself. The loop is fostered by "Citizen science", and the potential benefits for urban climate and air quality mapping is noticeable.

Figure 2-26 Examples of four participatory sensing projects mentioned in § 2.2.B.
Pictured at top, from left to right: AirCasting platform, aimed at collecting air quality data from citizens measurements in order to create collective maps ("AirCasting," n.d.); Safecast project, one of the most successful example of participatory sensing and citizens science. People voluntary collected data about post-Fukushima earthquake radiation from the nuclear site, using a mobile sensor, in order to increase knowledge and awareness ("Safecast," n.d.) . The third example is one of the several kickstarter campaigns launched in 2014 all addressed at developing sensors devices for mapping the spatial distribution impact, and limiting personal exposure ("Kickstarter TZOA Air-Tracker," n.d.). Business interest is very high, following the recent increase in citizens' interest in pursuing healthy lifestyles, which requires knowledge about outdoor activities and pollution (where to go running, which streets are better to avoid while cycling, etc.). Besides personal sensing, and wearable sensing devices, all of these projects address the social media sharing factor, and the willingness to contribute to participatory sensing, a collective mapping of urban environmental local problems, such as hotpots, for the community.
Pictured at bottom: logo of Everyaware project, a play on words between "everyware" concept (Greenfield, 2006) and citizens' awareness (Everyaware Project, 2014).

Conclusion

This chapter reviewed literature examples in theoretical studies and practical examples of mapping urban climate and air quality. Annex 1 included an overview of the most relevant sensing networks for urban climate and air quality. The paradigm shift from modeling to sensing was presented, and the need for profit from sensing was underlined. In fact, sensing seems to have beneficial characteristics, such as being real-time, improving scale and resolution, being affordable (thanks to the availability of low-cost sensors) and enhance citizens' participation.

However, there are unresolved research challenges in using sensing:

- impact on urban planning and definition of the proper scale and resolution
- accuracy, cost efficiency and real-time fidelity, data accessibility and privacy.

This research aims to explore sensing for urban climate and air quality, and aims to give a contribution in this context, as described in the next chapter.

References

Air Quality Egg. (n.d.). Retrieved December 29, 2014, from http://airqualityegg.com/

Air Sensors 2014. (n.d.). Retrieved December 29, 2014, from https://sites.google.com/site/airsensors2014/home

Air-quality | EveryAware. (n.d.). Retrieved December 29, 2014, from http://www.everyaware.eu/activities/case-studies/air-quality/

AirBeam: Share & Improve Your Air by HabitatMap. (n.d.). Retrieved December 29, 2014, from https://www.kickstarter.com/projects/741031201/airbeam-share-and-improve-your-air

AirCasting. (n.d.). Retrieved December 29, 2014, from http://aircasting.org/

Akbari, H., & Rose, L. S. (2001). Characterizing the fabric of the urban environment: A case study of Salt Lake City, Utah. *Lawrence Berkeley National Laboratory*. Retrieved from http://escholarship.org/uc/item/0wk718sm

ANSYS Fluent. (n.d.). Retrieved December 29, 2014, from http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Fluent

Arling, J., O'Connor, K., & Mercieca, M. (2010). *Air Quality Sensor Network for Philadelphia*. Philadelphia. Retrieved from http://wireless.ece.drexel.edu/air_quality/

Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, *23*(1), 1–26. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0037267157&partnerID=40&md5=c8b373dd14c04f053a08bdb60f7273ce

Arya, S. P. (1999). Air pollution meteorology and dispersion.

Barrett, K., de Leeuw, F., Fiala, J., Larssen, S., Sundvor, I., Fjellsbø, L., … Černikovský, L. (2008). Health impacts and air pollution–an exploration of factors influencing estimates of air pollution impact upon the health of European citizens. *ETC/ACC Tech Pap*, *13*.

Basara, J. B., Illston, B. G., Fiebrich, C. A., Browder, P. D., Morgan, C. R., McCombs, A., … Crawford, K. C. (2011). The Oklahoma city micronet. *Meteorological Applications*, *18*(3), 252–261. doi:10.1002/met.189

Batty, M. (1976). *Urban modelling*. (L. Martin & L. March, Eds.) (p. 381). Cambridge, UK: Cambridge University Press. Retrieved from http://www.casa.ucl.ac.uk/urbanmodelling/

Batty, Mi. (1997). The Computable City. *International Planning Studies*, *2*(2), 155–173. doi:10.1080/13563479708721676

BeACON - The BErkeley Atmospheric CO2 Observation Network. (n.d.). Retrieved December 29, 2014, from http://beacon.berkeley.edu/

Bellucci, F., Bogner, J. E., & Sturchio, N. C. (2012). Greenhouse gas emissions at the urban scale. *Elements*, *8*(6), 445–449.

Borga, G. (2014). City Sensing. *Milano IT: Franco Angeli*.

Brandsma, T., & Wolters, D. (2012). Measurement and statistical modeling of the urban heat island of the city of Utrecht (the Netherlands). *Journal of Applied Meteorology and Climatology*, *51*(6), 1046–1060. doi:10.1175/JAMC-D-11-0206.1

Briggs, D. J. D., Collins, S., Elliott, P., Fischer, P., Kingham, S., Lebret, E., … Van Der Veen, A. (1997). Mapping urban air pollution using GIS: a regression-based approach. *International Journal of Geographical Information Science*, *11*(7), 699–718. doi:10.1080/136588197242158

Britter, R., & Hanna, S. (2003). Flow Dispersion in Urban Areas. *Annual Review of Fluid Mechanics*. doi:10.1146/annurev.fluid.35.101101.161147

Bruse, M. (2004). ENVI-met website. *Online: Http://www.envimet.com*.

Bueno, B., Hidalgo, J., Pigeon, G., Norford, L., & Masson, V. (2013). Calculation of Air Temperatures above the Urban Canopy Layer from Measurements at a Rural Operational Weather Station. *Journal of Applied Meteorology and Climatology*, *52*(2), 472–483. doi:10.1175/JAMC-D-12-083.1

Bueno, B., Norford, L., Pigeon, G., & Britter, R. (2011). Combining a Detailed Building Energy Model with a Physically-Based Urban Canopy Model. *Boundary-Layer Meteorology*, *140*, 471–489. doi:10.1007/s10546-011-9620-6

Bueno, B., Norford, L., Pigeon, G., & Britter, R. (2012). A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate. *Building and Environment*, *54*, 116–125. doi:10.1016/j.buildenv.2012.01.023

Busato, F., Lazzarin, R., & Noro, M. (2014). Three years of study of the Urban Heat Island in Padua: Experimental results. *Sustainable Cities and Society*, *10*, 251–258. doi:10.1016/j.scs.2013.05.001

Buttstädt, M., Sachsen, T., Ketzler, G., Merbitz, H., & Schneider, C. (2011). A new approach for highly resolved air temperature measurements in urban areas. *Atmospheric Measurement Techniques Discussions*, *4*(1), 1001–1019. doi:10.5194/amtd-4-1001-2011

Calabrese, F., Colonna, M., Lovisolo, P., Parata, D., & Ratti, C. (2011). Real-time urban monitoring using cell phones: A case study in Rome. *Intelligent Transportation Systems, IEEE Transactions on*, *12*(1), 141–151.

Calabrese, F., Kloeckl, K., & Ratti, C. (2008). Wikicity: Real-time location-sensitive tools for the city. *Handbook of Research on Urban Informatics: The Practice and Promise of the Real-Time City*, 390–413.

Calabrese, F., & Ratti, C. (2006). Real time rome. *Networks and Communication Studies*, *20*(3-4), 247–258.

CamMobSens. (n.d.). Retrieved December 29, 2014, from http://www.escience.cam.ac.uk/mobiledata/

Campbell, A. T., Eisenman, S. B., Lane, N. D., Miluzzo, E., & Peterson, R. A. (2006). People-centric urban sensing. In *Proceedings of the 2nd annual international workshop on Wireless internet* (p. 18). ACM.

Carneiro, C., Morello, E., Ratti, C., & Golay, F. (2009). Solar Radiation over the Urban Texture: LIDAR Data and Image Processing Techniques for Environmental Analysis at City Scale. In J. Lee & S. Zlatanova (Eds.), *3D Geo-Information Sciences* (Vol. 2009, pp. 319–435). Springer.

CENS: Center for Embedded Networked Sensing. (n.d.). Retrieved December 29, 2014, from https://research.cens.ucla.edu/

Centro de Operações Prefeitura do Rio de Janeiro | Acompanhe em tempo real tudo o que está acontecendo na cidade do Rio. (n.d.). Retrieved December 30, 2014, from http://www.centrodeoperacoes.rio.gov.br/

Chen, F., Bornstein, R., Grimmond, C. S. B., Li, J., Liang, X., Martilli, A., … Wang, Y. (2012). Research priorities in observing and modeling urban weather and climate. *Bulletin of the American Meteorological Society*, *93*(11), 1725–1728. doi:10.1175/BAMS-D-11-00217.1

Chen, L., & Ng, E. (2009). Sky View Factor Analysis of Street Canyons And Its Implication For Urban Heat Island Intensity. *plea2009.arc.ulaval.ca*, *2*, 22–24. Retrieved from http://www.plea2009.arc.ulaval.ca/Papers/1.CHALLENGE/1.2 City/ORAL/1-2-07-PLEA2009Quebec.pdf

Chen, L., & Ng, E. (2011). Quantitative urban climate mapping based on a geographical database: A simulation approach using Hong Kong as a case study. *International Journal of Applied Earth Observation and Geoinformation*, *13*(4), 586–594. doi:http://dx.doi.org/10.1016/j.jag.2011.03.003

Ching, J., Burian, S., Chen, F., Cionco, R., Hultgren, T., McPherson, T., … Hanna, A. (2009). National Urban Database and Access Portal Tool, NUDAPT. *Bulletin of the American Meteorological Society*, *90*(8), 1157–1168. Retrieved from http://opensky.library.ucar.edu/collections/OSGC-000-000-000-427

CITI-SENSE. (n.d.). Retrieved December 29, 2014, from http://www.citi-sense.eu/

Clairity. (2014). *An Air Quality Sensor Network for MIT ' s Campus* (p. 74). Retrieved from http://clairity.mit.edu/site/documents/report.pdf

CLAIRITY: MIT's Air Quality Network. (n.d.). Retrieved December 29, 2014, from http://clairity.mit.edu/site/html/

Clougherty, J. E., Kheirbek, I., Eisl, H. M., Ross, Z., Pezeshki, G., Gorczynski, J. E., … Matte, T. (2013). Intra-urban spatial variability in wintertime street-level concentrations of multiple combustion-related air pollutants: the New York City Community Air Survey (NYCCAS). *Journal Of Exposure Science & Environmental Epidemiology*, *23*(3), 232–240. doi:10.1038/jes.2012.125

Common Sense — Mobile sensing for community action. (n.d.). Retrieved December 29, 2014, from http://www.communitysensing.org/

Copenhagen wheel project. (n.d.). Retrieved December 29, 2014, from http://senseable.mit.edu/copenhagenwheel/

Crouse, D., Goldberg, M. S., & Ross, N. A. (2009). A prediction-based approach to modelling temporal and spatial variability of traffic-related air pollution in Montreal, Canada. *Atmospheric Environment*, *43*(32), 5075–5084.

CUHK. (2009). *Urban Climatic Map and Standards for Wind Environment - Feasibility Study FINAL REPORT* (p. 518). Hong Kong.

CycleApp | Air Quality of Cycling Routes in Montreal. (n.d.). Retrieved December 30, 2014, from http://traq-research.mcgill.ca/cycleapp/montreal/

Di Sabatino, S., Leo, L. S., Cataldo, R., Ratti, C., & Britter, R. (2010). Construction of digital elevation models for a southern European city and a comparative morphological analysis with respect to Northern European and North American cities. *Journal of Applied Meteorology and Climatology*, *49*(7), 1377–1396. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77957727742&partnerID=40&md5=ed542b6e542f0ed060350be7138351dc

Diappi, L. (2004). *Evolving Cities: Geocomputation In Territorial Planning*. Burlington: Ashgate.

Dodge, M., Doyle, S., Hudson-Smith, A., & Fleetwood, S. (1998). Towards the virtual city: VR & internet GIS for urban planning.

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*(1), 31–44. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204600000347

Evans, S. (2009). *3D cities and numerical weather prediction models: An overview of the methods used in the LUCID project* (No. 148) (Vol. 44, pp. 0–18). London, UK: Centre for Advanced Spatial Analysis.

Everyaware Project. (2014). *Everyaware Project - Final Report Period* (p. 56). Turin, IT. Retrieved from http://www.everyaware.eu/resources/deliverables/D7.3.pdf

Fernando, H. J. S., Zajic, D., Di Sabatino, S., Dimitrova, R., Hedquist, B., & Dallman, A. (2010). Flow, turbulence, and pollutant dispersion in urban atmospheres. *Physics of Fluids*, *22*(5), 51301. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=51059623&site=eds-live

Gal, T., & Sumeghi, Z. (2007). Mapping the roughness parameters in a large urban area for urban climate applications. *Acta Climatologica ET Chorologica*, *40-41*, 27–36. Retrieved from http://www2.sci.u-szeged.hu/eghajlattan/akta07/027-036.pdf

Givoni, B. (1998). *Climate considerations in building and urban design*. *Building* (pp. 241–300). Retrieved from http://books.google.com/books?id=MGkArZ_berAC&pgis=1

Goldsmith, S., & Crawford, S. (2014). *The Responsive City: Engaging Communities Through Data-Smart Governance*. John Wiley & Sons.

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal*, *69*(4), 211–221.

Greenfield, A. (2006). *Everyware: The dawning age of ubiquitous computing*. New Riders.

Grimmond, C., & Oke, T. (2002). Turbulent Heat Fluxes in Urban Areas : Observations and a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS). *Journal of Applied Meteorology*, *41*(7), 792–810.

Grimmond, C. S. B., Blackett, M., Best, M. J., Baik, J. J., Belcher, S. E., Beringer, J., … Coutts, A. (2011). Initial results from Phase 2 of the international urban energy balance model comparison. *International Journal of Climatology*, *31*(2), 244–272.

Grimmond, C. S. B., Blackett, M., Best, M. J., Barlow, J., Baik, J. J., Belcher, S. E., … Zhang, N. (2010). The international urban energy balance models comparison project: First results from phase 1. *Journal of Applied Meteorology and Climatology*, *49*(6), 1268–1292. Retrieved from http://journals.ametsoc.org/doi/abs/10.1175/2010JAMC2354.1

Gross, N. (1999). The earth will don an electronic skin. *Business Week, August*, *30*.

Harman, I. N. (2003). *The energy balance of urban areas*. *The energy balance of urban areas*. The University of Reading.

Hasenfratz, D., Saukh, O., Walser, C., Hueglin, C., Fierz, M., & Thiele, L. (2014). Pushing the spatio-temporal resolution limit of urban air pollution maps. In *Pervasive Computing and Communications (PerCom), 2014 IEEE International Conference on* (pp. 69–77). IEEE.

Hatzopoulou, M., Weichenthal, S., Barreau, G., Goldberg, M., Farrell, W., Crouse, D., & Ross, N. (2013). A web-based route planning tool to reduce cyclists' exposures to traffic pollution: A case study in Montreal, Canada. *Environmental Research*, *123*, 58–61.

Hernández-Muñoz, J., & Vercher, J. (2011). Smart cities at the forefront of the future internet. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-20898-0_32

Heusinkveld, B. G., Steeneveld, G. J., van Hove, L. W. a., Jacobs, C. M. J., Holtslag, a. a. M., & Hove, L. W. A. (2014). Spatial variability of the Rotterdam urban heat island as influenced by urban land use. *Journal of Geophysical Research: Atmospheres*, *119*(2), 677–692. doi:10.1002/2012JD019399

Heusinkveld, B. G., Van Hove, L. W. A., Jacobs, C. M. J., Steeneveld, G. J., Elbers, J. A., Moors, E. J., & Holtslag, A. A. M. (2010). Use of a mobile platform for assessing urban heat stress in Rotterdam. In *Proceedings of the 7th Conference on Biometeorology, Freiburg, Germany* (pp. 433–438).

Hofman, J., Lefebvre, W., & Janssen, S. (2014). Increasing the spatial resolution of air quality assessments in urban areas: A comparison of biomagnetic monitoring and urban scale modelling. *Atmospheric …*, *92*, 130–140. Retrieved from http://www.sciencedirect.com/science/article/pii/S1352231014002854

House-Peters, L. A., & Chang, H. (2011). Modeling the impact of land use and climate change on neighborhood-scale evaporation and nighttime cooling: A surface energy balance approach. *Landscape and Urban Planning*, *103*, 139–155. doi:10.1016/j.landurbplan.2011.07.005

Hudson-Smith, A., Milton, R., Dearden, J., & Batty, M. (2007). *Virtual cities: digital mirrors into a recursive world*. Centre for Advanced Spatial Analysis (UCL).

Ito, M., Katagiri, Y., Ishikawa, M., & Tokuda, H. (2007). Airy notes: An experiment of microclimate monitoring in shinjuku gyoen garden. In *Networked Sensing Systems, 2007. INSS'07. Fourth International Conference on* (pp. 260–266). IEEE.

Jacobs, J. (1961). *The Death and Life of Great American Cities-Vintage* (p. 459). New York: Vintage Books, Random House.

Jang, M., & Suh, S.-T. (2010). U-city: new trends of urban planning in Korea based on pervasive and ubiquitous geotechnology and geoinformation. In *Computational Science and Its Applications–ICCSA 2010* (pp. 262–270). Springer.

Järvi, L., Grimmond, C. S. B., & Christen, A. (2011). The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver. *Journal of Hydrology*, *411*(3–4), 219–237. doi:http://dx.doi.org/10.1016/j.jhydrol.2011.10.001

Jerrett, M., Arain, A., Kanaroglou, P., Beckerman, B., Potoglou, D., Sahsuvaroglu, T., … Giovis, C. (2004). A review and evaluation of intraurban air pollution exposure models. *Journal of Exposure Science and Environmental Epidemiology*, *15*(2), 185–204.

Katzschner, L., & Thorsson, S. (2009). Microclimatic Investigations as Tool for Urban Design. In *INTERNATIONAL CONFERENCE ON URBAN CLIMATE* (Vol. 7).

Kickstarter TZOA Air-Tracker. (n.d.). Retrieved December 30, 2014, from https://www.kickstarter.com/projects/tzoa/meet-tzoa-the-worlds-first-enviro-tracker

Kitchin, R. (2014). The Real-Time City? Big Data and Smart Urbanism. *GeoJournal*, *79*(1), 1–14. Retrieved from http://link.springer.com/article/10.1007/s10708-013-9516-8

Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., & Britter, R. (2011). Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment—a review. *Journal of Aerosol Science*, *42*(9), 580–603. Retrieved from http://www.sciencedirect.com/science/article/pii/S0021850211000887

Lee, H., Han, H., Leem, T., Yigitcanlar, T., Ho Lee, S., Hoon Han, J., & Taik Leem, Y. (2008). Towards ubiquitous city: concept, planning, and experiences in the Republic of Korea. *Knowledge-Based Urban Development: Planning and Applications in the Information Era*, 148–170.

Lee, T. W., Lee, J. Y., & Wang, Z.-H. (2012). Scaling of the urban heat island intensity using time-dependent energy balance. *Urban Climate*, *2*, 16–24.

Lindberg, F. (2007). Modelling the urban climate using a local governmental geo-database. *Meteorological Applications*, *14*(3), 263–273.

Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*, *52*(7), 697–713.

Manfredini, F., Pucci, P., & Tagliolato, P. (2012). Mobile phone network data. new sources for urban studies. *Geographic Information Analysis for Sustainable Development and Economic Planning: New Technologies.Hershey PA, USA: IGI Global*, 115–128.

Mariani, L., & Pangallo, G. S. (2005). Approccio qualitativo all'analisi degli effetti urbani sul clima. *Rivista Italiana Di Agrometerologia*, *2*, 31–36.

Martino, M., Britter, R., Outram, C., Zacharias, C., Biderman, A., & Ratti, C. (2010). Senseable City. *Digital Urban Modelling and Simulation*.

Masson, V., Grimmond, C. S. B., & Oke, T. R. (2002). Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *Journal of Applied Meteorology*, *41*(10), 1011–1026.

Matte, T., Ross, Z., & Kheirbek, I. (2013). Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: Design and implementation. *Journal of Exposure …*, (October 2012), 223–231. doi:10.1038/jes.2O12.126

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International Journal of Biometeorology*, *51*(4), 323–334.

Mead, M. I., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., … Hodgson, T. F. (2013). The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, *70*(5), 186–203.

Melhuish, E., & Pedder, M. (1998). Observing an urban heat island by bicycle. *Weather*, *53*(4), 121–128.

Mensink, C., De Ridder, K., Deutsch, F., Lefebre, F., & Van de Vel, K. (2008a). Examples of scale interactions in local, urban, and regional air quality modelling. *Atmospheric Research*, *89*(4), 351–357. doi:10.1016/j.atmosres.2008.03.020

Mensink, C., De Ridder, K., Deutsch, F., Lefebre, F., & Van de Vel, K. (2008b). Examples of scale interactions in local, urban, and regional air quality modelling. *Atmospheric Research*, *89*(4), 351–357.

Mills, G. (2006). Progress toward sustainable settlements: A role for urban climatology. *Theoretical and Applied Climatology*, *84*, 69–76. doi:10.1007/s00704-005-0145-0

Mitchell, R. B., & Rapkin, C. (1954). *Urban Traffic--A Function of Land Use*. Columbia University Press.

Morello, E., & Ratti, C. (2009a). A digital image of the city: 3D isovists in Lynch's urban analysis. *Environment and Planning B: Planning and Design*, *36*(5), 837–853. doi:10.1068/b34144t

Morello, E., & Ratti, C. (2009b). Sunscapes: "Solar envelopes" and the analysis of urban DEMs. *Computers, Environment and Urban Systems*, *33*(1), 26–34. doi:10.1016/j.compenvurbsys.2008.09.005

Muller, C., & Chapman, L. (2013). Sensors and the city: a review of urban meteorological networks. *International Journal …*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/joc.3678/full

Mun, M., Reddy, S., Shilton, K., Yau, N., Burke, J., Estrin, D., … Boda, P. (2009). PEIR, the personal environmental impact report, as a platform for participatory sensing systems research. In *Proceedings of the 7th international conference on Mobile systems, applications, and services* (pp. 55–68). ACM.

Murty, R. N., Mainland, G., Rose, I., Chowdhury, A. R., Gosain, A., Bers, J., & Welsh, M. (2008). Citysense: An urban-scale wireless sensor network and testbed. In *Technologies for Homeland Security, 2008 IEEE Conference on* (pp. 583–588). IEEE.

Nadeau, D. F., Brutsaert, W., Parlange, M. B., Bou-Zeid, E., Barrenetxea, G., Couach, O., … Vetterli, M. (2009). Estimation of urban sensible heat flux using a dense wireless network of observations. *Environmental Fluid Mechanics*, *9*(6), 635–653.

Nunez, M., & Oke, T. R. (1977). Energy Balance of an Urban Canyon.

NYC Community Air Survey. (n.d.). Retrieved December 29, 2014, from http://www.nyc.gov/html/doh/html/environmental/community-air-survey.shtml

Offenhuber, D., & Ratti, C. (2014). *Decoding the City. Urbanism in the Age of Big Data*. (D. Offenhuber & C. Ratti, Eds.). Berlin, Boston. doi:10.1515/9783038213925

Oke, T. R. (1984). Towards a prescription for the greater use of climatic principles in settlement planning. *Energy and Buildings*, *7*(1), 1–10.

Oke, T. R. (1987). *Boundary layer climates* (Second., Vol. Routledge, p. 435). London and New York: Routledge. Retrieved from http://books.google.com/books?hl=en&lr=&id=K_2dW7crfVIC&oi=fnd&pg=PP1&dq=Boundary+Layer+Climates&ots=112YqtIAbW&sig=OpORoBqDxjfdojOonDHY-OjpGzk

Oke, T. R. (2004). *Initial guidance to obtain representative meteorological observations at urban sites*. *geog.ubc.ca* (Vol. 81). World Meteorological Organization Geneva. Retrieved from http://www.geog.ubc.ca/~toke/IOM-81-UrbanMetObs.pdf

OpenSense. (n.d.). Retrieved December 29, 2014, from http://www.opensense.ethz.ch/trac/

OpenSense Live Data Browser. (n.d.). Retrieved December 29, 2014, from http://data.opensense.ethz.ch/position.html

Overeem, A., & Robinson, J. R. (2013). Crowdsourcing urban air temperatures from smartphone battery temperatures. *Geophysical …*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/grl.50786/full

Participatory Sensing Application. (n.d.). Retrieved December 30, 2014, from http://www.smartsantander.eu/index.php/blog/item/181-participatory-sensing-application

Paulsen, H., & Riegger, U. (2006). SensorGIS-Geodaten in Echtzeit. *GIS-Business*, *8*(2006), 17–19.

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings*, *37*(7), 762–776. doi:10.1016/j.enbuild.2004.10.010

Ratti, C., & Claudel, M. (2015). *The Future of the City*. (J. Calamia & K. Boller, Eds.) (p. 237). Yale University Press.

Ratti, C., Di Sabatino, S., & Britter, R. (2006). Urban texture analysis with image processing techniques: Winds and dispersion. *Theoretical and Applied Climatology*, *84*(1-3), 77–90. doi:10.1007/s00704-005-0146-z

Ratti, C., & Richens, P. (2004). Raster analysis of urban form. *Environment and Planning B: Planning and Design*, *31*(2), 297–309. doi:10.1068/b2665

Ratti, C., Robinson, D., Baker, N., & Steemers, K. (2000). LT Urban: the energy modelling of urban form. In *Proceedings of PLEA*.

Real Time Rome. (n.d.). Retrieved December 30, 2014, from http://senseable.mit.edu/realtimerome/

Ren, C., Ng, E. Y., & Katzschner, L. (2011). Urban climatic map studies: a review. *International Journal of Climatology*, *31*(15), 2213–2233. doi:10.1002/joc.2237

Resch, B., Britter, R., & Outram, C. (2011). Standardised geo-sensor webs for integrated urban air quality monitoring. *Environmental Monitoring*, 513–528. Retrieved from http://senseable.mit.edu/papers/pdf/2011_Resch_UAQM_EM.pdf

Resch, B., Mittleboeck, M., Lipson, S., Welsh, M., Bers, J., Britter, R., … Blaschke, T. (2011). Integrated urban sensing: a geo-sensor network for public health monitoring and beyond.

Robinson, D., Haldi, F., Kämpf, J., Leroux, P., Perez, D., Rasheed, A., & Wilke, U. (2009). CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning. In *Proc. Building Simulation*.

Robinson, J., Kocman, D., Smolnikar, M., Mohorcic, M., & Horvat, M. (2014). Empowerment in practice-insights from CITI-SENSE project in Ljubljana. In *EGU General Assembly Conference Abstracts* (Vol. 16, p. 5458).

Ross, S. L., & Oke, T. R. (1988). Tests of three urban energy balance models. *Boundary-Layer Meteorology*, *44*(1-2), 73–96. doi:10.1007/BF00117293

Ruvolo, J. (2013). Bridging The Divided City. *Cityscapes*, *3*, 58–68. Retrieved from http://www.cityscapesdigital.net/2013/05/30/bridging-the-divided-city/

Safecast. (n.d.). Retrieved December 30, 2014, from http://blog.safecast.org/

Sanchez, L., Galache, J. A., Gutiérrez, V., Hernández, J. M., Bernat, J., Gluhak, A., & García, T. (2011). SmartSantander: The meeting point between Future Internet research and experimentation and the smart cities. In *Future Network & Mobile Summit (FutureNetw), 2011* (pp. 1–8). IEEE.

Sandifer, J., & Mountain, K. (2014). Remote Sensing and Identifying the Urban Heat Island from Space: An Overview. *Heat Islands*, 9.

Sassen, S. (2014). Saskia Sassen talk at MIT Senseable "City Engaging Data 2013" conference.

Sensaris - Wireless sensors. (n.d.). Retrieved December 29, 2014, from http://www.sensaris.com/

Sensing City. (n.d.). Retrieved December 29, 2014, from http://www.sensingcity.org/

Sensor City. (n.d.). Retrieved December 29, 2014, from http://www.sensorcity.nl/

Sensorcon | American Made Single Gas Meters and Environmental Sensors. (n.d.). Retrieved December 29, 2014, from http://sensorcon.com/

Seto, K. C., & Christensen, P. (2013). Remote sensing science to inform urban climate change mitigation strategies. *Urban Climate*, *3*, 1–6.

Shepard, M. (2011). *Sentient city: Ubiquitous computing, architecture, and the future of urban space*. The MIT press.

Simon, H. A., & Chase, W. G. (1973). Skill in chess: Experiments with chess-playing tasks and computer simulation of skilled performance throw light on some human perceptual and memory processes, *61*(4), 394–403. Retrieved from http://link.springer.com/chapter/10.1007/978-1-4757-1968-0_18

SmartSantander Maps. (n.d.). Retrieved December 29, 2014, from http://maps.smartsantander.eu/

Solene - Software for simulating of sunshine, lighting and thermal radiation | Cerma. (n.d.). Retrieved December 29, 2014, from http://www.cerma.archi.fr/?q=en/solene-software-simulating-sunshine-lighting-and-thermal-radiation-0

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, *31*(2), 200–217.

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. doi:10.1175/BAMS-D-11-00019.1

Steyn, D., & Mathur, R. (2014). *Air Pollution Modeling and its Application XXIII*. (R. Mathur, Ed.)*Springer eBooks; Springer Proceedings in Complexity,* (p. 640). Cham: Springer International Publishing : Retrieved from http://ctwfind0.wesleyan.edu/wesleyan/Record/wu.2990211

Street, M., Reinhart, C., Norford, L., & Ochsendorf, J. (2013). Urban heat island in Boston–an evaluation of urban air-temperature models for predicting building energy use. Retrieved from http://www.ibpsa.org/proceedings/BS2013/p_1492.pdf

Stroh, E., Harrie, L., & Gustafsson, S. (2007). A study of spatial resolution in pollution exposure modelling. *International Journal of Health Geographics*, *6*, 19. doi:1476-072X-6-19 [pii]

Sullivan, J., & Collins, J. M. (2009). The use of low-cost data logging temperature sensors in the evaluation of an urban heat island in Tampa, Florida. In *Papers of the Applied Geography Conferences* (Vol. 32, p. 252).

Sun, X., Du, J., & Zhou, J. (2013). Application of participatory sensing in meteorological information service system. *Applied Mechanics and Materials*, *385-386*, 1887–1890. doi:10.4028/www.scientific.net/AMM.385-386.1887.

Svensson, M. K. (2004). Sky view factor analysis – implications for urban air temperature differences. *Meteorological Applications*, *11*, 201–211. doi:10.1017/S1350482704001288

The SOLWEIG-model. (n.d.). Retrieved December 29, 2014, from http://gvc.gu.se/english/research/climate/urban-climate/software/solweig

Thepvilojanapong, N., Ono, T., & Tobe, Y. (2010). A deployment of fine-grained sensor network and empirical analysis of urban temperature. *Sensors*, *10*(3), 2217–2241.

Timmermans, R. M. A., Denier van der Gon, H. A. C., Kuenen, J. J. P., Segers, A. J., Honoré, C., Perrussel, O., … Schaap, M. (2013). Quantification of the urban air pollution increment and its dependency on the use of down-scaled and bottom-up city emission inventories. *Urban Climate*, *6*(0), 44–62. doi:http://dx.doi.org/10.1016/j.uclim.2013.10.004

Toppi, T., Zangheri, P., & Paolini, R. (2009). Simplified method for modification of weather data file for energy simulations within urban areas. *Proc. of the 8th Workshop CIB W108 …*. Retrieved from http://www.irbnet.de/daten/iconda/CIB16454.pdf

Treville, A. (2011a). LCA methodology as a support tool for decision makers in policy and planning for sustainable development. Case study for a Developing Country. *ELCAS2011: Proceedings of the 2nd International Exergy, Life Cycle Assessment and Sustainability Workshop \& Symposium, 19 - 21 June 2011, Nisyros Island, Greece*, 691–698. Retrieved from http://www.elcasnet.com/elcas2011/index.htm

Treville, A. (2011b). Proposal of an impact prediction tool for the environmental assessment of projects and spatial planning, based on LCA. *ELCAS2011: Proceedings of the 2nd International Exergy, Life Cycle Assessment and Sustainability Workshop \& Symposium, 19 - 21 June 2011, Nisyros Island, Greece*, 708–715. Retrieved from http://www.elcasnet.com/elcas2011/index.htm

Treville, A. (2013). Heatwaves and UHI: Modeling the inter-relationships between climate effects and the built environment for designing resilient cities. In F. Musco & E. Zanchini (Eds.), *Proceedings of climate changes cities conference on climate adaptation in urban areas, Venice, 23-24 May 2013* (pp. 111–114). Venice: Corila.

Treville, A., Vandini, L., & Cegna, R. (2014). The Visual Language Technique in Urban Studies Research: Investigation, Interpretation and Communication of City Complexity . In L. Cocchiarella (Ed.), *The Visual Language of Technique*. Springer.

Unger, J. (2009). Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *International Journal of Environment and Pollution*. doi:10.1504/IJEP.2009.021817

Unger, J., Savić, S., & Gál, T. (2011). Modelling of the annual mean urban heat island pattern for planning of representative urban climate station network. *Advances in Meteorology*, *2011*.

United States Environmental Protection Agency. (n.d.). Next Generation Air Measuring. Retrieved December 07, 2014, from http://www.epa.gov/airscience/next-generation-air-measuring.htm

Van den Dobbelsteen, A., Broersma, S., & Stremke, S. (2011). Energy potential mapping for energy-producing neighborhoods. *International Journal of Sustainable Building Technology and Urban Development*, *2*(2), 170–176.

Voogt, J., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment*, *86*(3), 370–384.

Wang, Z.-H., Bou-Zeid, E., & Smith, J. A. (2010). Application of a sensor network to study the energy budget in urban canopies. In *Proceedings of 15th symposium on meteorological observation and instrumentation, Atlanta*.

World Health Organization. (2006). *Air Quality Guidelines. Global Update 2005* (p. 485global). Copenhagen, DK: World Health Organization. Retrieved from http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/

World Meteorological Organization. (2008). *Guide to Meteorological Instruments and Methods of Observation*. Geneva, Switzerland: Genf, Schweiz: Secretariat of the WMO. Retrieved from http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf

Yao, R., Luo, Q., & Li, B. (2011). A simplified mathematical model for urban microclimate simulation. *Building and Environment*, *46*(1), 253–265. doi:10.1016/j.buildenv.2010.07.019

CHAPTER 3

3. MATERIALS AND METHODS | RESEARCH QUESTIONS AND METHODOLOGY

Introduction

What hypothesis and questions are chosen? What is the research plan to address them?

Chapter one introduced the problems of urban planning in the face of worsening urban climate and air quality, and the need to improve knowledge on urban climate and air quality at the local level so that cities can address policies, plans and measures to face current challenges at the proper level. Chapter two introduced mapping as necessary to study the spatial and temporal variation of heat and pollutant concentration within cities, to identify hotspots, to assess vulnerability, and to study morphology and urban structure responsibility on UC+AQ. Describing how mapping relies on modeling and sensing, an interpretation of the shift from modeling to sensing was discussed, and the final hypothesis suggested that sensing has the potential to improve mapping in scale, resolution, real-time responsiveness, and participation.

The next chapter therefore aims to explore the opportunity and limits of sensing in urban climate and air quality mapping, with a two-step research strategy. In order to explore the current status of city sensing, the first step includes studying strengths and challenges in worldwide city sensing cases. In the second step, a specific project is designed, in order to experiment in the field with its limits and explore the opportunity of this innovative approach for urban planning to study urban climate and air quality at the people scale. In fact, considering the limits of a stationary sensing network in reaching a proper resolution for air quality and urban climate mapping, a mobile sensing campaign was needed.
Therefore, a field experiment was designed and executed, by testing and using sensors and exploring sensing opportunities in mapping air quality and urban climate parameters.

3.1. RESEARCH GOALS

The introductory chapters one and two mentioned the reasons why urban climate and air quality (UC+AQ) problems are of interest to planners, and the main arguments arising from the evidence of the need for improving the mapping approach, profiting from sensing opportunities:

- How is urban climate and air quality currently being mapped?
- Since it is necessary to map at the people scale, how to map UC+AQ in cities at a local scale with high resolution?
- Since sensing appears to be an essential component, how can it be used in integrating modeling and improve mapping UC+AQ?
- Can new real-time information from city sensing integrate city modeling, and improve city response and monitoring?

- Given the impact of climate change and heatwaves on UC+AQ, and the need for planning low carbon emission and resilient cities, can spatial and environmental planning improve their planning processes with the help of new data and mapping at the local/neighborhood level?
- Can spatial and environmental planning profit from the city sensing in studying the effect of urban morphology and land use on UC+AQ, and define local mitigation and adaptation measures?
- Can this new paradigm shift, from modeling to sensing, help improve mapping and ultimately UC+AQ in cities?

From the short description of the mapping process for urban climate and air pollution, it is evident how modeling is traditionally the essential component, whereas sensing is a recent approach that is growing thanks to the cost reduction and performance enhancement of sensor technology.
However, there are several unresolved research challenges for city sensing in mapping urban climate and air quality, among which some can be identified as following:

- What is the impact on urban planning (spatial and environmental) and design, how can they benefit from city sensing?
- How can it improve scale and resolution, which seems to be fundamental for exposure studies at the people's level? What are its accuracy, location precision, cost efficiency and real-time fidelity for this purpose?
- How to face the issues coming from data accessibility and privacy?
- Is it likely to expect a potential impact on health care, the insurance sector, and housing markets?
- What are the technology challenges, such as interoperability in terms of data exchange formats, optimizing data routing algorithms and network connectivity?
- How to control external factors, such as radical weather conditions, malfunctioning hardware, connectivity, theft or vandalism, bias from citizens participation data?

The aim of this work is to contribute to these research challenges, with more focus on the first two points, as described in detail in the next two sections.

3.1.A - Exploring the potential of sensing for mapping urban climate and air quality (people's scale and resolution)
3.1.B - Identifying the limits of sensing for mapping urban climate and air quality (cost and technology, affordability and reliability)

3.1.A - Exploring the potential of sensing for mapping urban climate and air quality (people's scale and resolution)

As mentioned in Ch. 1, within a city, urban climate and air pollution show significant spatial and temporal variability. "Temperatures from one side of a street to the other, from a park to an industrial neighborhood, or one suburb to another may be significantly different, and the nature of these differences changes through time" (C. S. B. Grimmond, 2007, p. 85). In mapping urban climate and air pollution, it is therefore necessary to define a proper scale and resolution.

- The need for mapping at a "proper scale", and the help of local sensing
- The need for mapping with a "proper resolution", and the help of fine-grained sensing

The need for mapping at a "proper scale", and the help of local sensing

As recalled in § 2.3.B, the current people exposure to heat/pollutants estimation made by environmental and health agencies is generally based on air quality maps with restricted spatial resolution, because they are generated from air sensor networks at a high scale, mostly regional.
At the same time, people location is generally considered with simplified estimates of population distributions (static residential population densities). Except from few targeted studies, some of them mentioned in § 2.2, there is no systematic study on the impact of heat and pollutants concentration at the local scale (see § 1.1). However, a European study about health impact caused by air pollution, explored the intra-urban air differences within cities (Barrett et al., 2008, p. 43), concluding that exposure for urban populations may be of the order of 20% greater than estimated by a simple urban average, because of scale averaging which gives misleading results. Considering a large scale, in fact, target groups of population with high exposure are being averaged across a larger number.
Two main reasons for the need of improving the scale of air pollution studies can be outlined, based on the results of the study:

- The current exposure is underestimated because of the scale of the studies; because of high population density in high-polluted areas, accounting for smaller scale will increase the estimations on the real exposure.
- The current exposure is underestimated because of the daily movement of citizens along highly polluted road corridors, and in addition, because of the amount of people living in rural/suburban areas (where the estimations are made) but commuting to more polluted central areas.

Since exposure is estimated on people, there is a need for a people's scale exposure mapping. While data of individuals' presence within the urban environment can be derived from a mobility pattern from mobile phone data

analysis (Calabrese et al., 2011; Manfredini et al., 2012), pollution data can only derived through fine grained sensing.
Thanks to recent availability of technology, and the diffusion of pervasive sensing, a new paradigm in urban air quality studies is about to come.

Spatial and temporal Local scale
Considering the “people’s scale”, mapping processes should focus at the urban climate and air pollution near the ground, up to 2 m above the surface, at the “pedestrian level”. The scale can either refer to canopy level phenomena or the urban canyon. Additionally, considering a pedestrian moving around on outdoor spaces, and the wind and air mixing in the canyon, in order to assess its exposure, it is necessary to expand the focus to the surrounding streets, therefore considering a “local/neighborhood level” (10^1-10^2 m).
A number of sensors within the urban environment can therefore unveil the spatial pattern of air pollutant and heat concentration, by observation at the local scale.

However, the complexity of air phenomena requires deeper considerations, and as anticipated in §§ 2.1 and 2.2, the complex relationships among the factors involved in the creation of a pollutant or heat concentration, require careful reflections. For example, some air parameters, such as ozone concentration, can be mostly dependent on meteorological factors and show irrelevant spatial variation. Some other parameters, such as NOx, can show spatial variations connected to the proximity of their emitting sources (such as traffic or residential heating by fuel combustion). Other parameters, such as PM2.5, being able to travel over space, can show spatial variation mostly connected to urban design factors, such as enclosed pockets of polluted heat concentration within urban areas (UHI), might be the most studied at the local level, nevertheless its spatial variation deserves further exploration.
In fact, even if the relative differences over space between the parameters considered are actually small, therefore presenting a small variation from a minimum to a maximum recorded value, the exposure difference and the human health effect can be significantly higher. This aspect is connected to the “averaging” issue of scale, but with an additional element of analysis. In exposure studies and risk assessments, the values of interest are generally the peak ones, in both space and time, while the average is used as a baseline. In exposure studies, the WHO recommends standards for air pollution concentration that are averaged on time (1 hour, 21 hours, etc.. see § 1.2.A) according to specific pollutants and to monitoring system capabilities (World Health Organization, 2006).
Improving scale with air sensing is therefore the privileged way to detect “hotspots”, spatial peaks of harmful concentration above certain thresholds. While hotspots for some pollutants, such as UFP, can be spatially relevant at an urban or regional scale, pollutants like PM10 require a local scale spatial analysis.

Local scale can be reached with local sensing, such as a local sensing network.
In fact, thanks to recent availability of technology, and the diffusion of sensing, a local air sensing network can unveil the spatial pattern of air pollutant and heat concentration, at the people's scale, rather than using the data coming from scarce high-scale monitoring stations.

Therefore, considering urban climate and air quality mapping for urban planning and design interest, the most pertinent research question that arises is the following:
- *What is the proper scale, the people's scale, and how can sensing help?*

The need for mapping with a "proper resolution", and the help of fine-grained sensing

As anticipated in § 2.3.B., besides scale, the spatial resolution and representativeness are fundamental aspects to be considered in improving mapping for air quality and urban climate studies. In fact, urban context is characterized by large variations within continuous physical phenomena over small temporal and spatial scales, making point measurements less likely to be representative of the system as a whole.
Because of the high heterogeneity of urban areas, also in terms of urban morphology, the spatial representativeness of urban measurements must be questioned; moreover, because of logistical constraints, traditional data-assimilation techniques developed for rural areas are often used for urban stations but are not likely to be appropriate (F. Chen et al., 2012).

Spatial and temporal resolution

When defining resolution, according to the scale considered, the number of observations or of modeled characteristics per square meter strongly depends on urban structure: one single data can be representative of a large area, such as a parking lot or a park, while in some cases the highest significant resolution can require observations at pace of 1 meters, such in presence of turbulence inside a street canyon.
In fact, sensing observations are always made "at a limited rate and for a limited time interval over a limited area".
"In practice, observations should be designed to be sufficiently frequent to be representative of the unsampled parts of the (continuous) variable, and are often taken as being representative of a longer time interval and larger area. The user of an observation expects it to be representative, or typical, of an area and time, and of an interval of time" (World Meteorological Organization, 2008, pp. III–2–2).

In order to map urban climate and air pollution at a local level in urban environments, it is therefore necessary to carefully consider that each measurement is representative of a "small area" around the sensor (and small time), and therefore a "high" number of observations are needed.
However, because of the complexity of the phenomena involved, and the "averaging" always applied in observations, thorough considerations need to be made in order to study the "optimal" sensing strategy. For example: *"A typical example of sampling and time averaging is the measurement of temperature each minute (the samples), the computation of a 10 min average (the sampling interval and the sampling function), and the transmission of this average (the observation) in a synoptic report every 3 h. When these observations are collected over a period from the same site, they themselves become samples in a new time sequence with a 3 h spacing. When collected from a large number of sites, these observations also become samples in a spatial sequence. In this sense, representative observations are also representative samples"* (World Meteorological Organization, 2008, pp. III–2–2).

A better spatial resolution is recommended in both climate studies, such as UHI magnitude quantification (Stewart, 2011) and air pollution and exposure research (Stroh et al., 2007), and in order to cover more representativeness, a larger number of observations need to be made.
Representativeness can be therefore only improved by increasing and averaging the number of measurements in time by logging at a "small" amount of time (from seconds to hours, according to the phenomena mapped) and in time, by getting data at a "small" distance between each other (from one to hundreds of meters, according to the phenomena mapped).

High representativeness can be reached with high resolution sensing, such as mobile sensing.
In fact, thanks to performance enhancement and price reduction, affordable low-cost sensors are being used extensively, for personal and participatory sensing, providing fine-grained diffused data, and thus covering high resolution in time and space.

Therefore, considering urban climate and air quality mapping for urban planning and design interest, the pertinent question that arises is the following:
- *What is the proper resolution, and how can sensing help?*

3.1.B - IDENTIFYING THE LIMITS OF SENSING FOR MAPPING URBAN CLIMATE AND AIR QUALITY (COST AND TECHNOLOGY, AFFORDABILITY AND RELIABILITY)

A secondary research goal of this work, but strongly connected to the previous section, is the exploration of the limits of sensing.
It seems that, at least to some extent, sensing can be beneficial for urban climate and air quality mapping, and it is actually fundamental for reaching a proper scale and resolution, therefore addressing people's exposure, and urban planning and design need for defining local measures.
However, the only way to get such high-density air quality data is the use of low-cost sensors; cost of sensors can limit their pervasive use, while performance challenges arise when comparing local sensing data to governmental monitoring station data. Additionally, privacy and transparency of data from city sensing, are two of the most challenging aspects preventing the necessary access to personal information for the data analysis.

- Cost and technology, affordability and reliability
- Other: transparency, privacy, unpredicted reaction to increased awareness

Cost and technology, affordability and reliability

As shown in § 2.1.B and § 2.2.B, about air sensing for urban climate and air quality, recent performance enhancement of sensing technology and price reduction of the sensor devices, has led to the flourishing of a multitude of projects.
In fact, a number of sensor networks, as described in chapter 2, are being developed, though many challenges are emerging. It is likely that "the growing establishment of such networks will further decrease prices and improve component performance". "This will particularly be so if the environmental regulatory structure moves from a mathematical modelling base to a more pervasive monitoring structure" (Resch, Mittleboeck, et al., 2011).
In addition, besides stationary sensor networks, mobile sensing is the most recent sensor technology spreading in the market: several Kickstarter campaigns were launched in 2014, all addressed at developing sensor devices for mapping the spatial distribution of air pollution, and at limiting personal exposure. Business interest is very high, following the recent increase in citizens' interest in pursuing a healthy life-style, which requires knowledge about outdoor activities and pollution (where to go running, which streets is better avoiding while cycling, etc.). Besides personal sensing, and wearable sensing devices, all the projects address the social media sharing factor, and the willingness to contribute to a participatory sensing, a collective mapping of urban environmental local problems, such as hotpots, for the community.

However, accuracy issues from the low-cost technology sensors arise as the main obstacle for its scientific use for research, since data coming from such sensors may not be comparable with data from governmental agencies, which is the data currently used for exposure studies.

In particular, in the field of urban climate and heat within the city, sensors measuring temperature can be as small as a few millimeters (such as the Sensirion SHTC1, 2 x 2 x 0.75 mm), allowing them to even be integrated with smartphones.
In the field of air quality, instruments capable of measuring particulate matter are becoming increasingly important, besides the traditional instruments (Morpurgo, Pedersini, and Reina, 2012). In fact, while the traditional gravimetric methods require time for analysis and provide off-line results, optical instruments monitor real-time air quality, in simple and compact instruments.
However, while the former measure the particulate concentration in weight per volume unit, the latter observe size of the airborne particulate matter, and the comparison between the two results is problematic. Issues with accuracy are also relevant for these kinds of devices, and further research is needed, as they might provide meaningful results when used in arrays (big data approach, see § 2.2.3).
The same challenges are shared by electrochemical sensors for air pollutants, which are small low-cost gas sensors, used for sensing parts-per-million (ppm) or even parts-per-billion (ppb). While they seem to be the only way to allow the deployment of scalable high-density air quality sensor networks at fine spatial and temporal scales, post-processing of data and artifact removal are needed. Further research and improvement can strengthen their increasing use, in both static and mobile configurations, in assessing the scientific, health and legislative implications of urban air quality (Mead et al., 2013).

Finally, considering the use of sensing devices by individuals in personal sensing and participatory sensing scenarios, whose platforms, as shown in ch. 2, are continuously growingly in number and density of data, other issues arise, concerning the quality of the data shared from un-calibrated sensors.
This pertains to the “citizen science” debate, whether data from amateur or nonprofessional scientists can contribute or not to scientific research. In fact, besides the accuracy question, volunteer-generated data might introduce bias into the data, especially in the field of air quality where health risk is affecting the individuals.

Therefore, considering urban climate and air quality mapping for urban planning and design interest, at the proper local scale and high-resolution, the question that arises is the following:
- *What is the trade-off between cost and technology, affordability and reliability, of sensing?*

Other: transparency, privacy, unpredicted reaction to increased awareness

A final question arises from the above research questions in their sequence: in order to study urban climate and air pollution, and to limit its impact on human health, local scale and high resolution mapping is needed. In order to get this quality mapping, city sensing is needed, combining low-cost sensor networks and

mobile sensing. Participatory scenarios are emerging and contributing to increase the amount of data necessary for such high-density mapping.
However, in order to perform the data analysis, personal information from individuals is needed, such as the geo-location of the data gathered. When data is shared from a wearable, personal health information might be included in some cases. Some studies, as presented in ch.2, might assess the simultaneous presence of pollutants and people within the urban environment, using "big data" sources, such as mobile phone tracking. Privacy ethics therefore arise, and this is a particularly controversial and ongoing international debate.

For the purpose of this study, the interest is limited to urban climate and air quality, in relationship to the potential unpredicted reaction to increased awareness. Since air quality at the local scale is a result of many factors, such as city form and wind, some local areas, street, squares, or even green areas, might show persistent low-quality air, which suggests avoiding outdoor activities for citizens. Potentially, even running or cycling in a public park with certain air condition monitored by sensors can be more harmful than other areas.
However, the main expected results of air sensing in participatory scenarios, like the European "Everyaware" project (see §2.2), is a positive output coming from an increased awareness, leading to more sustainable citizens' behavior and ultimately to a decrease of the local emissions, such as car emissions.

A final point worth mentioning relates to the potential reaction of insurance companies and real estate market business. It has been proven that air pollution and heat concentration increases exposure (discomfort of health risk) or energy consumption (UHI), affecting property values, especially for residential market (see §1.2).
However, fine-grained mapping is not currently available, except from few cases presented in ch.2, and those are not conducted by governmental organizations, even if they can potentially supplement air quality measurements for regulatory compliance. Nevertheless, US EPA, for example, is promoting research in low-cost technology, with grants, an annual conference and a 2014 air sensor guidebook (United States Environmental Protection Agency, 2014). It is therefore likely to happen in the short-medium term, mapping air quality can reach a proper scale and resolution, and a whole unexpected reaction may occur. Mapping might show bad quality differences from one neighborhood to another, from one street to another, according to local sources, urban morphology and weather parameters involved, comparable to noise mapping. Publicity and transparency of such mapping might raise business awareness, such as location of activities, insurance and property cost.

Therefore, considering urban climate and air quality mapping for urban planning and design interest, and the participatory scenarios coming from people sensing, the question that arises is the following:
- *What is the challenging effect of people sensing, such as transparency and privacy ethics?*

3.2. METHODOLOGY AND RESEARCH STRATEGY

As described in the previous section, the research questions arose from the general objective of "mapping urban climate and air quality", after a detailed literature review of the research problem, involving exploring the potential and limits of "air sensing":

1. *What is the proper scale, the people's scale, and how can sensing help?*
2. *What is the proper resolution, and how can sensing help?*
3. *What is the trade-off between cost and technology, affordability and reliability?*
4. *What is the challenging effect of people sensing in transparency and privacy ethics?*

Preliminary steps were therefore, the study of existing literature about urban climate and UHI, air quality and pollution, and about the role of urban planning. In addition, a literature review of modeling and sensing used for mapping was conducted, aimed at identifying the most noteworthy existing studies and projects worldwide.

Further steps relate to the objective of studying air mapping in a practical case (Milan); firstly modeling was studied and developed, and secondly the need for sensing emerged from the work, and a final step was consequently planned. An existing case study was selected (Cambridge, MIT), and additional fieldwork was designed, in order to explore the potential and limits of air sensing, both stationary and mobile. After data analysis, the potential and limits of air sensing were therefore explored.

3.2.A - Preliminary steps (exploring modeling in Milan)
3.2.B - Further steps (exploring sensing)

3.2.A - PRELIMINARY STEPS (EXPLORING MODELING IN MILAN)

- Literature review and research strategy
- Building a model and research strategy

Literature review and research strategy

Literature review is a process that supplements every step of the research: from the problem definition, to the formulation of the research question, the case study selections, the fieldwork design and the final analysis of results and discussion.

In order to determine the relations among the different factors involved in mapping urban climate and air quality, and to understand how broadly science addresses the topic of UHI and air pollutant concentration at a local scale, a literature review was conducted through available books, and papers, using scientific citation indexing services, such as Web of Science, Scopus, Taylor and

Francis and Google Scholar. Additionally key journals for the field of research where considered, such as:

- Atmospheric Environment	3.062
- Building and Environment	2.700
- Bulletin of the American Meteorological Society	11.574
- Energy and Buildings	2.465
- Environment and Planning B: Planning and Design	0.883
- International Journal of Climatology	3.398
- Journal of Applied Meteorology and Climatology	2.099
- Landscape and Urban Planning	2.606
- Urban Climate	n.a.

(Impact factor source: Journal Citation Index, ISI Web of Knowledge, 2013 JCR Science and Social Science edition)

Traditional search strategy was applied, such as defining “search queries” with Boolean operators for composite searches in correlated concepts, using “controlled keywords” and alternative keywords, and, such as: “Urban Climate”, “UHI”, “Air quality”, “Air pollution”, “Concentration”, “Urban planning”, “Spatial planning”, “Environmental planning”, “Air sensing”, “Urban modeling”, “City sensing”,
RSS of interest were created, and Alerts were set in order to get updated new resources available for the field of interest; relevant websites, newsletters, blogs and discussion lists were consulted, as well as “grey literature” coming from relevant organizations, such as WHO, WMO, US-EPA, EEA, etc. (see References).

Building a model and research strategy

In order to better understand the limits and potential of mapping urban climate and air pollution, a practical case was studied and developed. As explained in the previous chapters, it requires both modeling and sensing.

For the modeling part, in order to build a model according to the surface energy balance (§ 2.2), the following data were necessary, and therefore collected and analyzed:

- Topographic Geo-Database (requested to the municipal administration), which covers whole surface with land use data, volume data, building type, surface type (GIS based)
- D.E.M. (gathered at Laboratorio di Simulazione Urbana), which covers all building volumes

- Public Green System database (requested to the municipal administration), which covers all green areas, including trees details (species, dimension, age) (GIS based)
- 3D Model of the city center (gathered at Laboratorio di Simulazione Urbana), which covers all building volumes of the city center with accurate details (1:1000) (CAD based)
- Environmental Data (requested to local EPA and a NGO) local temperature, wind, air quality
- Other Databases (energy consumption for heating/cooling/lightening, mobility fluxes)

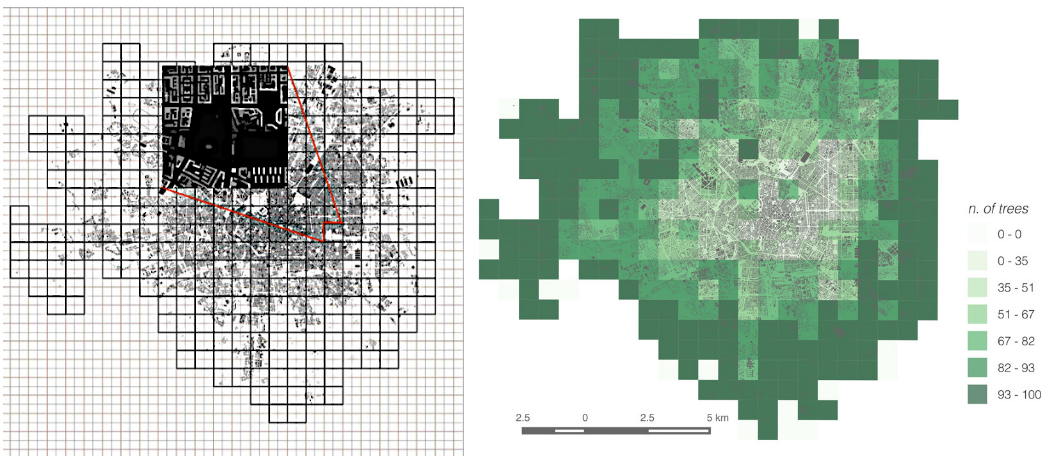
The case of Milan was chosen because of the data availability, which is extensive as above listed. In addition, the collaboration with SENSE project (Smart building ENvelope for Sustainable urban Environment, PRIN'09) at Laboratorio di Simulazione Urbana, Politecnico di Milano (under the supervision of Eugenio Morello and Claudio Comi) contributed to the initial steps of collecting research materials for this work.

However the purpose of the research is a broad exploration of urban climate and air pollution mapping for urban planning, notwithstanding the location of the mapping itself.

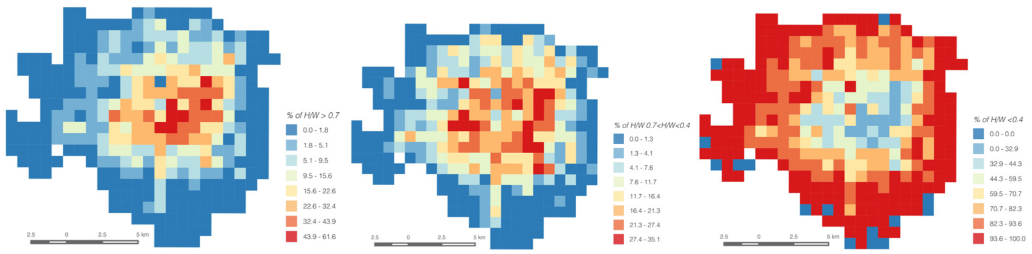
Considering that Milan is a place which lacks "extraneous effects due to topography", "water bodies", "and the downwind effect", which are factors that can provide a good case for studying "climate modification by urban area" (Oke, 1987), and since its compact structure determines high variation of density (and sky view factor) between different local areas, it seemed to be an appropriate case to study heat and pollutants concentration within the urban environment.

Based on the data necessary to build the model, as listed above, a selection of indicators needs to be calculated for all city areas divided into a number of frames (see

Figure 3-1) that were best related to the local level (see §§ 1.1, 1.2, 3.1 for definition of scale for the purpose of this work).



a) *b)*



c) *d)* *e)*

Figure 3-1
a) The 800x800 m grid (343 areas) build over the topographic geo-database of Milan and the digital elevation model (zoomed for one area). Most of the data about urban morphology are calculated using DEM raster imaging processing in Matlab environment.
b) Map generated from the model displaying the number of trees for each area. Source: author's elaboration in ArcGIS environment based on data provided by the Green Department of Milan Municipality.
c) d) e) Maps showing the morphology indicator H/W (height to weight ration) calculated for values <0.4, >0.7 and values in between. Source: author's elaboration in ArcGIS environment based on data available at Laboratorio di Simulazione Urbana.

Based on the international urban energy balance models comparison project (C. S. B. Grimmond et al., 2010, 2011) and air pollution studies (see air modeling, § 2.2.A), the indicators necessary for the model are the following (Table 3-1).

Data about urban morphology, the most relevant for the purpose of "manipulating" the urban structure and study of heat and air pollutant concentration results, can be calculated in MatLab environment, starting from DEM (Morello and Ratti, 2007; Carlo Ratti et al., 2005).

For the model, data available at Laboratorio di Simulation Urbana were used, such as "sky view factor"and "H/W" (see

Figure 3-1). Figure 3-2 includes data about population, in order to assess sensitivity and vulnerability to air pollution and heat stress (see §1.1.B).

In order to analyze the data, and the relationships among the factors, a GIS-based structured model is required, considering also that many indicators have a high spatial and temporal variation, and was therefore built.

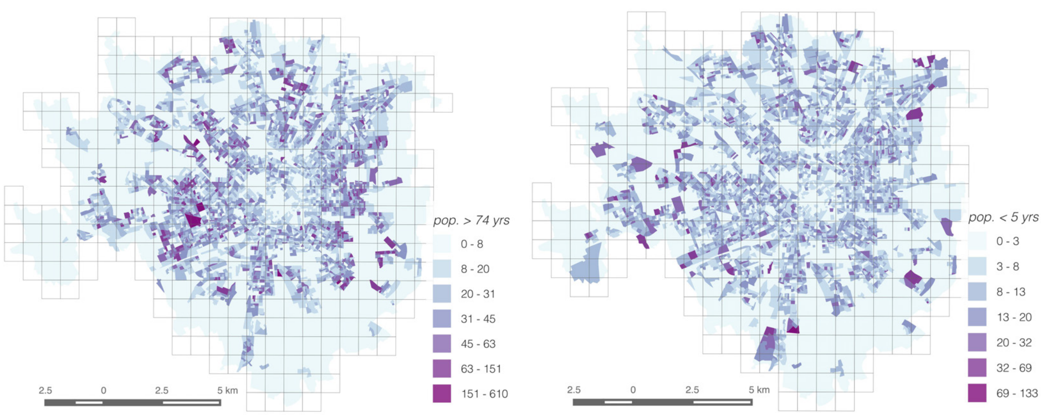


Figure 3-2
Density of population likely to be vulnerable to heat street and air pollution concentration: elderly > 74 years old (left) and children < 5 years old (right). Source: author's elaboration in ArcGIS environment based on data available at Laboratorio di Simulazione Urbana.

Table 3-1
Indicators collected for the model built for Milan (author's elaboration)

INPUT	affecting OUTPUT	INDICATORS available data	cate-gory	dependent on time? (if yes, it requires an encoding table)	unit (input) per frame (average per mq) per hour	from source
urban trees	latent heat (Q_E) air quality and GHG emission	trees green volumes (per species) per frame	land use	yes, seasonally	m3/m2	"public green" geo-database
grassland	latent heat (Q_E)	green area per frame		yes, seasonally (and irrigation condition)	m2/m2	topographic geo-database
rivers, ponds, lakes	latent heat (Q_E)	blue area per frame		no	m3/m2	topographic geo-database
soil and land cover	conduction heat (Q_G)	thermal proprieties (…)	material proprieties	no	(…)	literature - negligible? (Oke, 1987, pg. 274)
built environment	heat storage (ΔQ_S)	thermal proprieties: specific heat		no	MJ/K kg	literature - variable with materials (Oke, 1987, pg. 259)
		thermal proprieties: heat capacity			MJ/K m3	
		thermal proprieties: thermal conductivity			W/K m	
	net wave radiation (Rn)	radiation proprieties: albedo		no (except, albedo in snow season)	m2/m2	topographic geo-database; literature values (Mariani, 2005)
		radiation proprieties: emissivity		no (..)	m2/m2	topographic geo-database; literature values (…)
building energy consumption	anthropogenic heat (Q_F) air quality and GHG emission cost (€)	buildings volumes (residential, offices, …), age, ..	energy	yes, seasonally, and hourly (peak time)	m3/m2	DEM and topographic geo-database; ISTAT data (building age); literature (…)
car mobility	anthropogenic heat (Q_F)	mobility flux in main roads	mobility	yes, weekly and hourly (peak time)	n. running vechicles/m2	mobility database (PoliMI, Prof. Pucci)
urban form, texture (from urban DEM)	net wave radiation (Rn)	built volume, covered area, floor area, built perimeter, mean height of buildings,	urban morphology	no	m, m2, m3,	DEM and topographic geo-database
		sky view factor; H/W; surface to volume ratio;			m/m, 1/m	
		% of S oriented vertical surfaces; % of SE to SW oriented vertical surfaces [%]; passive zones / non passive zones ratio [-]; urban canyon aspect ratios [-]			%, -	
		…			…	
	advection heat ΔQ_A	roughness			adimensional	
climatic data	net wave radiation (Rn)	cloud cover	atmospheric data air quality	yes, seasonally, daily and hourly yes, seasonally, daily and hourly	adimensional	EPA and other Org.
		radiation			W/m2	
		humidity			%	
		wind speed, direction			m/s, …	
temperature	sensible heat (Q_H)	air temperature (at ABCD level)			°C	EPA and other Org. data + DIRECT SURVEY (converted in isotherms in GIS)
air quality data	air pollution concentration	PM2.5, PM10, NOx, CO2, O3, CO			µg/m3, ppm	EPA and other Org. data + DIRECT SURVEY (mobile sensing)
distance from city baricenter	---- (PCA analysis)	distance from city center	-	no	m	DEM and topographic geo-database

However, as recalled in the previous chapters, in order to map urban climate and air pollution at the local level, sensing is necessary. This is the crucial part of the research strategy, since sensing data is limited for the case of Milan.
In fact, sensing by using stationary monitoring stations data is not compatible with the scale and resolution addressed by this research, as shown in the air mapping examples in § 2.2 For example, Figure 3-3 shows the kriging map obtainable with all the available data about temperature concentration (UHI) from local EPA and the NGO at a specific hour of a day.

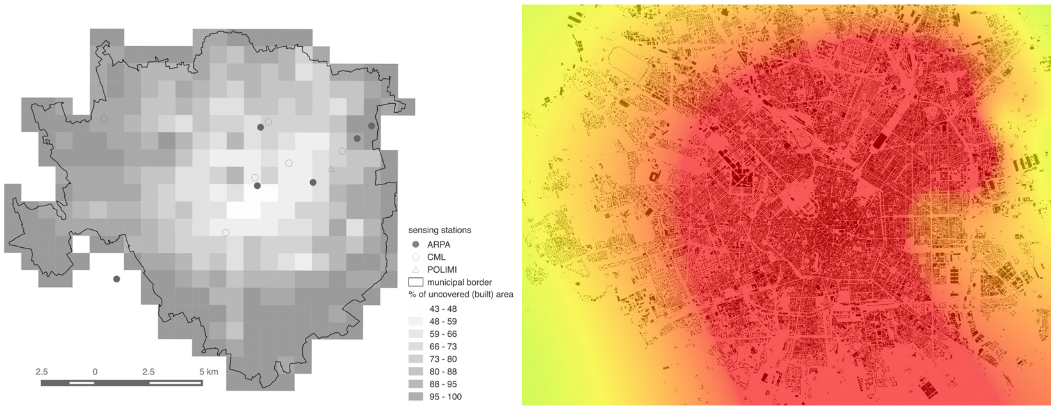


Figure 3-3
Pictured at left: Milan Municipal border and the grid built for the model. Urban climate and air quality data coming from the sensing stations available in Milan: ARPA (Regional Environmental Protection Agency), CML (voluntary participatory sensing network) and POLIMI (weather station installed at Politecnico di Milano. The map also displays the gradient percentage of uncovered build areas, from 0% (central areas of Milan) to 100% sub-urban green park areas of Milan. Source: author's elaboration based on Milan topographic database and data available at Laboratorio di Simulazione Urbana.
Pictured at right: geo-statistical interpolation using kriging technique (qualitative heatmap). The little number of sensing station does not allow a proper scale and resolution for urban climate and air quality mapping. Source: author's elaboration in ArcGIS environment based on data gathered from ARPA; CML, POLIMI stations (.

In order to overcome the limits of modeling, the research strategy therefore included exploring immersive and diffuse sensing components, which was considered necessary for the scale and resolution required by this work.
Since direct monitoring of a "transect", and expanding the results for a local air mapping, required external technology and competences, it was necessary to involve external research centers.

Furthers steps, therefore, relates to the research strategy in involving the best technology and competence in sensing for air quality mapping.

3.2.B - FURTHER STEPS (EXPLORING SENSING)

- Exploring sensing and research strategy
- Final steps

Exploring sensing and research strategy

Once modeling was explored, with its challenging limits in scale and resolution, sensing was the main focus of the research, as the key element for mapping urban climate and air quality.

Hence, considering the need for external technology and competences, it was necessary to involve external research centers, and a search for the best studies was conducted.
Because of the "communication" issue familiar to air studies at the urban level among urban planners and environmental sciences, climatology, epidemiology (Oke, 2006), a multidisciplinary approach is needed. Therefore, in order to avoid research focused on single aspects of the problem related to this work (i.e. turbulence or health risk in climate or health centers), urban planning research centers were considered. In fact, as already anticipated (§ 1.3.A), the role of planners can foster the multidisciplinary dialogue among the disciplines involved, and urban planning and design have a central and emerging role (Eliasson, 2000; Oke, 1984; Stone and Rodgers, 2001; Stone, 2005).
Based on the number of publications and the literature produced that was reviewed in this study (ch 1, 2), the prestige of the research centers and universities, the amount of developed projects and of ongoing projects, and the number of researchers dedicated to the research in the field related to the work of the thesis, two research centers that emerged above the rest:

- Senseable City Laboratory (SCL), at MIT, coordinated by C. Ratti
- Center for Advanced Spatial Analysis (CASA) at UCL, coordinated by M. Batty.

Both research centers have worked with air mapping for both climate and pollution, with outstanding projects, seminal work, and recognized results.

Considering that sensing is essential for answering the research questions based on mapping with a proper scale and resolution, Senseable City Laboratory was selected for a proposal of collaboration in the study.
In addition, the possibility of supervision by Rex Britter, besides Carlo Ratti, was a determinant factor, since his world leading experience, in both modeling and sensing for urban climate and air pollution, is well documented by his publications (Britter and Hanna, 2003b; Kumar, Fennell, and Britter, 2008; Resch, Britter, et al., 2011; Resch, Britter, and Ratti, 2012) .

See next section for the research strategy followed in the collaboration with SCL.

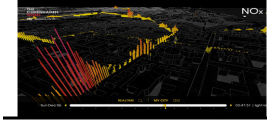
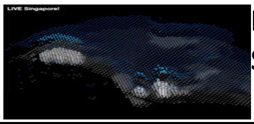
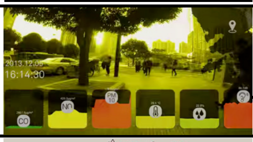
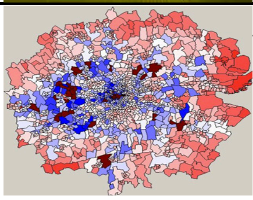
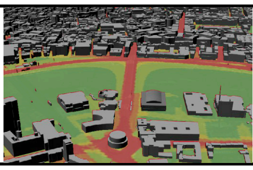
Lab	Research project		Year	mapping by modeling, by sensing	air parameters
SCL		**Copenhagen Wheel**	2009	sensing	air pollution (NOx, CO) temperature,
		**Live Singapore**	2010-ongoing	sensing	air pollution and UHI
		**One Country Two Lungs**	2014	sensing	air pollution (O, NOx, PM10) and temperature
CASA		**Arcadia**	2005-ongoing	modeling	adaptation and Resilience (includes modeling climate and pollution)
		**London Air Pollution**	2005-2009	modeling	air pollution (PM10, NO2 and NOx)

Table 3-2 Project at MIT Senseable City Laboratory (SCL) and at UCL Center for Advanced Spatial Analyses (CASA). Pictures and data from Lab's webpages casa.ucl.ac.uk and senseable.mit.edu ("Centre for Advanced Spatial Analysis," n.d., "MIT SENSEable City Lab," n.d.).

Final steps

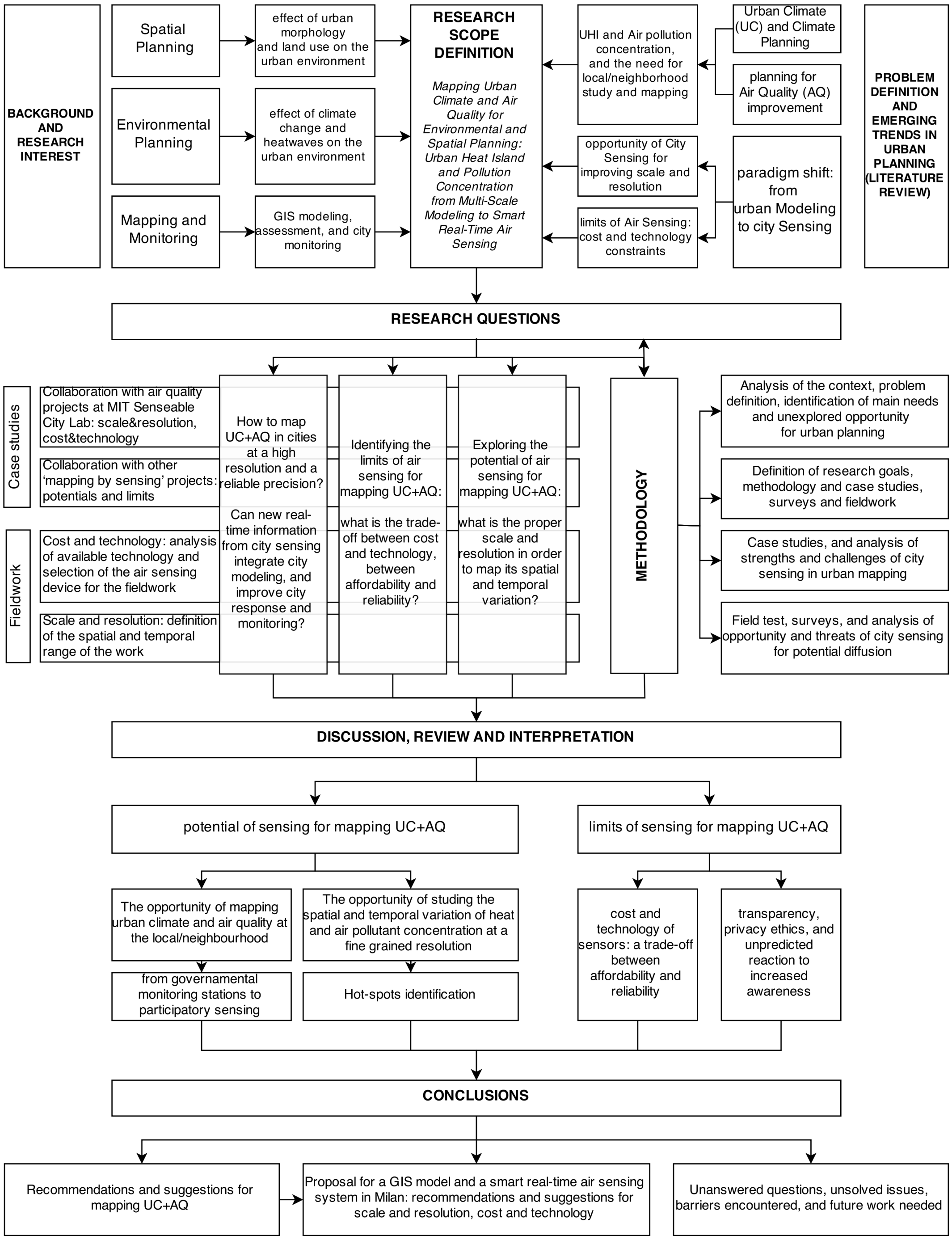
The collaboration with SCL, later described, followed the below list of steps:

- Involvement in the local sensor network air projects at MIT (Clairity, mentioned in § 2.2), mostly addressed exploring the first research question (sensing for improving scale)
- Design of a fieldwork mobile sensing, mostly addressed at exploring the second research question (sensing for improving resolution)
- Analysis of data from both the sensing network and the mobile sensing, in order to explore accuracy of the sensor technology (third research question)
- Involvement in "cutting-edge" mapping by sensing projects selected on the basis of the overall research questions (including health data and privacy issues).

As shown in the chart in the following page (Figure 3-4), the methodology selected brings the research questions through the case studies selected and the fieldwork designed.

In addition, specific methodology was used for the projects, case studies and fieldwork, data collection and data analysis and visualizations for mapping temperature and pollutants concentration, as described in the next section.

Figure 3-4 Overall methodology framework for the study (author's elaboration).



3.3. FIELDWORK DESIGN AND CASE STUDIES SELECTION

This section introduces the methodology and research steps involved in the fieldwork design and implementation, and in the case study selection.

3.3.A - Case studies selection
3.3.B – Fieldwork design strategy

3.3.A - CASE STUDIES SELECTION

- Selection of case studies
- Sensing network exploration: Research strategy steps

Selection of case studies

After selecting SCL as the appropriate spot-on research center for the purpose of this work, a brief analysis of the ongoing projects was conducted.
In fact, besides gathering information about relevant concluded projects, such as the Copenhagen Wheel and Two Lungs, the ongoing projects were examined. Table 3-3 shows the criteria used to frame the projects, considering the themes of this work sections, and the SCL projects intersections.

	§	THEMES INTERSECTED	CLAIRITY	UNDER-WOLDS	CITIVAN	URBAN CENTRALITY	OTHER (two lungs, etc.)
OVERALL MISSION	Intro	Improving citizens health (and the role and responsibility of urban planning)	x	x	x	-	-
	Intro	Improving urban planning with environmental mapping	x	x	x	-	-
RESEARCH FIELD	1.1	Urban climate and UHI	-	-	-	-	-
	1.2	Air Quality and Pollutant concentration	x	-	-	-	-
	1.3	Role of urban planning and design, climate change urgency	-	-	-	-	-
	2.1	Urban climate mapping		-	-	-	-
	2.2	Air pollution mapping	x	-	-	-	-
	2.3	From urban modeling to city sensing	x	x	x	x	x
RESEARCH QUESTIONS	3.1.A	Potential of air sensing: Improving scale (sensing networks)	x	-	-		-
		Potential of sensing: Improving resolution (mobile sensing)	-	-	x	-	-
	3.1.B	Challenges of air sensing: Accuracy and affordability	x	x	x	-	-
		Challenges of air sensing: transparency and privacy	x	x	-	x	-

Table 3-3
The research themes as included in the sections of this thesis (left) and their intersections with the ongoing projects at MIT-SCL in 2014.

The project "Clairity" was therefore individuated as the best for the research questions of this work. In fact, Clairity is the most innovative experience available worldwide in the field of air sensing at a local scale (as mentioned in the literature review in §2.2). However, supporting role collaborations with other projects was considered beneficial for the results.

Sensing network exploration: Research strategy steps

The collaboration with the projects involved the following research strategy steps:

- semi-structured interviews with the project designers, MIT Civil and Environmental Engineering faculty: Jesse Kroll, Colette Heald, Eben Cross
- supervision of leading researchers at SCL (Britter and Ratti), and collaboration with other experts and researchers at SCL working on big data analysis, visualization and mapping by sensing (Tracey Li, Sebastian Grauwin, Luis Carli, David Lee)
- participation in meetings and seminars (such as the official project launch, 2014 May 6^{th})
- collateral limited participation to the other projects mentioned in Table 3-3
- data collection from the Clairity sensing stations (Particulate matter, CO, NO, NO2, O3) and external source (MIT archive for DEM, MassDEP for governmental air quality data, Wunderground "scrapping" for meteorological data)
- data analysis, statistics and visualization, using Tableau (software for big data analysis) and ArcGIS
- comparing data from the network with data coming from governmental stations
- mapping air quality using kriging methods
- analysis of hotpots, by identifying thresholds (World Health Organization, 2006) and their temporal and spatial variation with data analysis (selecting a month of reference: May 2014).

Nevertheless, observing Table 3-3, Clairity project does not help answer the research question about improving resolution of mapping pollution, and in particular for urban climate (temperature).

It is therefore necessary to include the design of mobile sensing fieldwork. See next section for more details.

3.3.B - FIELDWORK DESIGN STRATEGY

- Mobile sensing design and exploration: Research strategy steps
- Assumptions and constraints of the research

Mobile sensing design and exploration: Research strategy steps

Considering the limits of stationary sensing network in reaching a proper resolution for air quality and urban climate mapping, a mobile sensing campaign is needed.
In fact, exploring the representativeness of the data gathered, additional sensing is needed.
Therefore, a field experiment was designed and executed, by testing and using sensors and exploring sensing opportunity in mapping air quality and urban climate parameters.

The design of the mobile sensing, called "Hot-spot", involved the following research strategy steps:

- selecting the proper sensor device, based on an extensive literature review of all existing technology for climate (temperature and humidity) and air pollution (particulate matter, and gases) (see §4.2). The parameters to consider for the comparison and selection are: "cost" (with a limit of $500, considered as the maximum for participatory sensing), "availability", "accuracy", "response time", "size" (Snyder et al., 2013; United States Environmental Protection Agency, 2013, 2014; World Meteorological Organization, 2008)
- open question interviews with two leading sensing technology company CEOs: Michael Setton (Sensaris, sensor devices) and John Saffell (Alphasense, unit gas sensor)
- semi-structured interviews with Clairity project designers, about the integration of the two projects (MIT Civil and Environmental Engineering faculty: Jesse Kroll, Colette Heald, Eben Cross)
- selecting the area for the mobile sensing, the exact path, the time, the speed and other parameters
- in particular, for the definition of the optimal path, analysis of the "Chinese postman problem" methodology, in order to find the shortest route through the area, that meets the following criteria: it is a closed circuit (it ends at the same point it starts), and it needs to go through every street at least once (Edmonds and Johnson, 1973)
- supervision of leading researchers at SCL (Britter and Ratti), and collaboration with other experts and researchers at SCL working on big data analysis and mapping by sensing (Tracey Li, Luis Carli, Alice Biroli)
- participation (with poster/oral presentations) in meetings and conference, such as the US-EPA Air sensing conference at Research Triangle Park, June 9-10th 2014 (Treville, Li, Nyhan, Britter, and Ratti, 2014)

- fieldwork execution and data collection from the sensor device (Particulate matter, temperature, humidity, VOC) and external sources (MIT archive for DEM, MassDEP for governmental air quality data, Wunderground "scrapping" for meteorological data)
- data analysis, statistics and visualization, using Tableau (software for big data analysis) and ArcGIS
- combining data from mobile sensing with data from the sensor network (clairity), in particular, for particulate matter concentration mapping
- mapping air quality using kriging methods
- analysis of scale and resolution, by aggregating and mapping data at different levels: 1000m, 100m, 10, 1m, and calculating the resulting averaging error
- analysis of hotpots, by identifying thresholds (World Health Organization, 2006) and their temporal and spatial variation with data analysis.

Issues such as cost and accuracy, affordability and reliability were addressed in the data analysis and comparison of data with governmental data and other sensors, such as the particulate matter data from the mobile device (Sensaris) and Clairity (Dylos data).
Issues such as transparency and privacy were addressed during the literature review process in selecting the sensing device, and in the implementation of the Clairity web platform.

Assumptions and constraints of the research

Since this study is not funded by a private or public institution, there are not constraints defined by an external group. The main constraint of this study is the two years research time in the three years PhD program, one mostly dedicated to modeling at Politecnico di Milano, and the other dedicated to sensing, mostly spent at MIT.
The methodology and the research strategy for this work were designed to be able to conduct the research in two years period.
One of the main challenges faced during the study is the lack of comprehensive studies on air sensing, and the amount of time spent to review all the existing devices before selecting one. In fact, several papers exist, but in order to avoid bias and second-hand material, and considering that new sensors are emerging in the recent months, with a high concentration of releases in 2014, a personal up-to-date review was needed.
Budget constraint was also a limit: using a large number of devices, and consequently involving a large number of collaborators, probably would have improved some considerations in the discussion of the results. However, since the purpose of the study was not achieving a local fine-grained mapping, but to explore the process, the potential and the limits of urban climate and air quality mapping, the tools, methods and researchers involved, was considered fairly appropriate.

Conclusion

After defining the research questions, the selected methodology was described.
Once modeling was explored in terms of limitations in scale and resolution, a thorough exploration of sensing was conducted through the sensor network and the mobile sensing fieldwork.
The final result, foreseen by the methodology, is a detailed discussion about the potential and limits of sensing in mapping for urban climate and air quality, based on the evidence coming from the development of the research steps (§ 6.1). Additionally, considering the preliminary steps in modeling conducted at Politecnico di Milano, and the sensing research and expertise acquired at MIT, a proposal for future work for integrating modeling with a mobile sensing project is included in the thesis (§ 6.2).

References

Barrett, K., de Leeuw, F., Fiala, J., Larssen, S., Sundvor, I., Fjellsbø, L., … Černikovský, L. (2008). Health impacts and air pollution–an exploration of factors influencing estimates of air pollution impact upon the health of European citizens. *ETC/ACC Tech Pap*, *13*.

Britter, R., & Hanna, S. R. (2003). Flow and dispersion in urban areas. *Annual Review of Fluid Mechanics*, *35*(1), 469–496.

Calabrese, F., Colonna, M., Lovisolo, P., Parata, D., & Ratti, C. (2011). Real-time urban monitoring using cell phones: A case study in Rome. *Intelligent Transportation Systems, IEEE Transactions on*, *12*(1), 141–151.

Centre for Advanced Spatial Analysis. (n.d.). Retrieved December 30, 2014, from http://www.bartlett.ucl.ac.uk/casa

Chen, F., Bornstein, R., Grimmond, C. S. B., Li, J., Liang, X., Martilli, A., … Wang, Y. (2012). Research priorities in observing and modeling urban weather and climate. *Bulletin of the American Meteorological Society*, *93*(11), 1725–1728. doi:10.1175/BAMS-D-11-00217.1

Edmonds, J., & Johnson, E. (1973). Matching, Euler tours and the Chinese postman. *Mathematical Programming*. Retrieved from http://link.springer.com/article/10.1007/BF01580113

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*(1), 31–44. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204600000347

Grimmond, C. S. B. (2007). Urbanization and global environmental change: local effects of urban warming. *Geographical Journal*, *173*(1), 83–88. doi:10.1111/j.1475-4959.2007.232_3.x

Grimmond, C. S. B., Blackett, M., Best, M. J., Baik, J. J., Belcher, S. E., Beringer, J., … Coutts, A. (2011). Initial results from Phase 2 of the international urban energy balance model comparison. *International Journal of Climatology*, *31*(2), 244–272.

Grimmond, C. S. B., Blackett, M., Best, M. J., Barlow, J., Baik, J. J., Belcher, S. E., … Zhang, N. (2010). The international urban energy balance models comparison project: First results from phase 1. *Journal of Applied Meteorology and Climatology*, *49*(6), 1268–1292. Retrieved from http://journals.ametsoc.org/doi/abs/10.1175/2010JAMC2354.1

Kumar, P., Fennell, P., & Britter, R. (2008). Effect of wind direction and speed on the dispersion of nucleation and accumulation mode particles in an urban street canyon. *Science of the Total Environment*, *402*(1), 82–94. Retrieved from http://www.sciencedirect.com/science/article/pii/S0048969708004622

Manfredini, F., Pucci, P., & Tagliolato, P. (2012). Mobile phone network data. new sources for urban studies. *Geographic Information Analysis for Sustainable Development and Economic Planning: New Technologies.Hershey PA, USA: IGI Global*, 115–128.

Mead, M. I., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., … Hodgson, T. F. (2013). The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, *70*(5), 186–203.

MIT SENSEable City Lab. (n.d.). Retrieved December 30, 2014, from http://senseable.mit.edu/

Morello, E., & Ratti, C. (2007). Raster Cities: image processing techniques for environmental urban analysis. In K. Thwaites, S. Porta, O. Romice, & M. Greaves (Eds.), *Urban Sustainability through Environmental Design: approaches to time, people and place responsive urban spaces* (pp. 119–122). London, UK: Spon Press.

Morpurgo, A., Pedersini, F., & Reina, A. (2012). A low-cost instrument for environmental particulate analysis based on optical scattering. *… Conference (I2MTC), 2012 …*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6229220

Oke, T. R. (1984). Towards a prescription for the greater use of climatic principles in settlement planning. *Energy and Buildings*, *7*(1), 1–10.

Oke, T. R. (1987). *Boundary layer climates* (Second., Vol. Routledge, p. 435). London and New York: Routledge. Retrieved from http://books.google.com/books?hl=en&lr=&id=K_2dW7crfVIC&oi=fnd&pg=PP1&dq=Boundary+Layer+Climates&ots=112YqtIAbW&sig=OpORoBqDxjfdojOonDHY-OjpGzk

Oke, T. R. (2006). Towards better scientific communication in urban climate. *Theoretical and Applied Climatology*, *84*(1-3), 179–190.

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings*, *37*(7), 762–776. doi:10.1016/j.enbuild.2004.10.010

Resch, B., Britter, R., & Outram, C. (2011). Standardised geo-sensor webs for integrated urban air quality monitoring. *Environmental Monitoring*, 513–528. Retrieved from http://senseable.mit.edu/papers/pdf/2011_Resch_UAQM_EM.pdf

Resch, B., Britter, R., & Ratti, C. (2012). Live Urbanism–Towards SENSEable Cities and Beyond. In *Sustainable Environmental Design in Architecture* (pp. 175–184). Springer. Retrieved from http://link.springer.com/chapter/10.1007/978-1-4419-0745-5_10

Resch, B., Mittleboeck, M., Lipson, S., Welsh, M., Bers, J., Britter, R., … Blaschke, T. (2011). Integrated urban sensing: a geo-sensor network for public health monitoring and beyond.

Snyder, E. G., Watkins, T. H., Solomon, P. a, Thoma, E. D., Williams, R. W., Hagler, G. S. W., … Preuss, P. W. (2013). The changing paradigm of air pollution monitoring. *Environmental Science & Technology*, *47*(20), 11369–77. doi:10.1021/es4022602

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, *31*(2), 200–217.

Stone, B. (2005). Urban heat and air pollution: An emerging role for planners in the climate change debate. *Journal of the American Planning Association*, *71*(1), 13–25. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360508976402

Stone, B., & Rodgers, M. O. M. (2001). Urban form and thermal efficiency: How the design of cities influences the urban heat island effect. *Journal of the American Planning Association*, *67*(2), 186–198. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360108976228

Stroh, E., Harrie, L., & Gustafsson, S. (2007). A study of spatial resolution in pollution exposure modelling. *International Journal of Health Geographics*, *6*, 19. doi:1476-072X-6-19 [pii]

Treville, A., Li, T., Nyhan, M., Britter, R., & Ratti, C. (2014). Urban Hot-Spots : A Smart Real-Time Sensor Network for Urban Climate Stress & Air Quality Mapping pollution and Urban Heat Islands. In *Air Sensors 2014 - A New Frontier. Monitoring Technology for Today's World* (p. 2014). Research Triangle Park, NC: United States Environmental Protection Agency. Retrieved from https://sites.google.com/site/airsensors2014/26_AirSensor-EPA_poster_small.pdf?attredirects=0&d=1

United States Environmental Protection Agency. (2013). *Roadmap for Next Generation Air Monitoring*.

United States Environmental Protection Agency. (2014). *Air Sensors Guidebook* (p. 73). Research Triangle Park, NC: US Environmental Protection Agency. Retrieved from ww.epa.gov.ord

World Health Organization. (2006). *Air Quality Guidelines. Global Update 2005* (p. 485global). Copenhagen, DK: World Health Organization. Retrieved from http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/

World Meteorological Organization. (2008). *Guide to Meteorological Instruments and Methods of Observation*. Geneva, Switzerland: Genf, Schweiz: Secretariat of the WMO. Retrieved from http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf

CHAPTER **4**

4. PROJECTS AND RESULTS | CASE STUDIES AND FIELDWORK

Introduction

What was done during the case studies and the fieldwork? What data was collected?

As the methodological chapters described, the research strategy designed to explore the questions demanded collaboration with an external research center with high-profile experience in sensing, and Senseable City Laboratory was considered appropriate in technology and competences. In order to explore the four questions, multiple case studies needed to be considered, according to their interference with this work. As mentioned in ch. 3, Clairity was the project that was studied mostly for exploring the first research question (sensing for improving scale), while additional fieldwork project was specifically designed by the author to explore the second research question (sensing for improving resolution). Additional collaboration with other projects was considered beneficial in order to explore the overall research questions, and in particular the last two (challenges of sensing).

This chapter therefore presents the main characteristics of the projects from the perspective of the research questions of this work. Data collected from Clairity (§ 4.1) and from the execution of the fieldwork (§ 4.2) will be later analyzed and discussed in chapter 5.

4.1. COLLABORATION WITH CLAIRITY: A LOCAL SENSOR NETWORK FOR AIR QUALITY AT MIT CAMPUS

As mentioned in § 2.2.B., Clairity is a project aimed at monitoring air quality within the MIT campus with the use of 24 real-time low-cost sensors nodes (Alphasense and Dylos, monitoring CO, NO, NO2, O3, PM10, PM2.5) installed in areas of major activity.

As evidenced in the research strategy, collaborating with this project, being unique worldwide and innovative in addressing the objective of mapping air quality by sensing, was considered crucial for the following analysis and discussion.

A description of the project follows, stressing the four themes of the research questions.

4.1.A – Project scale and resolution
4.1.B - Cost and technology, transparency and publicity

4.1.A - PROJECT SCALE AND RESOLUTION

- Spatial and temporal scale
- Spatial and temporal resolution

Spatial and temporal scale

The declared objective of the project is to "assess the exposure of the MIT population to airborne pollution" (Clairity, 2014, p. 4), even though the work is limited to the design and implementation of a distributed air quality sensor network on MIT campus.

Therefore, the scale of the air quality mapping is deliberately the people's scale, within the MIT campus environment.
In fact, while the Massachusetts Department of Environmental Protection operates air quality monitoring stations at few locations in the greater Boston area, there is no system currently in place that provides a real-time picture of the air on MIT's campus specifically. The two closest stations measuring particulates are 3.4 and 3.9 km away from the MIT, and the closest stations measuring NO2 are 1.3 and 3.9 km away (Figure 4-1).

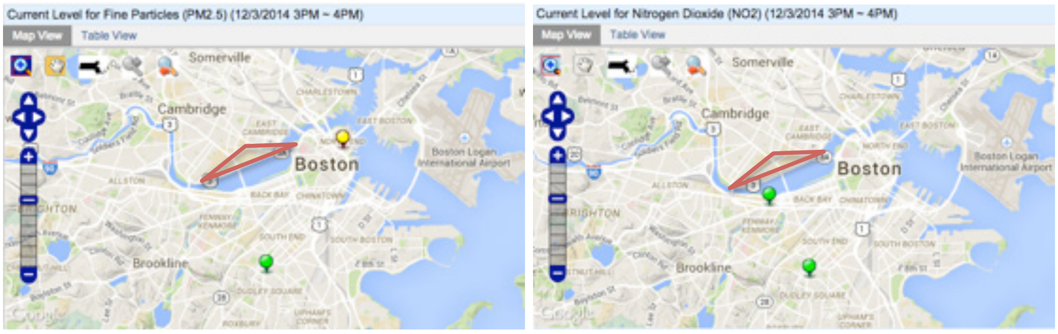


Figure 4-1
Pictured at left: location of the two closest sensing stations monitoring PM2.5 in relation to MIT campus (red triangle in the map). Pictured at right: location of the two closest sensing stations monitoring NO2 in relation to MIT campus. Source: Massachusetts Department of Environmental Protection ("MassDEP:: Air & Climate :: Air Quality & Monitoring :: MassAir," n.d.)

The sensors are installed inside the campus area, considering both the west and the east campus, which is an urban area of about 1 square kilometer, fully integrated with the urban texture of the city of Cambridge, in the greater Boston area.
The spatial scale is therefore the local scale, the people's scale, the scale of the air process within the urban environment. However, one sensor node was installed at the rooftop of a tower building (Green Building, 90 meters high), in order to have a 'clean air' mark, while the rest of the sensor nodes are deployed in order to observe how pollutants are dispersed throughout campus.
The temporal scale considered is limited to the date of project launch, may 2014, since no previous recordings are available at this scale. The project is intended to stay active for several years, though maintenance work is necessary to replace some sensors (some low-cost sensors life is estimated in 2/4 years). Data is recorded in real-time, at the resolution later specified.
While the temporal scale is limited, in comparison to the data available from the governmental sensor network, the spatial scale is the strength of the project, and it potentially allows quantifying the air quality at the local scale instead of the broader scale of the Massachusetts Department of Environmental Protection (regional / Great Boston scale).

Spatial and temporal resolution

Determining the resolution of such sensing projects is the most challenging part, considering also the lack of comprehensive studies, and guidelines and recommendations. In fact, most of the guidelines for air measurements, such as the ones for meteorological observation (Oke, 2004; World Meteorological Organization, 2008) do not consider the influence of the local environment, and recommend positioning the instruments at a certain distance from known influencing factors (shading, etc.).

The scale of Clairity, instead, is local, and local influences of the urban environment are inevitably included in the measurements. For this reason, the rationale in deploying the sensors was to identify "typical" and recurrent air quality situations.

As the analysis in chapter 5 and the discussion in chapter 6 will show, there might be no prefixed resolution that can be determined: using too many sensors at a small distance could lead to useless data, and waste of efforts, while sensors placed at a significant distance might mislead the representativeness of their results.

However, the project designers decided for a maximum number of 25 sensors, due also to budget constraints and to the uncertainty of the results, and likely also to the uncertainty of the real need of a larger number.

In this sense, the resolution was already determined, and it was just a matter of selecting the locations with the best "representativeness" of the expected measurements, such as: "roof tops", "parking lots/garages", "major intersections", "food service areas", "community cross section", "cogeneration power plant".

In fact, several considerations were taken in selecting the locations, considering also the capabilities of the sensor nodes, community concerns and how pollutants disperse throughout the campus. It is therefore clear that subjective considerations were made in selecting the best locations:

- Because the primary sources for the pollutants measured by Clairity sensor nodes are car emissions, power plant exhaust, chemical solvent vapors and smoke, the deployment scheme focused on areas where these sources were considered to be prevalent (food service locations, traffic intersections and parking lots throughout MIT's campus).
- Because a declared objective of the project is raising awareness, the deployment scheme selected locations considered to be well-seen by the community members along their normal travel route.
- Because air pollution measurements at a local scale are relevant to assess people exposure, the deployment scheme selected the locations that were considered to be most frequented by the MIT community.
- Because an aim of the project is to cover the entire campus, the deployment scheme overall covered a wide cross section of the MIT campus, considered representative enough to see how pollutants are dispersed throughout the campus.

- Because the mounting scheme utilizes a pole or pipe, the deployment scheme selected locations that were considered easy to install and not easy to vandalize (i.e. determining the height from ground).

Figure 4-2
Map displaying MIT campus in Cambridge, MA, and the location of the outdoor Clairity stations. The black lines are the Voronoi polygons created around the stations. Source: author's elaboration.

The resulting locations of the 24 sensor nodes, within 1 square kilometer of the urban areas of the campus, provide a density of 1 node per 40.000 square meters, and a spatial distance between two sensors of maximum 400 meters.
Considering only outdoor nodes, and only nodes providing full data in the period considered (May 2014) with no malfunctioning episodes, the amount of sensing nodes is 9 as showed in Figure 4-2.

However, challenges in representativeness of the data from a given location do occur, considering also that 7 locations are indoor nodes, and they might represent data for a limited ambient air volume, and that the air volume areas around outdoor nodes is affected by multiple factors, such as wind, building volumes, etc. Considering only the location, the theoretical representativeness of the outdoor sensing nodes is displayed in Figure 4-2, using Voronoi polygons.
The original idea of the project was to include mobile sensing with nodes installed in MIT facility vehicles and shuttles. However, due to technical constraints, the project currently only monitors air quality by the 24 stationary nodes.

About the temporal resolution of this sensing project, this is also an advantage in comparing data with the Massachusetts Department of Environmental Protection measurements. In fact, while the latter provides hourly data, the time resolution of the Clairity network was set to 10 seconds. A better resolution allows improvements in studying the air pollutant distribution in the area. See the next section for a comparison of simultaneous data coming from the two sources.

4.1.B - COST AND TECHNOLOGY, TRANSPARENCY AND PUBLICITY

- Cost and technology
- Transparency and publicity

Cost and technology

One objective of this work is to explore the trade off- between cost and technology in mapping by sensing for urban climate and air pollution, and the Clairity example is helpful in this sense. Low-cost technology is the one possibility for monitoring at a local scale (in the field of air sensors), and Clarity inevitably uses low-cost sensors.
Among the low-cost technology available in the field of air sensing, three main categories exist: electrochemical sensors for monitoring gases, optical sensors for detecting particulate matter, and temperature and humidity sensors.

Monitoring temperature and humidity

Measuring temperature and humidity is somehow less challenging than particulates and gases, and several low-cost exist all with acceptable accuracy (see next section for a brief overview). The sensor selected for Clarity network was the “DHT22 temperature and relative humidity sensor”, one of the low-cost, high accuracy, and high temperature and humidity measurement range. The sensor uses a capacitive humidity sensor and a thermistor to measure the surrounding air, and spits out a digital signal on the data pin at a frequency of 0.5 Hz, or once every 2 seconds. The cost of a single sensor is of about $13.

Monitoring particulate

As for particulate matter sensing, there are several low-cost sensors devices but with less clear accuracy and more expensive compared to the temperature and humidity sensor.
As anticipated in §3.1.B, low-cost sensors all measure particles by optical instruments instead of expensive gravimetric methods. Based on optical light scattering, they are able to detect and count particles distinguishing different sizes, such as “coarse” and “fine” (see next section for a brief overview). For this reason, their results are not directly comparable with gravimetric measurements, providing concentration according to the definition of particulate matter, such as PM2.5 or PM10. However, a correlation can be explored, as discussed in §5.2.A.
That said, the device selected for monitoring particulate in Clairity was the “Dylos”, model DC11000; according to the manufacturer, the device is capable of detecting small particles down to 0.5 micron, and large particles with a size range calibrated to 2.5 microns and above (“Dylos DC1100 Professional Air Quality Monitor,” n.d.).
Dylos devices, in fact, have been used in several studies that included monitoring particles, providing data with acceptable quality results (Dacunto et al., 2013; Northcross et al., 2013; Semple, Apsley, and MacCalman, 2013). In detail, the Dylos consists of a small fan that maintains an airflow through the device, a laser beam and photodiode system that measures particulate matter, a screen that

displays the results, and a power source. The Dylos reports the particle count per cubic foot of air, and it does so in two different size bins: coarse particles (diameters between 10 micrometers and 2.5 micrometers) and fine particles (diameters less than 2.5 micrometers). As air is channeled through the system, the Dylos counts particles by scattering light by the particles in the air. This scattered light is then picked up by the photodiode, which registers a voltage based on the amount of scattered light.
The cost of single device is around $290.

Monitoring gases

As for the remaining pollutants to monitor besides particles, air quality standards vary across countries, while the WHO recommends some gases (World Health Organization, 2006), and the US -EPA set standards for CO, Lead, NO2, O3, SO2 ("National Ambient Air Quality Standards (NAAQS) | Air and Radiation | US EPA," n.d.).
Considering that lead and sulfur dioxide are usually related to specific sources such as emissions from certain industrial activities, and the MIT campus is located in a residential-commercial area in the center of Cambridge, they were excluded from the monitoring activity of the network The gases selected for monitoring were therefore: CO, O3, NO and NO2.
The low-cost sensor devices to monitor the selected gases were chosen among the available technology, and the Alphasense electrochemical sensors were selected. In fact, Alphasense sensors have been extensively used in many sensing projects because of their acceptable accuracy (many sensor networks mentioned in §2.2.B implemented these sensors). In addition, a recent study proved how CO, NO and NO2 electrochemical sensors can be used for reliable air quality measurements in the urban environment (Mead et al., 2013).
The sensors work by facilitating a chemical reaction, either reduction or oxidation, which results in a voltage based on the concentration of the pollutant. This registered voltage data is reported as two voltage values, and undergoes a specific conversion, according to a calibration curve.
The cost of a single sensor is about $210; because each node has four, the cost of the gas sensor per node is about $840.

Besides the sensing component, every monitoring node has other infrastructures that were built to hold together the sensors (a 3D-printed case), to store the data gathered, and to transmit the data to the server (a printed circuit board, PCB, and a Raspberry Pi computing unit). Power supply for all nodes, and a waterproofing box for the 17 outdoor locations were added.
The final cost per node is $1.345 (Clairity, 2014, p. 49)

As can be noted, the cost of the overall sensing node is quite low compared to a governmental monitoring station (which can cost about $100,000), as the unit sensors, such the Dylos for PM, cost much less than a particulate mass concentration (such as FDMS-TEOM 1405-F, which alone costs $24600) (Snyder et al., 2013, p. 11372).

Strengths and challenges of such low-cost sensing, in particular in relation to the reliability of mapping air quality, will be discussed in the next chapter.

Transparency and publicity

As data is collected by the sensing node installed in the selected locations, as a stationary sensor network, without the contribution of data from users, there is no privacy issue connected to this project. Data is automatically gathered, and no direct involvement from people is required, neither for providing complementary data nor for exposure test campaign.

Transparency and publicity were clear objectives of the project, and because it pertains to pollution exposure and health issues, which can create misinterpretation or "panic", an effective and optimal communication strategy was needed. However, the main objective of the communication design was focused on raising awareness of the air quality situation within the campus (expected to be critical in certain conditions, see cap.5).
The Clairity project designers decided on the creation of various informational displays, such as articles in MIT magazines and newspapers, and two interactive screen displays with the website installed within the campus. Additionally, an exhibit in the MIT Museum was created and installed (summer 2014). An email address, clairity@mit.edu, was also established to provide an outlet for public questions and feedback.

The main component of the communication strategy, however, was the website; its objectives included: establishing a database for collected data that the website would draw from; converting the raw data into a readable and understandable form; conveying the importance of the data users would see, and displaying the information from the air quality sensor network in an aesthetically pleasing way. The finalized site therefore consists of several pages, with the homepage showing a map of MIT's campus, and all of the air quality nodes on campus ("Clairity: MIT's Air Quality Network," n.d.).
The option to download a CSV file of the data is made available for personal analysis. Urban climate data, temperature and humidity, were not included in the website, either for mapping or for downloading.
Each node is colored in red, yellow and green (good, moderate, unhealthy), with specific designed thresholds.
In fact, as already mentioned, data from low-cost optical sensors are not directly comparable to governmental data for particulates, and a decision had to be taken in defining a specific "air quality index". Therefore, the colors shown on the map in real-time are a consequence of the thresholds defined.

Challenges regarding the effectiveness in communicating air quality data, the completeness of the information, and issues with the transparency of the air quality index in the map will be discussed in the next chapter.

4.2. FIELDWORK DESIGN AND IMPLEMENTATION: HIGH-RESOLUTION MOBILE AIR SENSING AT MIT CAMPUS

Because the case study of Clairity was not able to cover all the research questions of this work, the research strategy included fieldwork aimed at exploring the remaining challenges and limits of sensing for urban climate and air quality mapping.
In particular, the opportunity for sensing to improve the scale was explored by the local sensing network, while improving resolution required mobile sensing.
As previously mentioned, Clairity project included the idea of improving resolution by installing nodes on moving vehicles, but the challenges with this process and data gathering determined its exclusion from the final delivery.
Additionally, urban climate data, such as temperature and humidity included in Clairity, was not addressed in the project, as it did not reliably represent ambient outdoor air (but rather the air inside the node for calibration).
Therefore, a mobile sensing project was designed and implemented by the author, as described in the following sections, stressing resolution and other themes of the research questions (except for the fourth question regarding transparency, privacy and participation, which it not applicable due to the experimental nature of the fieldwork, involving only the researchers collecting data).

4.2.A – Planning spatial and temporal scale and resolution
4.2.B – Selecting cost and technology: literature review of existing sensors

4.2.A - PLANNING SPATIAL AND TEMPORAL SCALE AND RESOLUTION

- Spatial and temporal scale
- Spatial and temporal resolution

Spatial and temporal scale

The spatial scale of the project was planned in coherence with Clairity network: the MIT campus area was considered, including both the east and the west campus, which combined cover about 1 square kilometer, with the east part being mostly residential (dorms) and green (sport fields), and the west areas mostly research centers.
The measurements from the mobile sensing were planned to be comparable with both data from the governmental monitoring stations, and data from Clairity network.

Since mobile sensing relates to measurements done by the sensor while moving within the area, a defined path was necessary to be planned. The definition of the path included consideration about the spatial resolution of the sensing. See next section.

As for the temporal scale, the planned scale was also selected in order to have comparable data with other sources. However, while Clairity is a network functioning since its launch in May 2014, and the governmental data has been collected for decades, and is still running, the mobile sensing exploration was limited in the time scale. For the purpose of this research, only a few selected days were considered (May-June 2014), while future work might include the implementation of permanent mobile sensing (in the case of MIT area, as originally planned, or other locations).
The purpose of the fieldwork in this work, in fact, was not specifically to monitor air quality in the campus with mobile measurements, but to explore the potential of mobile sensing for future implementation (on vehicles, or more interestingly through people's sensing, see later), or to explore the limits for assessing its bail out.

Spatial and temporal resolution

The spatial representativeness and resolution was already mentioned to be one of the main advantages of mobile sensing. Few projects monitor air quality with mobile sensing, and as mentioned in § 2.2.B the one in Zurich and Lausanne is the most successful, yet with several challenges. For instance, the sensors are installed in public transportation vehicles with a defined route, and the opportunity for improving resolution is compromised by having limited coverage in the city.
In the original idea of Clairity mobile sensing on an MIT shuttle, the path was also inevitably limited by the bus route.
The fieldwork was planned ensuring that most of the campus was covered, in order to provide a "high" resolution for a more reliable air quality mapping at the local scale. Having measurements at a "high" pace increases the representativeness of the pollutants concentration observed in those points in the surrounding urban environment (see next chapters about "proper" "high" resolution definition).
Again, the objective of air quality mapping at a high resolution was to get an idea of how pollutants concentration vary within the campus, and theoretically, how their emissions dilute in the air and travel over space.
In addition, it is likely that some of the main air pollutant sources include busy street intersections and street segments of high traffic flow, and the stationary sensing network is not capable of detecting their exact location, being already pre-selected in selection (as described in the previous section, selecting the location of a stationary sensor, especially at the local scale for a local scale study, is a challenging aspect with little literature available for recommendations).
Assessing urban climate, in terms of humidity and temperature, was also included, since the measurements from Clairity were not representative of the ambient air (see next chapter for discussion).

From a spatial point of view, all major roads and paths were included in the definition of the coverage, in order to comprise all the possible locations of a pedestrian moving or standing outdoors within the campus. Figure 4-3 shows the geometrical network built in order to plan the fieldwork sensing.
A limited indoor path was included, as some Clairity nodes are installed in indoor locations; however, the overall interest of the fieldwork and of this research, is the outdoor air pollution and urban climate mapping, in relation to outdoor exposure.

Figure 4-3
Mobile sensing path within the MIT campus. Red lines represent indoor paths while red triangles represent indoor sensing nodes. The circle corresponds to the main entrance of the campus. Source: author's elaboration.

In the design process of the path, the problem of covering all the network tracts with the least amount of travels was addressed, in order to have the same density of measurements per tract. In mathematics, it is referred to as the "Chinese postman problem" methodology, or route inspection problem: finding the shortest closed path or circuit that visits every edge of a (connected) street network (Edmonds and Johnson, 1973). A first tentative route was designed, although modification occurred in the presence of vertices with even degrees and in the presence of some obstacles (building sites).

Designing the temporal resolution for mobile sensing was conducted considering the minimum significant interval of measurements. However, two large variables influenced the temporal resolution definition: device technology and velocity of the sensing.
Device characteristics, also in terms of limitations of "logging time" (interval between to measurements) are later described in the next section. The velocity of the planned mobile sensing is clearly connected to the spatial resolution required.
Therefore, in order to get the highest possible spatial resolution, two considerations were made:
-the minimum logging time of the devices is usually 1 second

-the spatial resolution of data logged by a sensor on a moving vehicle (car or bike) or a moving pedestrian is determined by the velocity.
Therefore, a sensor mounted on a car running at 20km/h velocity would provide a spatial resolution of 5.6 meters, mobile sensing using a bike riding at a speed of 10km/h would provide measurements at a 2.8 pace, and finally, a pedestrian moving around the path with a portable sensing device at about 5 km/h would provide 1.4 meters.
Considering the scale of the project, the area of the campus, the pedestrian option was selected. For larger areas, the biking option can be suitable, according also to the parameters considered. In fact, as detailed in the next chapter, the "proper" resolution depends on the pollutants (or heat) measured, and on the variability of the factors within the area.

Fieldwork design	Notes
Limitations and assumptions	
Assumptions	Mapping UC+AQ parameters using low-cost sensing at the MIT campus. It is assumed that the sensor to be used measures the air condition at the people's scale, even if it does not consider the turbulence and continuous air mixing happening in the urban air.
Limitations	Low-cost technology constrains are considered in data quality and comparability problems (particulates counts and concentration). See § 5.2.B for technical limitations of the fieldwork.
Proposal and method	
Proposal	Measuring UC+AC parameter at a proper scale and resolution, using sensor devices with appropriate affordability and reliability according to specific preliminarily designed criteria.
Method	Literature research of existing devices, designing criteria for testing and selection, testing selected devices, selecting the final device according to specific criteria, execution and data analysis.

Table 4-1
Fieldwork design characteristics. See Table 4-2 for the implementation characteristics. Source: author's elaboration.

4.2.B - SELECTING COST AND TECHNOLOGY: LITERATURE REVIEW OF EXISTING SENSORS

In order to select the sensors to be used in the mobile sensing fieldwork, two strategies can be followed: design a DIY (do-it-yourself) sensor, or buy a commercially available sensor. Many mobile sensing projects described in § 2.2.B include DIY sensors, the most notable being AirCasting ("AirCasting," n.d.) with the detailed description about how to build an air quality sensor step by step, with an open source structure. While the main advantage is to involve hobbyists, to control the device performance, to personalize the unit sensors included, and to ideally limit the cost, many issues occur. In fact even the AirCasting platform itself has recently switched to a commercial available device (AirBeam) because of the limitations of the DIY device, such as the poor design making it less attractive for public participation, technical problems in the electrical connectivity, and comparability of results between users.

- Criteria and review of existing sensors and sensor devices
- Multi-sensor devices, and selection for fieldwork mapping

Criteria and review of existing sensors and sensor devices

The strategy used in the design of the mobile sensing for the fieldwork therefore included buying a sensor device among the ones commercially available, or potentially borrowing from existing devices designed for specific academic projects.

The low-cost attribute was one of the essential criteria for the distinction between the sensors to be considered and the one to exclude from the selection; a maximum of $500 was set to be a valid threshold considering one of the research questions involving the potential of sensing for public participation, and the willingness to pay a participant (affordability and reliability).

While some work considers $2000-2500 as a threshold for defining low-cost sensors (Snyder et al., 2013; United States Environmental Protection Agency, 2014), most of the literature examples consider "low-cost" an air sensor device of costing about $100-500$ (Budde, Busse, and Beigl, 2012; Mead et al., 2013; Northcross et al., 2013; Young, Chapman, Muller, Cai, and Grimmond, 2014).

In fact, the desired device for air quality mapping requires being selected according to the following criteria:

- inexpensiveness: affordability for participatory sensing scenarios (<$500);
- usability: avoiding frequent maintenance and expert calibration;
- compactness: ideally embeddable to existing ubiquitous technology, or comparable and linkable to smartphones;
- accuracy: measuring data with an "acceptable" meaningfulness (see § 5.2 for a discussion about this).
- responsiveness: providing high-resolution data with its timeliness of readings.

Because sensor devices are built using unit sensors, a first review of unit sensors is conducted, in order to select the desired unit component of the device.

The low-cost unit air sensors that are commercially available worldwide share most of the technical characteristics and technology, with different: size, cost, accuracy, sensitivity, and response time.
See glossary for definitions, such as accuracy, sensitivity, and response time.

<u>Urban climate: temperature and humidity sensors for mobile sensing</u>
In particular, considering temperature and humidity unit sensors, the characteristics may vary between:

- size: from 2 to 200 mm (longest dimension);
- cost: from $2 to 70;
- accuracy for temperature: from 0.1 to 3 °C;
- accuracy for humidity: from 1 to 4 RH;
- response time for temperature: from 2 to 30 s;
- response time for humidity: from 2 to 20 s.

See **Annex 2** for a comparative table among the unit sensors considered.

Several studies use and review temperature and humidity devices, mostly for urban climatology studies, such as identifying UHI with mobile sensing (Brandsma and Wolters, 2012; Busato et al., 2014; Buttstädt et al., 2011; Heusinkveld et al., 2010, 2014; Lindberg, 2007). However, the purpose of these studies is mostly focused on a single fieldwork for collecting high-quality data, and high cost and high size instrumentations are generally used. Therefore, they are not considered to be suitable for this research work.
Considering studies specifically focused on mapping urban climate with low-cost sensors, Young et al (Young et al., 2014) compared ASM, Hobo and iButton devices and demonstrated good performance relative to national standards in the laboratory, with accuracy of about 0.22 °C (at -22°C to 30°C).
Taking to the extreme of low-cost and compactness of sensors for mapping urban climate, Overeem et al. (Overeem and Robinson, 2013) demonstrated the potential of using estimates from urban air temperatures measures coming from smartphone temperatures for relatively accurate daily urban canopy layer air temperatures. However, considering the need for a real-time measurement instead of daily data, and considering the need of a high-resolution and local scale objective, this approach is not suitable for the purpose of this work, while still helpful for discussion in § 5.2.
Other devices exist, measuring climate parameters as small plug-ins into smartphone (Shaka weather station) or integrated watches. See **Annex 2** for a brief description.

Moreover, most of the sensor devices used for air quality mapping include temperature and humidity, either for urban climate mapping or solely for the purpose of calibrating the pollution data. See following section.

Air quality sensors for mobile sensing
Considering air pollutants unit sensors, they mainly differ in

- size: from 7 to 70 mm (longest dimension),
- Cost: from 9 to 450$
- Detection limit, Accuracy, sensitivity (high variations among chemical gases sensors and among optical dust sensors).

See **Annex 2** for a comparative table among the unit sensors considered.

Air quality: dust/aerosol/particulate sensors
As anticipated, only low-cost devices under 500$ were considered for the purpose of the fieldwork and this research work. Studies using more sophisticated and expensive portable devices for mobile sensing, such as TSI P-Trak, DustTrak, or Met-One Aerocet, very popular among researches (Elen et al., 2013; Peters, Theunis, Van Poppel, and Berghmans, 2013) were reviewed for comparison in the trade-off between affordability and reliability.

Recognized studies using Dylos for particulate measurements are growing and all investigate the use of this optical dust sensor for fine-particle monitor ((Dacunto et al., 2013; Northcross et al., 2013; Semple et al., 2013). However, besides the accuracy demonstrated (apart from the interpretation issues coming the conversion from counts to mass, see § 5.2), the size of the sensor and its prevalent "stationary" use make it not suitable for the mobile sensing planned for the fieldwork. In fact, besides being low-cost and with an "acceptable" accuracy, the size and weight of the sensor desired requires being relatively small, of about a smartphone (in order to explore the potential use for participatory sensing scenarios).

Other studies using low-cost and portable devices for particulates mostly use and compare the Shiney and the Sharp sensors, two light scattering devices. They share the same operation principle: a light beam is emitted into a measurement chamber, and the presence of particulates alter the light refraction and the amount of light scattered is detected (in some models a heating resistor create an updraft) (Budde et al., 2012; Budde, El Masri, Riedel, and Beigl, 2013; Morpurgo et al., 2012). The biggest challenged of such sensors are calibration procedures and accuracy and comparability of measurements. However, their characteristics make them the unit sensors of most the devices listed in **Annex 2**, considered for the selection process for the fieldwork.

Taking to the extreme of low-cost and compactness of sensors for mapping aerosol, a recent study demonstrated how a project called i-SPEX (collaboration between Leiden Observatory, TU Delft, and private partners) uses massproducible optical add-on for smartphones for delivering crucial information on atmospheric aerosols that is complementary to data from professional instrumentation (Snik et al., 2014). However, while the spatiotemporal resolution and coverage (about 2km regional scale), the aerosol parameters and the quasi-real-time characteristicsare not suitable for this research work, the project's results are useful for discussing the potential of mapping air quality by sensing. See website ("iSPEX: measure aerosols with your smartphone," n.d.) for maps elaborated with the help of this add-on sold at 2.50$ cost).

<u>Air quality: gas sensors</u>
Commercially available low-cost sensors for NO2, NO, CO, and VOC are generally used for safety applications such as detecting CO poisoning. Therefore, few of them are intended to be used in the ppb-range that is relevant for urban air quality, and are generally "metal oxide" or "electrochemical" sensors.
Among them, some unit sensors are popular among researches for mobile sensing studies, aiming at detecting gases, such as CO and NOx, in fieldwork experiments (Crouse et al., 2009; Elen et al., 2013; Tsujita, Yoshino, Ishida, and Moriizumi, 2005).
One of the most the recognized study in the field of low cost mobile sensing for gases is the recent work by Mead et al. (Mead et al., 2013), which demonstrated the use of Alphasense gas sensor for monitoring air quality in mobile and stationary networks.

However, considering issues such as the cross-sensitivity of gases (such as between NO2 and O3), and the overall objective of this research work, focused in mapping air quality for human health exposure, and the impact of particulates on health, fine particulate were chosen as the main pollutant to map in the fieldwork research (see next section).

Multi-sensor devices, and selection for fieldwork mapping
Multi-sensor devices assemble unit sensors in one instrument, with the help of basic infrastructure, mainly: a case, a printed circuit board, and a computing unit (such as Arduino or Raspberry Pi). They can be designed for personal sensing or participatory sensing (in this case, associated to a public web platform). They can be commercially available devices, DIY projects, or devices specifically designed for research projects.
From a technical point of view, they can be designed to be stationary (such as the ones monitoring indoor ambient air), or portable. However, even stationary devices, like the before mentioned Dylos, has been used for mobile sensing when coupled with external battery for power, and are included in this review.

Considering the criteria mentioned in the previous section, all the devices with the desired characteristics were reviewed, in order to select the ones for the fieldwork mapping. In particular, their characteristics vary between:

- what they measure: gases, dust, temperature, humidity, noise, radiation
- size: from 50 to 150 mm (longest dimension)
- cost: from 9 to 450$
- accuracy, sensitivity (according to the unit sensors included)

See **Annex 2** for a comparative table among the devices considered.

After a literature review of the existing devices (see **Annex 2**), in their potential for mapping both urban climate and air pollution for the fieldwork at the MIT campus, the following devices were considered for the fieldwork mapping:

- Sensaris EcoSense ECO2sense, ECO3sense, EcoPMv.1, v.2 and v.3:
- a DIY device commissioned to MIT D-Lab (R. Fletcher), including Alphasense sensors

In fact, those devices resulted appropriate for the purpose of the work, being:

- inexpensive suitable for participatory scenarios (<500$);
- usable: do not require specialist expert calibration and frequent maintenance, easy to use, and both have a mobile App (Mobisense and EcoMobileLive), for real-time data;
- accurate and responsive: preliminary tests showed high-resolution data, and adequate timeliness of readings.

Several tests and experiments were conducted using the devices, in order to assess the accuracy, resulting in a final selection of the EcoPM v.3 device for the fieldwork mapping. See § 5.2 for the analysis of results.

Fieldwork implementation	Notes
Measure and resolution	
Measure	PM2.5, PM10, VOCs, temperature, humidity, latitude and longitude and additional metadata (i.e. indoor/outdoor, presence of local emission source)
Resolution	Time resolution of 1 second, corresponding to a space resolution of about 1.5 meter (distance between each reading, according to speed). Coverage: MIT campus, both east and west areas, see Figure 4-3.
Reliability, cost and technology	
Cost and reliability	Detectable particle size approximately 1µm, time response 1 second, temperature accuracy ±0.3 °C, humidity accuracy ±2-5 %RH, cost: 300$ for the final sensor used (other sensors were preliminary used and tested). See Annex 2 for more detailed info.
Technology	Portable device (121x66x40 cm sixed box), connected via Bluetooth to a smartphone, connected via wi-fi to server for data streaming. Optical light scattering technology for particles detection, and traditional technology for other parameters (see Annex 2 for detailed information about unit sensors)

Table 4-2
Fieldwork implementation characteristics. See table Table 4-1 for the design characteristics. Source: author's elaboration.

4.3. COLLABORATION WITH 'MAPPING BY SENSING' PROJECTS AT SCL-MIT

As mentioned in the research methodology, while collaborating with Clairity and while designing and executing the fieldwork, exploring mapping by sensing project was considered necessary in order to gain a better understanding of the strengths and challenges of sensing, for both the fieldwork design and the data analysis and interpretation. For example, since data from sensing has the characteristics of "big data", mapping by sensing requires big data analysis comprehension and interpretation of the resulting urban pattern (i.e machine learning techniques).
More generally, sensing and mapping for air quality and health, and most of the issues of scale and resolution, cost and technology are shared among "sensing" projects, and the collaboration was directly beneficial for this work for exploring the opportunities and limitations, and its possible future development.

4.3.A – Sensing and mapping for air quality and health
4.3.B – Sensing and big data analysis for mapping urban patterns

4.3.A - SENSING AND MAPPING FOR AIR QUALITY AND HEALTH

- One Country Two Lungs: mapping air quality and urban climate in Hong Kong
- Underworlds: mapping human health by smart sewage

One Country Two Lungs: mapping air quality and urban climate in Hong Kong

The collaboration with the "One Country Two Lungs" project was temporally restricted to the final part of the process", in a limited contribution in preparing the materials for the launch of the project, in February 2014 ("One Country Two Lungs," n.d.), under the supervision of Rex Britter and Carlo Ratti.
The project aimed at assessing air quality and urban climate in Hong Kong and Shenzen, a metropolitan area where 17.4 million people live, with two cities very close to each other but with different air pollution. In fact, congested streets, air conditioners, and the coal-powered electricity plants on mainland China create pollution, and tall buildings sequester stagnant air that is artificially warmed by the urban heat island, exacerbating the condition. Researchers estimate that air pollution costs Hong Kong about USD$2.4 billion a year in hospital admissions and lost productivity (Hedley et al., 2008). However, while being very close, Hong Kong and Shenzhen are split by a national border, separating China and its Special Administrative Region, and environmental conditions are different consistently across the border, even though it is porous to the thousands of citizens who regularly commute from one side to the other, and the air quality different is not "visible".
The project used low-cost mobile sensor devices, such as EcosensePM and Dylos, to measure temperature, humidity and air pollutants concentration (PM10, CO,

NO2) carried by a "human tracer", walking around the two cities and crossing the border.

The potential of mobile sensing is revealed in the results showing the differences in temperature and air pollution at the local scale and a high resolution, even though the focus of the project was on the metropolitan scale difference between the two cities. Potentially, it was possible to map the air quality and urban climate for the overall area by moving around in space for a certain amount of time, while, for the purpose of the project, the mapping process was conceived as an augmented reality video showing the variation of temperature, humidity, PM10, CO, NO2 (and noise), for a limited path.
However, strong limitations occurred when data analysis was carried out. In fact, the sensors used had discordant measurements values about particulates, while temperature and humidity showed consistent results. This discordance was due to a number of factors, mainly two: the low accuracy of the devices, in particular of the EcosensePM, and the different characteristics, "particulate counts" for Dylos sensor, and "particulate concentration" for EcosensePM. In fact, while particulate counts can theoretically be converted into mass, obtaining a concentration, issues with the reality of particulate composition occur, and the conversion is problematic. See § 5.2 for a discussion about the literature debate on particulate sensing with low-cost devices.

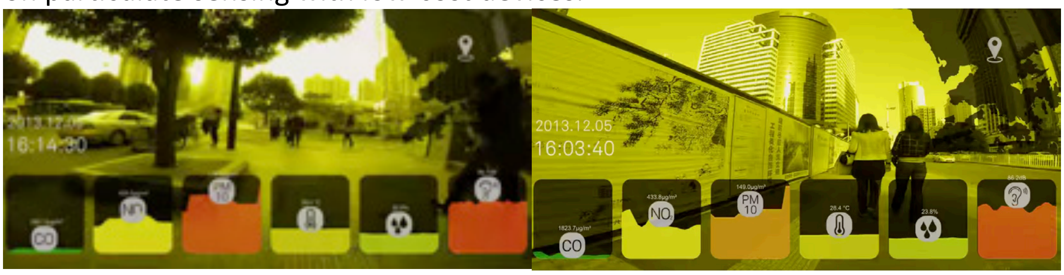


Figure 4-4
Two screenshot of the video about the MIT-SCL project "One country – two lungs". The map at the up-right corner shows the location of the measurements, which are displayed at bottom. While moving in space and time, air pollutant concentration, temperature and humidity vary according to the measurements monitored by the mobile sensors. Source: project's website ("One Country Two Lungs," n.d.)

Underworlds: mapping human health by smart sewage

The collaboration with "Underworlds" project started with a proposal of a smart sensing sewage infrastructure for Kuwait City, under the supervision of Carlo Ratti and Yaniv Turgeman. The project idea, which later won and awarded $4m in funding, was a real-time mapping of epidemiology through the collection and analysis of samples (biomarkers as sensors) in the city sewage system. Sewage, in fact, contains a vast reservoir of information from excreted biomarkers of endogenous human metabolism that directly reflects the exposure and stressors of urban community and their health.

While a large prototype is set to be implemented in Kuwait City in 2017, in partnership with Kuwaiti stakeholders including the Ministry of Health, Boston will be the first city to trial a "smart sewage" prototype in 2016.
The contribution to this project was therefore centered in mapping community health characteristics in the Boston area, including Cambridge, Charlestown and Brookline, and the definition of the scale and resolution of the sensing network. A test campaign was conducted in Boston and Cambridge, 2 real-time sample locations, and it preliminary results showed how influenza virus was detected earlier than the day the first hospital spotted the disease.
In fact, the possibility of deploying sensors to quantitatively measure these specific biomarkers in sewage from communities might allow a new approach to the study of cities and their urban environment, people and technology, and a proper sensing network need to be designed. Developing biomarkers as sensors both for psychoactive substances and health and lifestyle factors is a recent and emerging research topic aimed at pushing the boundaries of genomics and epidemiology. Community drug testing via the analysis of drugs metabolites in sewage, referred to as "sewage epidemiology", has been used in the estimation of drug use in specific cities in Europe, North America, and Australia (Reid, Harman, Grung, and Thomas, 2011). Specific biomarkers have been proposed for a real-time estimation of small-area population ((Daughton, 2012a), while more recent techniques, such as using isoprostanes, have been proposed as potential biomarkers to measure the collective and systematic oxidative stress response of an entire community as a wider measure of community health ((Daughton, 2012b). Ongoing research, such as the European COST 054/13, also aims to increase the space-time resolution of the sewage analysis approach, while recognizing the importance of integration between epidemiology and social sciences ((European Cooperation in the field of Scientific and Technical Research, 2013).

In order to build a local sensor network, it is necessary to go beyond traditional single-disciplinary approaches. Identifying the relationship between the "underworld" and the surface urban world and people, requires bringing together scientists with an integrated analytical approach at the urban scale. In particular, three different components, belonging to different disciplines, can be highlighted as essential for understanding sewage behavior and people, the physical engineering infrastructure of the sewage, its network grid topology model, and the characteristics and demographics of the communities contributing to the wastewater flow.
The collaboration was focused on the multi-component aspect of the sensing network, in both local scale and high-resolution design. A geospatial and demographic analysis was built to understand the variation of variables over space and time, according to three different parameters:
1. <u>Physical/geographical condition:</u>
Sewage behavior is influenced by and need to be explored in terms of engineering and urban planning components: sewers' physical characteristics and typology (i.e. separated and mixed with rain drainage), access points and

nodes (i.e. valves, pumps), geographic morphology (i.e. slope, waterlands), land use (i.e. residential, industrial, commercial).

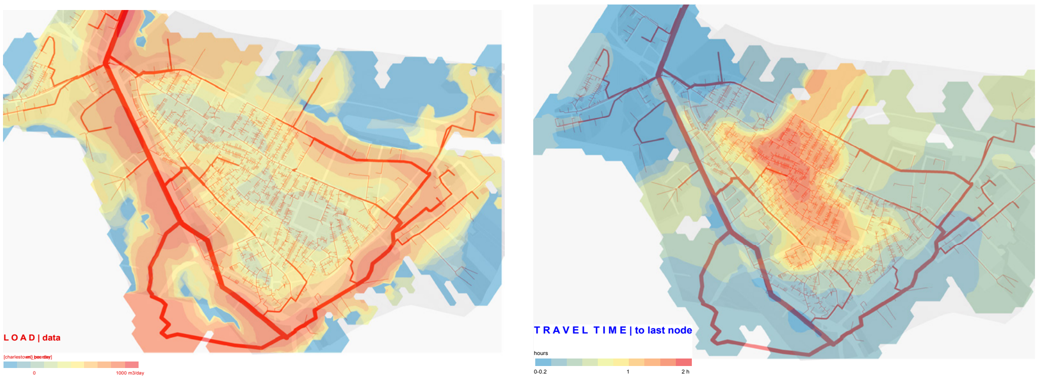


Figure 4-5
Mapping undersurface flows (load and travel time) in Charlestown, Boston, MA. Source: Author's elaboration.

2. Network topology:

A network topology analysis is necessary in order to understand the sewage behavior and the wastewater flow: the network connectivity influences the sewage, going from a "linear model" to power law complexity, and fractal structure (i.e. analysis of number of incoming and outgoing pipes per nodes, initial load by distance). A mathematical hierarchy analysis can detect self-similarity within the network (i.e. pipe length and nodes by total incoming load).

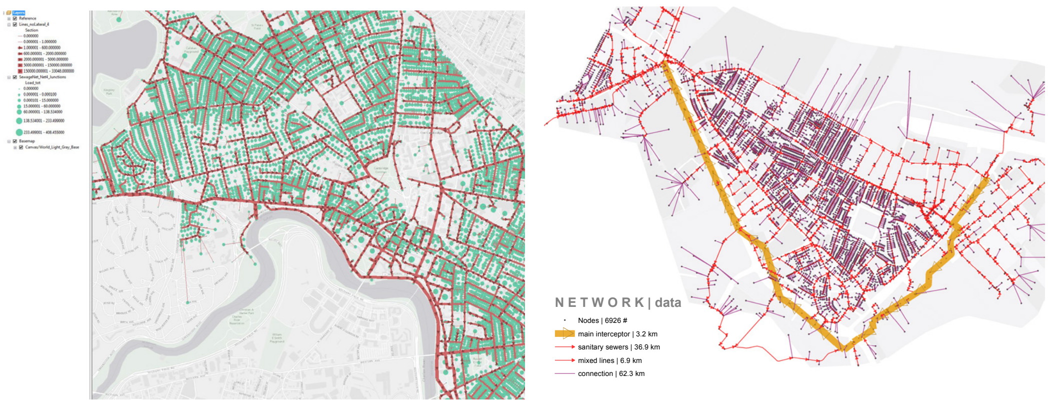


Figure 4-6
Exploring network topology and sensor displacements in Cambridge, MA, and Charlestown, Boston, MA. Source: Author's elaboration.

3. Urban conditions:

Thirdly, exploring the characteristics and demographics of the population living a specific catchment area is essential to fully understanding the sewage sampling results. In fact as evidenced by recent literature (Daughton, 2012b) sewage wastewater is influenced by people's genetic features (i.e. metabolism, gender, "ethnicity"), people's lifestyle (i.e. age, diet, hygiene, income, mobility, cooking habits, water consumption), and environmental factors (i.e. weather, seasons). Social science and urban planning approaches help reveal the distribution of those variables over neighborhoods and ultimately over a city.

Figure 4-7
Mapping demographics in Charlestown, Boston, MA. Source: Author's elaboration.

The potential of this project is high, and an integrated research approach with a focus at the urban and community scale, and with the help of an appropriate sampling strategy with optimal sampling locations and frequency, can lead to the modeling of the sewage network and the people who use it. Scale and resolution need further research, in order to link the representativeness of a sample, and the community living in the catchment area (Figure 4-7). Various outcomes are reachable from this perspective, using theoretical models and GIS analysis. A real-time smart sewage network can act as a surveillance system in detecting potential sewage leakage, illegal connection, and behavior during heavy rain/flooding. Furthermore, it can correlate wastewater flow and mobility of people's presence over time among different urban areas (i.e. traffic network, mobile phone tracking); with the help of anonymous health records from local hospitals (i.e. recent epidemic data), the system can also explain how epidemics spread across neighborhoods in the city over time, and inform strategies for deploying medications and quarantine.

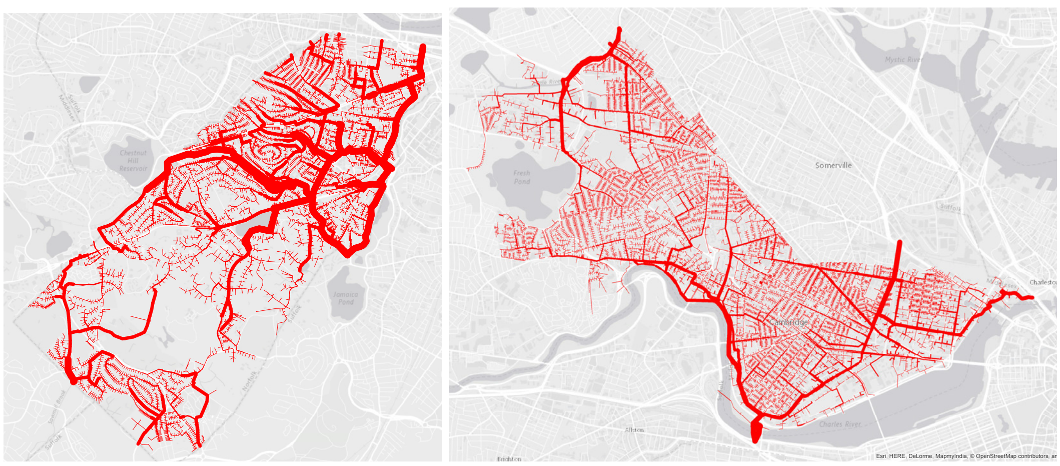


Figure 4-8
The sewage network of Brookline (left) and Cambridge (right), Boston area. Source: Author's elaboration.

However, some concerning challenges can be underlined.

Firstly, a challenge common to air sensing, the representativeness of the samples and the proper resolution required in order to perform a reliable mapping. In fact, while air quality depends on factors related mainly to urban morphology, weather and emissions, health data coming from the sensors depend on the 3 conditions above mentioned, which are more challenging to measure at the local scale and at the proper resolution. Preliminary mapping processes, in fact, included modeling for "network topology" and modeling for "physical/geographical" (i.e. wastewater flow) at a small resolution (1m). However, "urban condition" had different scale and resolution: data form the parcel division file has the smallest scale and resolution available (about 1 family building) while demographics data comes from the minimum census districts available (about 20 parcels each), and land use data comes from urban planning zoning plan (variable).

Finally, temperature or rainfall data was collected from a regional scale weather station.

It is therefore clear how mapping by sensing samples from the sewage is a complex process, which require further investigation. Figure 4-9 shows a tentative algorithm designed to select sample location according to the same level of representativeness desired (i.e. 100 inhabitants with same ethnicity, age, gender, income ratio).

Figure 4-9
Representativeness and optimal resolution study for Charlestown, Boston, MA. Source: Author's elaboration.

The last consideration brings to another challenge, regarding the use of health data coming from the sensing process and their representativeness of an individual, a family or a community living in the catchment area of the sample.

Privacy issues arise, as data is not connected directly at people's location but the modeling component potentially identifies the source. Since mapping will show different health conditions within the urban environment, a potential connection of some diseases with specific social enclaves might arise ethical concerns in the usage of data. It is likely that human microbiome travels along the city and "contaminate" different areas with commuting, making demographics data unreliable. However, a future sophistication of the model could include mobility pattern from mobile phone tracking in order to combine people presence and data collected.

This final aspect is common to air quality and urban climate sensing: it is essential to map pollutants and heat concentration in the urban areas although the hotpots are put in relationship with people presence. In fact, central business district or university area might have few residents in the census data, but high people density during hot and polluted days. See § 6.1.B for more about this.

4.3.B - SENSING AND BIG DATA ANALYSIS FOR MAPPING URBAN PATTERNS

- Citivan: a mobile sensing project for mobility and air quality in Cape Town
- Big data and urban spatial patterns

Citivan: a mobile sensing project for mobility and air quality in Cape Town

The collaboration with Citivan project was aimed at understanding the potential of sensing technology (low-cost) in a developing country context, with scarcity of resources and emerging urban problems, such as air pollution and urban climate, and other health and environment concerns (traffic congestions, safety). A proposal for ideas on how to improve mobility and air quality was requested by the Cape Town Transportation Authority, and the team at Senseable City Laboratory developed a sensing project.
The contribution to project, conducted under the supervision of Assaf Biderman, associate director of SCL), was focused on exploring the potential of sensing with low-cost scenarios, using existing infrastructure and considering the social and political background of Cape Town.
The existing infrastructure considered for installing the sensing component was the shared buses transportation system, also called minibustaxi (MBT). After an extensive literature review and several interviews with locals, the complex mobility situation of the city emerged. MBT are the main mean of transportation, and they inefficiently all run from suburbs ("townships") to the city center, creating traffic congestions and consequent air pollution concentration. Thanks to the 2010 Worldcup and recent enhancement in the public mobility systems, new rapid bus transit (BRT) are being deployed, yet covering only the central business part of the city, which is the least populated and serves the highest income area (see Figure 4-10).

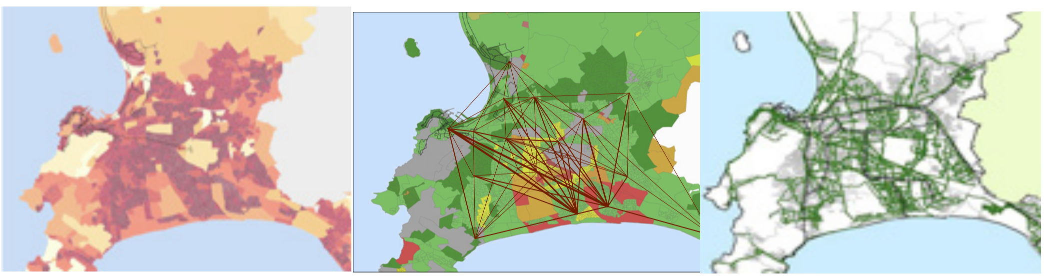


Figure 4-10
The public bus network overlapped to a population density heatmap map (left), and a social-income index map (center). The network represents the desired movements, form townships to the central business district, north-west. On the right, the shared minibus network of Cape Town: since it covers all urban areas, sensing can create the opportunity to improving and formalizing within the public system. Source: Author's elaboration.

According to four tiers of the proposal, GPS, accelerometer and air quality sensors could be installed in the minibutaxis at low cost, therefore collecting data that would ultimately improve performance and accountability of the systems, and improve quality of life in Cape Town.

While there are still not prototypes or data about its expected success, the Transport Authority of Cape Town later accepted the project proposal, and is going to implement a partial version of it, as a pilot project in 2015.

The potential of this idea can be underlined by the fact that mapping by sensing could help improving MBT challenges (illegality, public disorder, overtrading, un-safety) by top-down process generated by sensing (tracking and monitoring). At the same time, a bottom-up process is enhanced by a faring and rating system that involve citizens requiring for a better quality, while keeping the opportunity of the MBT (accessibility, frequency, availability, flexibility).
The low-cost aspect is also a remarkable strength of this project for the diffusion of sensing, especially in a limited resource context of a developing country. Pervasive sensing is therefore useful to get local scale and high resolution information about the urban metabolism, in this case, people's mobility and air pollution. See § 6.1 for more discussion and considerations about this.

Big data and urban spatial patterns

Several projects puts emphasis on the shift from modeling to sensing, from making sophisticated models to analyses of big data for unexpected insights. In fact, as a collective, humanity produces five zettabytes of data every year and scientists and even scholars of the humanities are conducting studies to reveal unprecedented results (Aiden and Michel, 2013).

In the field of air quality, for instance, it is possible to interfere urban traffic pollutants concentration, such as NOx, by using a proxy with digital data coming from mobility, such as cars counts in traffic regulated central areas, gps-equipped taxi's data, etc. The 'power of big data' ("BBC News - Power of Big Data," n.d.) can therefore help understanding the relationship between the spatial structure of the city and the citizens' behavior.

The collaboration with the big data team at SCL was therefore aimed at exploring the potential coming from sensing data, by mapping using big data tools. In fact, as mentioned in § 2.3, besides direct sensing, indirect and opportunistic sensing can provide useful data for mapping urban spatial characteristic, such as pollution. The contribution to the team was aimed at mapping big data coming from economic transaction in order to find unexpected insights, such as preferred locations and in particular, if there was a connection between sales and urban centrality. In fact "urban centrality" has been used to study the spatial structure of human activity patterns (Zhong, Schläpfer, Arisona, and Ratti, 2014) or specifically to reveal the correlation between street centrality indices and economic activities location (Porta et al., 2012). Mapping Barcelona and Seville geo-tagged bank transactions from economic activities (such as bar, restaurants, hotels and all transaction made by POS), and mapping urban centrality indices, such as "clonesess", "betweenness" and "straightness", it was possible to get new insights. In fact, preliminary mapping results shows that, while the location of activities have strong connection with centrality, the sales volumes do not follow the same pattern. Further research will better explore the correlation with different categories of activities, in order to reveal possible different patterns, such between retails and food shops.

Figure 4-11
Mapping big data for exploring urban spatial pattern: Seville (Spain) urban centrality indices (closeness and betweenness, 1st and 2nd map) and correlation with activities locations (3rd map) and low correlation with sales volumes (4th map). Tools: ArcGIS and Matlab. Source: Author's elaboration.

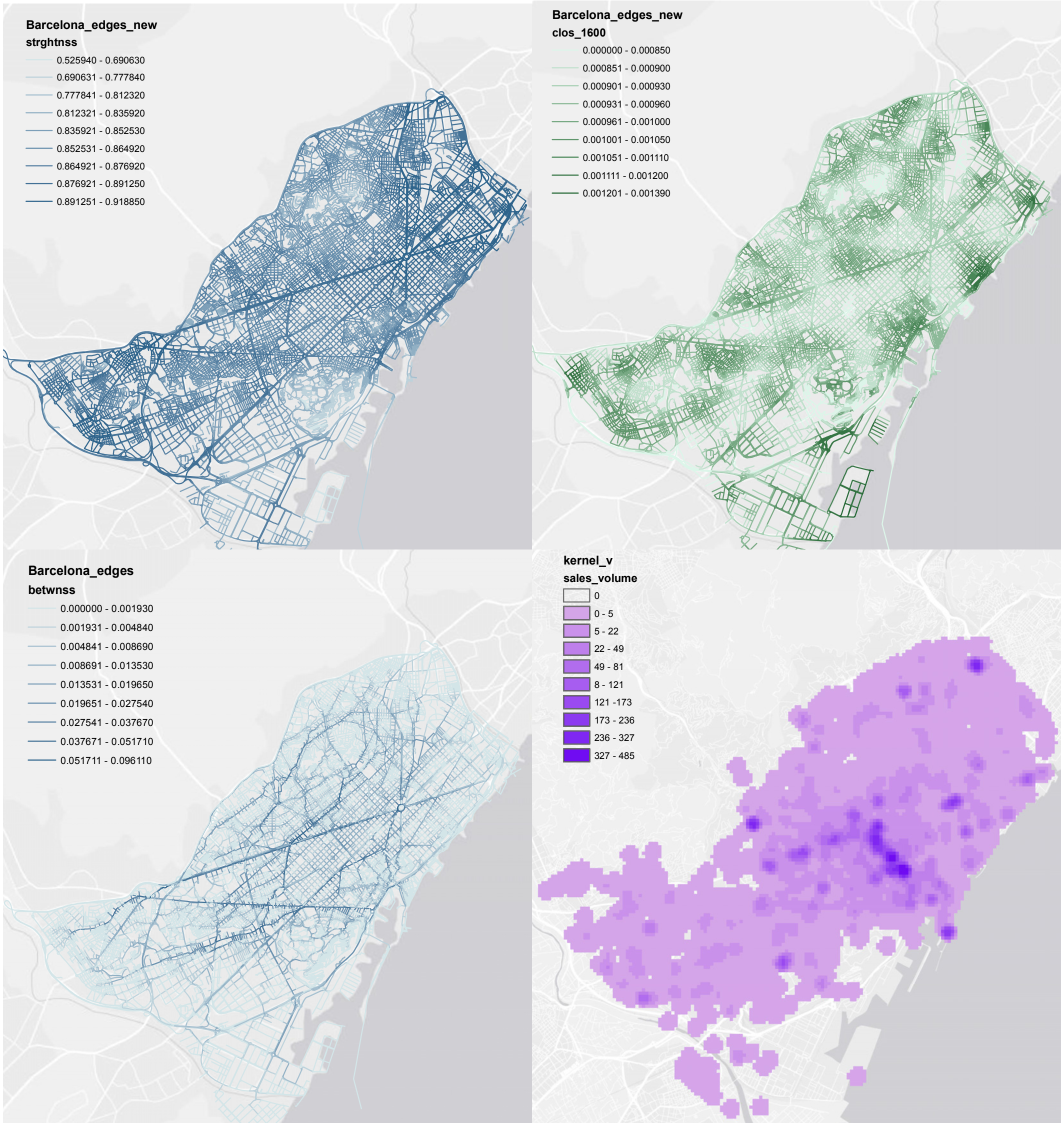


Figure 4-12
Mapping big data for exploring urban spatial pattern: Barcelona (Spain) urban centrality indices (straightness, closeness 1600,m and betweeneness, 1st and 2nd and 3rdmap) and correlation with activities sales volumes (4th map). Tools: ArcGIS and Matlab. Source: Author's elaboration.

Other mapping by sensing projects at SCL use massive data steams from user-generated content, such as social networks for exploring behavioral dynamics (Michael Szell, Grauwin, and Ratti, 2014), or taxi trips, for exploring the benefits of vehicle pooling with sharebility networks (Santi et al., 2013).
Another project uses data from users visiting public spaces, such as the Louvre museum, by using Bluetooth sensors installed to track people's inside the building, in order to map the paths pattern (Yoshimura et al., 2014). Similar tracking approach, with a different technology, was used in a different way in the Local Warming project, a vision of architectural climate control presented at the 2014 Venice Architecture Biennale. The installation included responsive infrared heating elements guided by motion tracking, creating a precise personal (and personalized) climate for each occupant, with an individual thermal 'clouds' following people through space ("Local Warming," n.d.).

Strengths of big data coming from sensing are the opportunity to explore large datasets from multiple sources and harnessing data for new insights into the spatial pattern within the urban environment. In some cases, it could be a low cost complement to traditional research, such as air pollution estimated for fast growing cities where urban reliable air data is not easily available.

However, challenges emerge to this quantitative assessment of urban patterns from big data. While privacy violation or intrusion raises the highest concerns (see ch. 5 and 6 for more about this), the partiality of data and their partial representativeness of people's pattern is often questioned in studies using social network data.
Additionally, bid data analysis might lead to loose sight of the informal reality of the city. Urbanization might very often not show on maps and charts, and the informality of cities can represent a substantial reality neglected by big data studies, which can lead to misinterpretation of results. In the ahead mentioned project, for example conclusions made using data from bank transactions do not consider informal sales, under the table pay, informal street vendors, or cash payments.

Conclusion

This chapter described the research steps involved in this work: the collaboration with an innovative local sensing project (Clarity), the fieldwork design and implementation (mobile air sensing at MIT campus) and the collaboration with “mapping by sensing” projects at SCL-MIT.

A critical review of the projects led to preliminary observation on the opportunity and challenges of sensing for urban climate and air quality mapping. For example, issues in representativeness of the sensing node locations were found. In addition, in selecting the sensor device for the fieldwork, numerous unexpected problems arose, such as data quality and data comparability with governmental data (i.e. for PM). Annex 2 included an overview of the most relevant mobile sensing available devices for mapping urban climate and air quality.

Data analysis from the measurements collected in the local sensing project collaboration and in the mobile sensing fieldwork is presented in the next chapter.

References

Aiden, E., & Michel, J.-B. (2013, December). The Predictive Power of Big Data. *Newsweek*. Retrieved from http://www.newsweek.com/predictive-power-big-data-225125

AirCasting. (n.d.). Retrieved December 29, 2014, from http://aircasting.org/

BBC News - Power of Big Data. (n.d.). Retrieved December 03, 2014, from http://www.bbc.com/news/business-29147254

Brandsma, T., & Wolters, D. (2012). Measurement and statistical modeling of the urban heat island of the city of Utrecht (the Netherlands). *Journal of Applied Meteorology and Climatology*, *51*(6), 1046–1060. doi:10.1175/JAMC-D-11-0206.1

Budde, M., Busse, M., & Beigl, M. (2012). Investigating the use of commodity dust sensors for the embedded measurement of particulate matter. *Networked Sensing Systems (INSS), 2012 Ninth International Conference on Networked Sensing*, 1–4. doi:10.1109/INSS.2012.6240545

Budde, M., El Masri, R., Riedel, T., & Beigl, M. (2013). Enabling Low-Cost Particulate Matter Measurement for Participatory Sensing Scenarios. In *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia (MUM 2013)*. doi:10.1145/2541831.2541859

Busato, F., Lazzarin, R., & Noro, M. (2014). Three years of study of the Urban Heat Island in Padua: Experimental results. *Sustainable Cities and Society*, *10*, 251–258. doi:10.1016/j.scs.2013.05.001

Buttstädt, M., Sachsen, T., Ketzler, G., Merbitz, H., & Schneider, C. (2011). A new approach for highly resolved air temperature measurements in urban areas. *Atmospheric Measurement Techniques Discussions*, *4*(1), 1001–1019. doi:10.5194/amtd-4-1001-2011

Clairity. (2014). *An Air Quality Sensor Network for MIT ' s Campus* (p. 74). Retrieved from http://clairity.mit.edu/site/documents/report.pdf

CLAIRITY: MIT's Air Quality Network. (n.d.). Retrieved December 29, 2014, from http://clairity.mit.edu/site/html/

Crouse, D., Goldberg, M. S., & Ross, N. A. (2009). A prediction-based approach to modelling temporal and spatial variability of traffic-related air pollution in Montreal, Canada. *Atmospheric Environment*, *43*(32), 5075–5084.

Dacunto, P. J., Cheng, K. C., Acevedo-Bolton, V., Klepeis, N. E., Repace, J. L., Ott, W. R., & Hildemann, L. M. (2013). Identifying and quantifying secondhand smoke in multiunit homes with tobacco smoke odor complaints. *Atmospheric Environment*, *71*, 399–407. doi:10.1016/j.atmosenv.2013.02.018

Daughton, C. G. (2012a). Real-time estimation of small-area populations with human biomarkers in sewage. *The Science of the Total Environment*, *414*, 6–21. doi:10.1016/j.scitotenv.2011.11.015

Daughton, C. G. (2012b). Using biomarkers in sewage to monitor community-wide human health: isoprostanes as conceptual prototype. *The Science of the Total Environment*, *424*, 16–38. doi:10.1016/j.scitotenv.2012.02.038

Dylos DC1100 Professional Air Quality Monitor. (n.d.). Retrieved December 04, 2014, from http://www.dylosproducts.com/ornodcproair.html

Edmonds, J., & Johnson, E. (1973). Matching, Euler tours and the Chinese postman. *Mathematical Programming*. Retrieved from http://link.springer.com/article/10.1007/BF01580113

Elen, B., Peters, J., van Poppel, M., Bleux, N., Theunis, J., Reggente, M., & Standaert, A. (2013). The Aeroflex: A bicycle for mobile air quality measurements. *Sensors (Switzerland)*, *13*, 221–240. doi:10.3390/s130100221

European Cooperation in the field of Scientific and Technical Research. (2013). *Sewage biomarker analysis for community health assessment* (pp. 1–25). Retrieved from http://w3.cost.eu/fileadmin/domain_files/ESSEM/Action_ES1307/mou/ES1307-e.pdf

Hedley, A. J., McGhee, S. M., Barron, B., Chau, P., Chau, J., Thach, T. Q., … Wong, C.-M. (2008). Air pollution: costs and paths to a solution in Hong Kong--understanding the connections among visibility, air pollution, and health costs in pursuit of accountability, environmental justice, and health protection. *Journal of Toxicology and Environmental Health. Part A*, *71*(9-10), 544–54. doi:10.1080/15287390801997476

Heusinkveld, B. G., Steeneveld, G. J., van Hove, L. W. a., Jacobs, C. M. J., Holtslag, a. a. M., & Hove, L. W. A. (2014). Spatial variability of the Rotterdam urban heat island as influenced by urban land use. *Journal of Geophysical Research: Atmospheres*, *119*(2), 677–692. doi:10.1002/2012JD019399

Heusinkveld, B. G., Van Hove, L. W. A., Jacobs, C. M. J., Steeneveld, G. J., Elbers, J. A., Moors, E. J., & Holtslag, A. A. M. (2010). Use of a mobile platform for assessing urban heat stress in Rotterdam. In *Proceedings of the 7th Conference on Biometeorology, Freiburg, Germany* (pp. 433–438).

iSPEX: measure aerosols with your smartphone. (n.d.). Retrieved December 31, 2014, from http://ispex.nl/en/gallery/

Lindberg, F. (2007). Modelling the urban climate using a local governmental geo-database. *Meteorological Applications*, *14*(3), 263–273.

Local Warming. (n.d.). Retrieved December 07, 2014, from http://senseable.mit.edu/localwarming2014/

MassDEP:: Air & Climate :: Air Quality & Monitoring :: MassAir version 1.5. (n.d.). Retrieved December 06, 2014, from http://public.dep.state.ma.us/MassAir/Pages/MapCurrent.aspx?pm=88502&ht=1&hi=102

Mead, M. I., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., … Hodgson, T. F. (2013). The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, *70*(5), 186–203.

Morpurgo, A., Pedersini, F., & Reina, A. (2012). A low-cost instrument for environmental particulate analysis based on optical scattering. *… Conference (I2MTC), 2012 …*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6229220

National Ambient Air Quality Standards (NAAQS) | Air and Radiation | US EPA. (n.d.). Retrieved December 28, 2014, from http://www.epa.gov/air/criteria.html

Northcross, A. L., Edwards, R. J., Johnson, M. A., Wang, Z.-M., Zhu, K., Allen, T., & Smith, K. R. (2013). A low-cost particle counter as a realtime fine-particle mass monitor. *Environmental Science: Processes and Impacts*, *15*, 433. doi:10.1039/c2em30568b

Oke, T. R. (2004). *Initial guidance to obtain representative meteorological observations at urban sites*. *geog.ubc.ca* (Vol. 81). World Meteorological Organization Geneva. Retrieved from http://www.geog.ubc.ca/~toke/IOM-81-UrbanMetObs.pdf

One Country Two Lungs. (n.d.). Retrieved December 03, 2014, from http://senseable.mit.edu/twolungs/

Overeem, A., & Robinson, J. R. (2013). Crowdsourcing urban air temperatures from smartphone battery temperatures. *Geophysical …*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/grl.50786/full

Peters, J., Theunis, J., Van Poppel, M., & Berghmans, P. (2013). Monitoring PM10 and ultrafine particles in urban environments using mobile measurements. *Aerosol and Air Quality Research*, *13*, 509–522. doi:10.4209/aaqr.2012.06.0152

Porta, S., Latora, V., Wang, F., Rueda, S., Strano, E., Scellato, S., … Latora, L. (2012). Street Centrality and the Location of Economic Activities in Barcelona. *Urban Studies*. doi:10.1177/0042098011422570

Reid, M. J., Harman, C., Grung, M., & Thomas, K. V. (2011). The current status of community drug testing via the analysis of drugs and drug metabolites in sewage. *Norsk Epidemiologi*, *21*(1), 15–23. doi:10.1016/j.drugalcdep.2011.06.007; Reid, M.J., Langford, K.H., Morland, J., Thomas, K.V., Analysis and interpretation of specific ethanol metabolites, ethyl sulfate, and ethyl glucuronide in sewage effluent for the quantitative measurement of regional alcohol consumption (2011) Alcohol Clin Exp Res, 35, pp. 1593-1599; Thomas, K.V., Reid, M.J., What else can the analysis of sewage for urinary biomarkers reveal about communities? (2011) Environ Sci Technol, , doi: 10.1021/es202522d; van Nuijs, A.L.

Santi, P., Resta, G., Szell, M., Sobolevsky, S., Strogatz, S., & Ratti, C. (2013). Quantifying the benefits of vehicle pooling with shareability networks. Retrieved from http://arxiv.org/abs/1310.2963

Semple, S., Apsley, A., & MacCalman, L. (2013). An inexpensive particle monitor for smoker behaviour modification in homes. *Tobacco Control*, *22*(5), 295–8. doi:10.1136/tobaccocontrol-2011-050401

Snik, F., Rietjens, J. H. H., Apituley, A., Volten, H., Mijling, B., Di Noia, A., … Keller, C. U. (2014). Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters. *Geophysical Research Letters*, *41*(20), n/a–n/a. doi:10.1002/2014GL061462

Snyder, E. G., Watkins, T. H., Solomon, P. a, Thoma, E. D., Williams, R. W., Hagler, G. S. W., … Preuss, P. W. (2013). The changing paradigm of air pollution monitoring. *Environmental Science & Technology*, *47*(20), 11369–77. doi:10.1021/es4022602

Szell, M., Grauwin, S., & Ratti, C. (2014). Contraction of online response to major events. *PloS One*, *9*(2), e89052. doi:10.1371/journal.pone.0089052

Tsujita, W., Yoshino, A., Ishida, H., & Moriizumi, T. (2005). Gas sensor network for air-pollution monitoring. *Sensors and Actuators B: Chemical*, *110*(2), 304–311. doi:10.1016/j.snb.2005.02.008

United States Environmental Protection Agency. (2014). *Air Sensors Guidebook* (p. 73). Research Triangle Park, NC: US Environmental Protection Agency. Retrieved from ww.epa.gov.ord

World Health Organization. (2006). *Air Quality Guidelines. Global Update 2005* (p. 485global). Copenhagen, DK: World Health Organization. Retrieved from http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/

World Meteorological Organization. (2008). *Guide to Meteorological Instruments and Methods of Observation*. Geneva, Switzerland: Genf, Schweiz: Secretariat of the WMO. Retrieved from http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf

Yoshimura, Y., Sobolevsky, S., Ratti, C., Girardin, F., Carrascal, J. P., Blat, J., & Sinatra, R. (2014). An analysis of visitors’ behavior in The Louvre Museum: a study using Bluetooth data. *Environment and Planning B: Planning and Design*, *41*(6), 1113–1131. doi:10.1068/b130047p

Young, D. T., Chapman, L., Muller, C. L., Cai, X.-M., & Grimmond, C. S. B. (2014). A Low-Cost Wireless Temperature Sensor: Evaluation for Use in Environmental Monitoring Applications. *Journal of Atmospheric and Oceanic Technology*, *31*(4), 938–944. doi:10.1175/JTECH-D-13-00217.1

Zhong, C., Schläpfer, M., Arisona, S., & Ratti, C. (2014). *Revealing the Changing Spatial Structure of Cities from Human Activity Patterns*. *mit.edu* (p. 26). Retrieved from http://web.mit.edu/schlmark/www/Zhong_Preprint.pdf

CHAPTER 5

5. DISCUSSION | DATA ANALYSIS AND INTERPRETATION

Introduction

What data from case studies and fieldwork shows? Is sensing feasible and useful for air quality mapping? What challenges were found?

Chapter 4 described the case studies considered helpful for this research, including collaborating and exploring a local sensor network at MIT (Clairity), planning and executing mobile sensing fieldwork (within MIT campus), and collaborating with city sensing projects.

This chapter will present data analysis and interpretation from the case studies, underlining the strengths and the challenges that emerged during this study.

In fact, while great opportunities in sensing for mapping urban climate and air pollution seem to be evident from the following analysis, such as improving scale and resolution, several issues still remain in the use of sensing, such as data quality and communication of results.

5.1. DATA ANALYSIS FROM THE LOCAL SCALE SENSING NETWORK (CLAIRITY)

The first advantage of having a local sensing network is to observe and monitor air quality at the local scale, the scale of the air that people breathe, the scale where citizens live. The 24 sensing stations of Clairity collect data providing information in real-time about the air quality across the MIT campus.

In order to explore its strengths and limits, some analyses were conducted, using all data available at the time of the analysis (raw data from all stations since Clairity launch). Considering only the particulate matter data, there is one reading every 3-6 seconds, providing a minimum amount of data of:

- 10 per minute, 600 per hour
- 14.400 per day, 432.000 per month

Therefore, considering only one month of data (May 2014), and only the particulate matter readings (fine and course from Dylos), for the 24 stations, more than 10 millions records were analyzed.

Since 10 million readings are not manageable with common tools (such as Excel), big data tools were used, such as Phyton (coding), Tableau (data analysis), and ArcGIS (analysis and visualization).

5.1.A – From governmental monitoring stations to a local scale sensing network
5.1.B – Spatial and temporal variation analysis

5.1.A - FROM GOVERNMENTAL MONITORING STATIONS TO A LOCAL SCALE SENSING NETWORK

- Preliminary observations
- Comparing data to governmental data

- Comparing data to weather data

Preliminary observations

As anticipated in § 4.1, Clairity nodes are located across the MIT campus for local air quality monitoring. Figure 5-1 shows their location in comparison to the Massachusetts Department of Environmental Protection monitoring stations. Of the 24 total nodes of Clairity, only the outdoor ones are considered in this section.

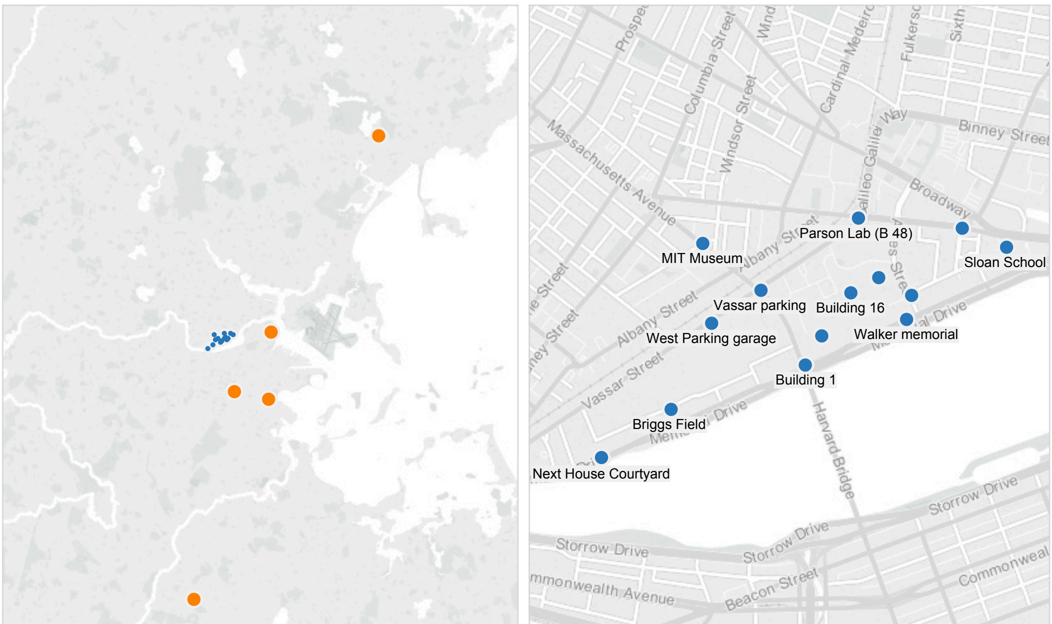


Figure 5-1
Pictured at left: MIT campus air quality sensing nodes (in blue) and the governmental monitoring stations (in orange). The different scale of the two sensing system is evident, metropolitan/regional scale for the latter, and local scale for the former. Pictured at right: a close view of the Clairity sensing nodes location within the MIT campus. Source: author's elaboration from cited websites ((“Clairity: MIT's Air Quality Network,” n.d., “MassDEP:: Air & Climate :: Air Quality & Monitoring :: MassAir,” n.d.).

At a first look of the monthly data (May 2014), a relatively high variation in values occurs among the sensing nodes.

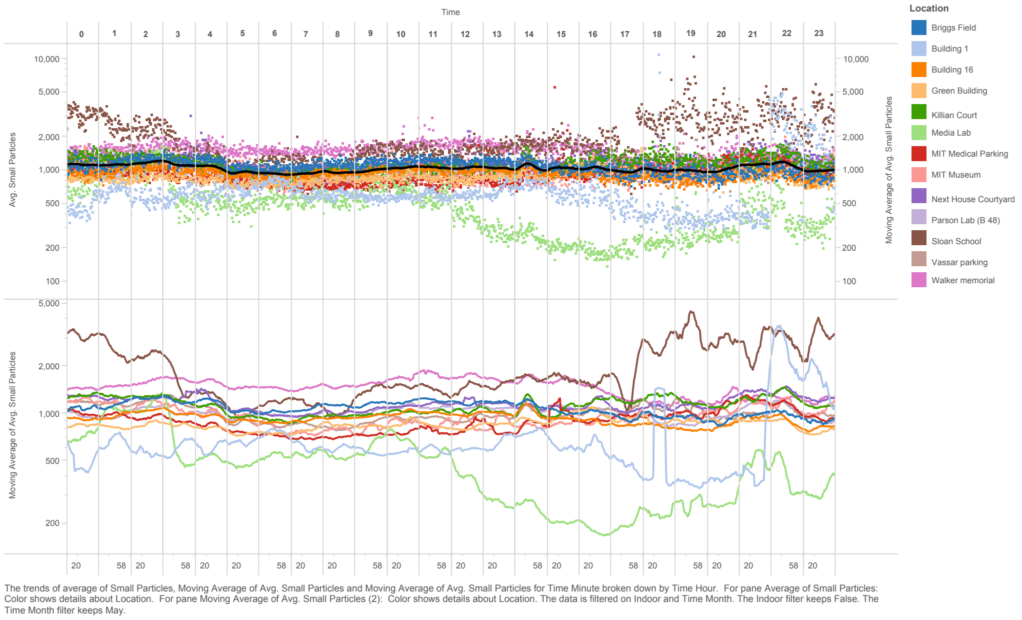


Figure 5-2
Extract from Clairity data about the month of May. Data shows the small particles average measurements, broken down by hour. Colors show details about locations, emphasizing the difference between the locations from the moving average. Source: author's elaboration from Clairity data.

Before going into the local scale analysis, comparing spatial variation, the first step considered to be useful is exploring the relationship between Clairity data and the official data (Massachusetts Department of Environmental Protection).
In fact, while the latter is more focused on the regional scale, Clairity should present similar variations for macroscale contribution of pollutants, with some variation due to the local characteristics particular to the area.
However, as anticipated, Clairity profits from the "low-cost sensor" generation, and it is one of the first, and probably the only one worldwide, example of a permanent local scale sensing network using low-cost sensors.

Comparing data to governmental data

Comparing data with the governmental observation would give a first idea of the accuracy of the network, before going further with a deeper elaboration.
Figure 5-3 presents the variation over the month of May, from day 1st to day 30th: as can be inferred, there is a general overall variation over time, similar to all locations spread within the MIT campus, which should be a result of macroscale conditions, such as weather and pollutants dispersion. In fact, since small particulates is the focus of this analysis, their size allows them to travel for kilometers (see § 1.2.A).

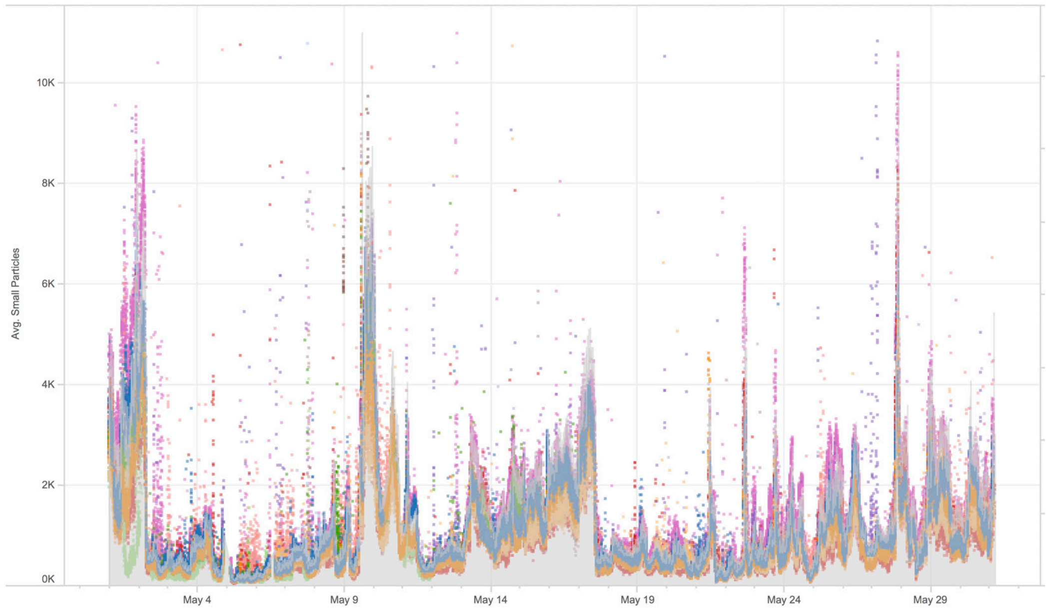


Figure 5-3
Data shows the variation of small particles measurements over time and space at the MIT campus. Data is broken down by minute, emphasizing the difference throughout the month of May. Source: author's elaboration from Clairity data.

Considering the data coming from the Massachusetts Department of Environmental Protection monitoring stations, at a distance of a few kilometers (see § 4.1.A), the small particle data (PM2.5) is not real-time, as discussed, and it is averaged every day. Comparing the averaged concentration data from Clairity (in time, 24 hours, and in space, an average of all nodes), and the governmental data, a high correlation is confirmed. Figure 5-4 confirms the first results: a low-cost sensor network can provide indications about air quality, complementing data from expensive sparse monitoring stations.

The differences between the two averages, therefore, must be connected to weather and local scale parameters.

Going through the month's data, there seems to be a high level of small particles at the regional level at the beginning of the month, detected in both networks, with a decrease around May 5-6, and a peak around day 9. Since the most relevant part of an air quality network is to detect the peaks, the concentration above health risk thresholds, the agreement between the two networks, the low-cost sensing and the governmental one, is promising for future developments. Sensing seems to really be helpful in complementing air quality data.

Following the timescale, another peak is detected at the MIT campus around day 16-17 while there is no spike in the data at the governmental stations. On the contrary, the spike detected around day 26-27 by official stations is not detected by Clairity. These differences need further exploration, they must be connected to macroscale conditions such as wind, altered at the local scale, for instance by building density.

The next section therefore is aimed at comparing weather conditions in order to better explore the data, in the overall aim of finding strengths and challenges of the Clairity network.

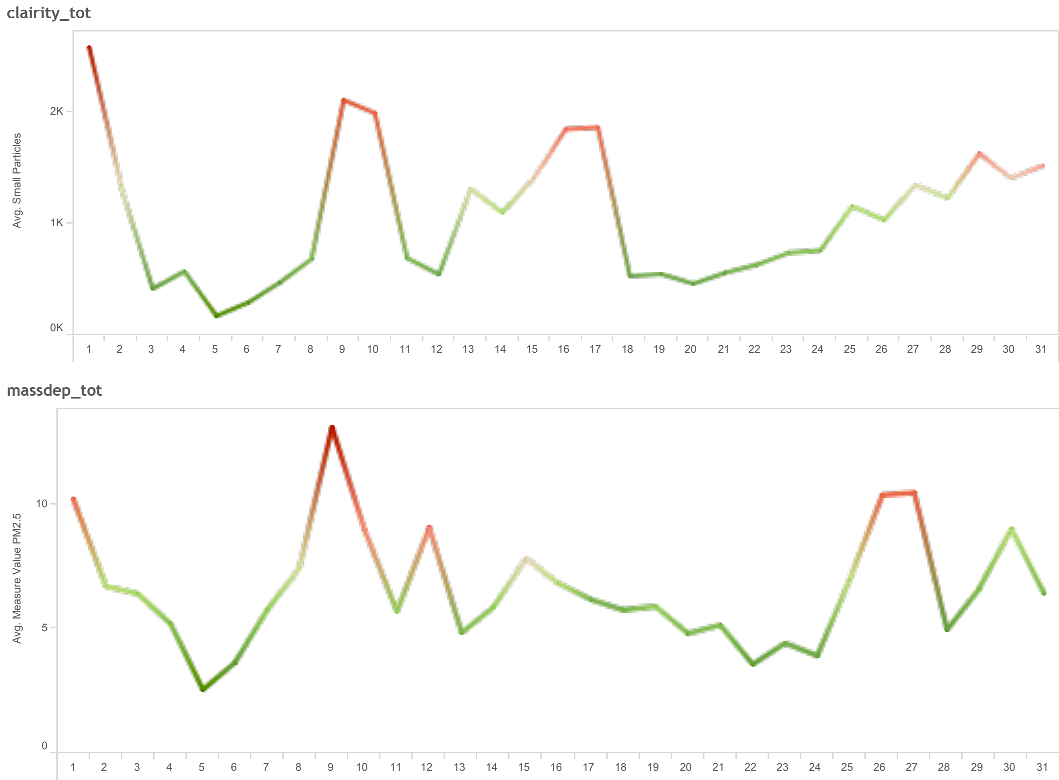


Figure 5-4
Comparison between air quality data (small particles/PM2.5) from the local sensing system at MIT campus (Clairity) and the governmental monitoring system (MassDEP). Data confirms the comparability between the monthly data trend, with differences to be analyzed at the local scale. Source: author's elaboration from Clairity and MassDEP data.

Comparing data to weather data

Since weather stations (US National Weather Service) are far from the MIT campus, and data is 24-hr averaged, it was decided to "scrape" data from Wunderground (see § 2.1.B) using a weather station located inside MIT campus (rooftop of the green building), providing hourly data ("Personal Weather Station: KMACAMBR9 by Wunderground.com," n.d.).

The comparison of small particles with wind intensity in the same time frame (Figure 5-5) shows how on windy days, such as day 5, low concentration of pollutants results from air mixing which explains, at least partially, the overall regional pattern of PM2.5. However, besides wind, there are other parameters involved, such as the quantity of pollutants emitted over May, not available for estimations (sources of PM are various, see § 1.2).

However, high wind intensity around days 15-17 and especially day 29 determined a decrease in pollutants concentration trend, that was detected at the regional scale but not at the local scale at MIT. The reason can be found in the building presence around Clairity stations, which can avoid wind circulation. In order to explore more this aspect a spatial analysis is needed, since Claitity nodes are located in different urban environments (such as the east campus with greenfields, and west campus with higher building density).

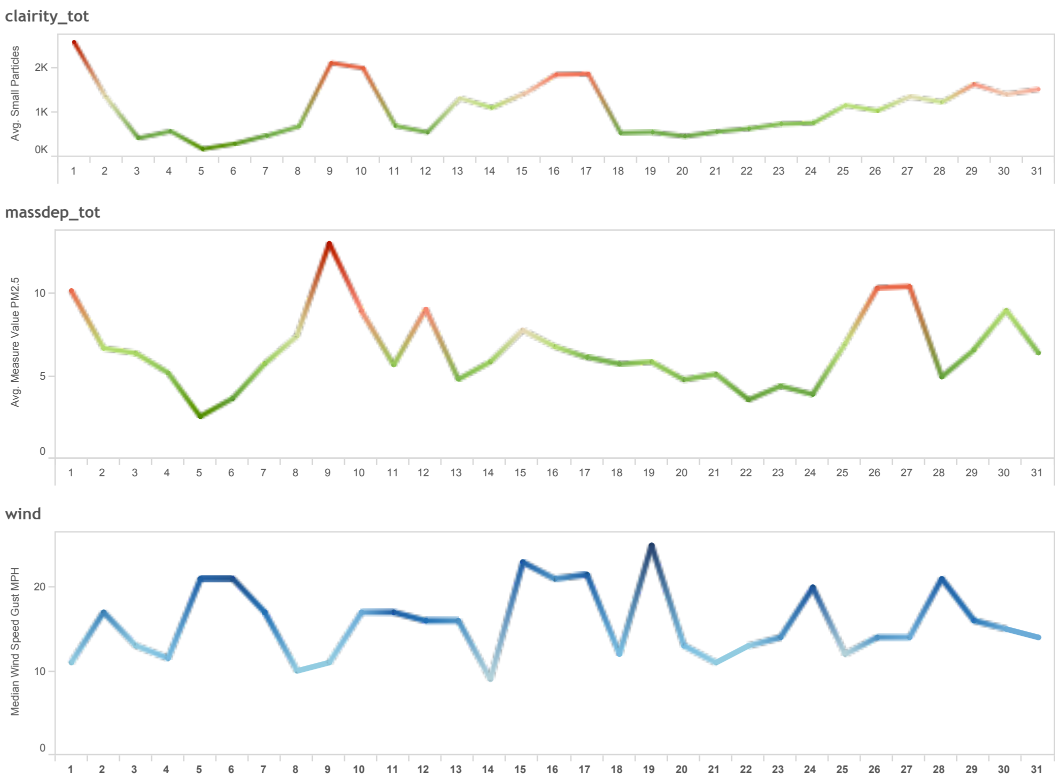


Figure 5-5
Comparison between air quality data (small particles/PM2.5) from Clairity/MassDEP and weather data (wind speed) collected by "data scrapping" from Wundergound. Data confirms the comparability between the monthly data trend, with differences to be analyzed at the local scale. Source: author's elaboration from Clairity, MassDEP and Wunderground data.

In fact, in Figure 5-6, the different values from the outdoor nodes show that the wind effect of May 28th in decreasing small pollutant concentration acted very differently among the different nodes; in particular, the nodes that sensed a decrease were the ones along the river (i.e. “next house courtyard”) or the green building rooftop (90 meters tall, much above all MIT buildings height), while other nodes did not measured a decrease in concentration (i.e. “MIT museum” and “”building 16”, within a dense urban environment).

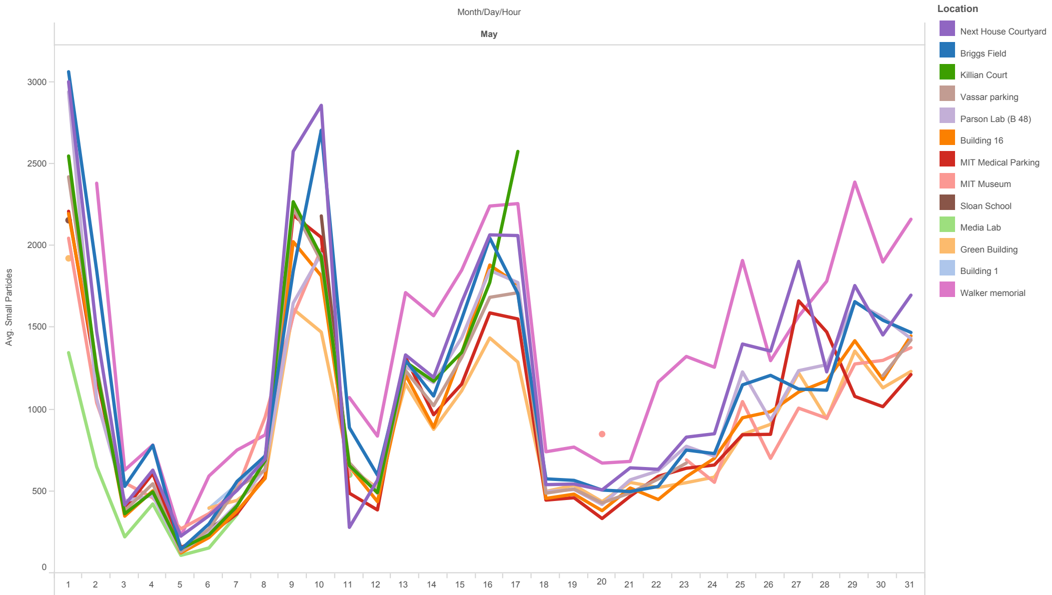


Figure 5-6
Small particles measurements (averaged by day) for the 13 outdoor Clairity nodes (names in legend correspond to the labels of Figure 5-1). Focusing on the timeframe around May 28th, the wind increase of Figure 5-5 has a different effect on the air mixing and resulting particles concentration measured in different locations. Source: author’s elaboration from Clairity data.

Other weather parameters, such as rainfall precipitation intensity and humidity were analyzed but they are not presented here, since the focus is more on exploring the potential of a local network rather than doing deep analysis of air concentration causes.

This brief analysis shows the value of having a local scale network in detecting differences in local air quality compared to the regional level.
Some technical issues can already be evidenced, such as the presence of “outliers”, probably due to temporary malfunctioning of a sensor, and the data gap for some nodes, where data are missing for days because of technical problems (somehow potentially altering the averaged data if not well-analyzed).

In order to explore the strength of the network in detecting local differences, potentially suggesting different actions for different local context, a spatial analysis is conducted in the next section.

5.1.B - SPATIAL AND TEMPORAL VARIATION ANALYSIS

- Spatial variation
- Temporal variation
- Indoor/outdoor relationship

Spatial variation

The availability of a local network allows studying air quality patterns at the local scale, potentially identifying local characteristics that affect pollutants concentration, both in terms of identifying local sources and local urban conditions (such as building density).

In order to do so, the focus is not on the mascoscale variation, as seen in the previous section, but on local differences among the locations. Figure 5-7 illustrates an extract from the data (May 20-31) showing large differences in the nodes behavior according to their different location.

The two nodes located along the high-traffic road along the river ("Next house courtyard" and "Walker Memorial") shows consistently higher values compared to the rest of the locations, probably linked to local emissions, although fine particles, as mentioned, travel in space and are not only generated by road traffic.

The wind influence on day 28 was already discussed in the previous section as a potential contribution to reducing concentration for most of the nodes, with a stronger effect on nodes in an open field (i.e. "next house courtyard) than nodes in the inner urban environment (i.e. "MIT museum").

However, explaining all local different behaviors (i.e. "MIT medical parking" around day 27-29) would need further investigation.

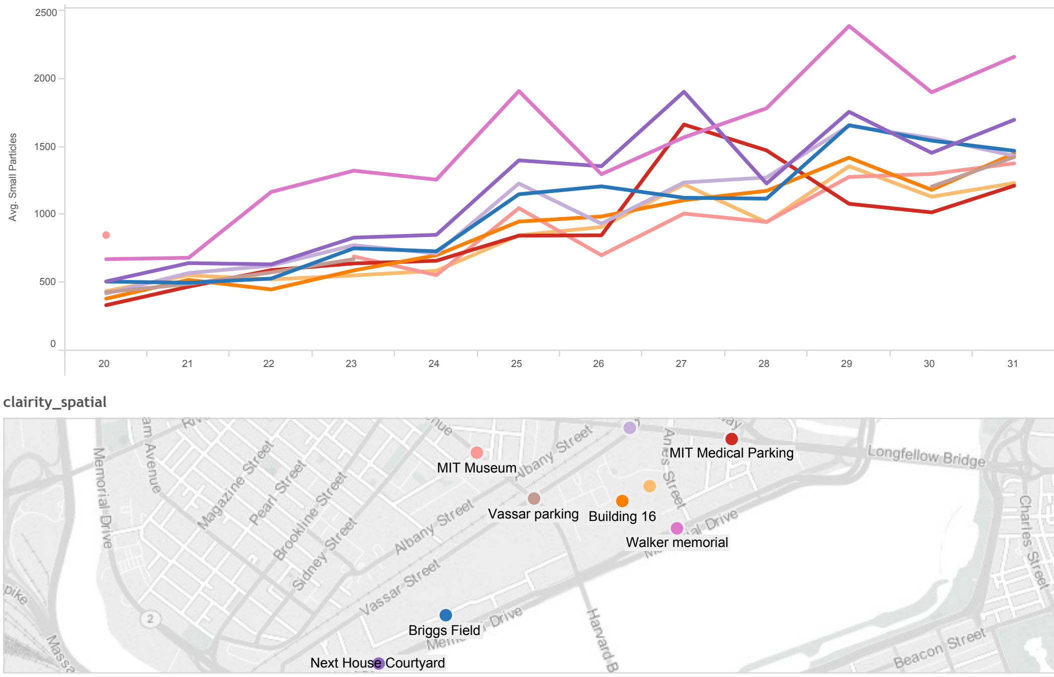


Figure 5-7
Spatial analysis of small particles measurements and their difference across locations at the MIT campus. Local behavior is influenced by air turbulence and mixing, which is different across the area in relationship to the different urban structure. Source: author's elaboration from Clairity data.

As can be understood from this brief analysis, local characteristics such as topography (i.e. distance from river), urban structure (i.e. building density and orientation), urban functions (i.e. car mobility) can be explored with the use of data from a local sensing network, and proper measures can be potentially addressed.

However, a fundamental remark needs to be underlined. Some nodes reveal consistently lower concentrations in relation to others because of their location, but the representativeness is not always equal to all nodes.
For example, focusing on the two nodes measuring consistently lower values of the previous image, “MIT museum” and “green building” two different considerations can be made. The “green building” node is located on the rooftop, therefore its representativeness is linked to a climate above the urban canopy level (see § 1.1.A), confirming the fact that higher concentrations are found inside urban canyons, because of air flows (see § 1.1.A).
A second consideration related to the “MIT museum”, which is located on a high-built area and close to a high-traffic road, yet measuring lower values. Again, the repetitiveness of a node is not only due to the spatial coordinates, but on the height (such as for the green building) and other affecting parameters, such as the distance from a wall. In the case of the “MIT museum”, the sensing was positioned on the museum wall and below an archway, limiting its representativeness to a smaller spatial area around the node, compared to other nodes installed on street poles where they might be representative of a larger volume around them.
Considering the different range of representativeness of the nodes, making a map with kriging techniques, such as in Figure 5-8, is highly questionable.

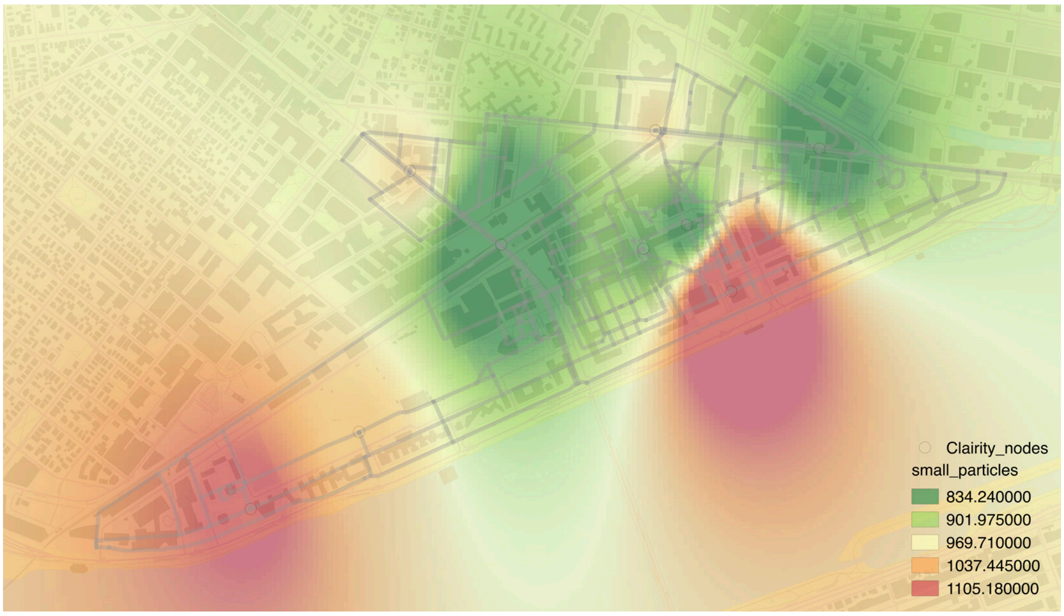


Figure 5-8
Mapping air quality (small particles) at MIT campus during the timeframe of May 20-31, using kriging techniques. Data shows the challenging representativeness of the data. Source: authors’ elaboration from Clairity data (data averaged using Tableau features, and visualized using QGIS interpolation analysis).

In order to overcome this representativeness problem, the sensing node locations should have as many homogenous conditions as possible. Alternatively, and it is the case of § 5.2, a higher resolution data from mobile sensing, can connect the locations and help understand the spatial variation and the representativeness of each node.

Temporal variation

From a temporal perspective, air quality data presented so far was aggregated on a daily basis, while low-cost sensors used in Clairity allow exploring data at a 3-6 seconds resolution. This is a high value for studying air quality in relation to people presence and exposure. Some examples of this potential can be presented.

Figure 5-9 shows the overtime difference considering the 24 hour average data for the month of May. The differences cannot be related to weather or geographic conditions, since the pattern is clearly different in weekdays and weekends; therefore, the main factor contributing to temporal variation is likely connected to local emission pattern that is different during weekdays and weekends. In fact, an expected difference in car mobility, and consequent emissions, would suggest different patterns in the daily air quality. Figure 5-9 confirms the hypothesis, with much higher total pollutant concentration monitored by the local network during weekdays, and especially in the rush-hours around 3 pm and around 9pm. This pattern seems to be consistent across all locations, with a few local exceptions, that would require further exploration (i.e. early morning peaks in “next house courtyard”).

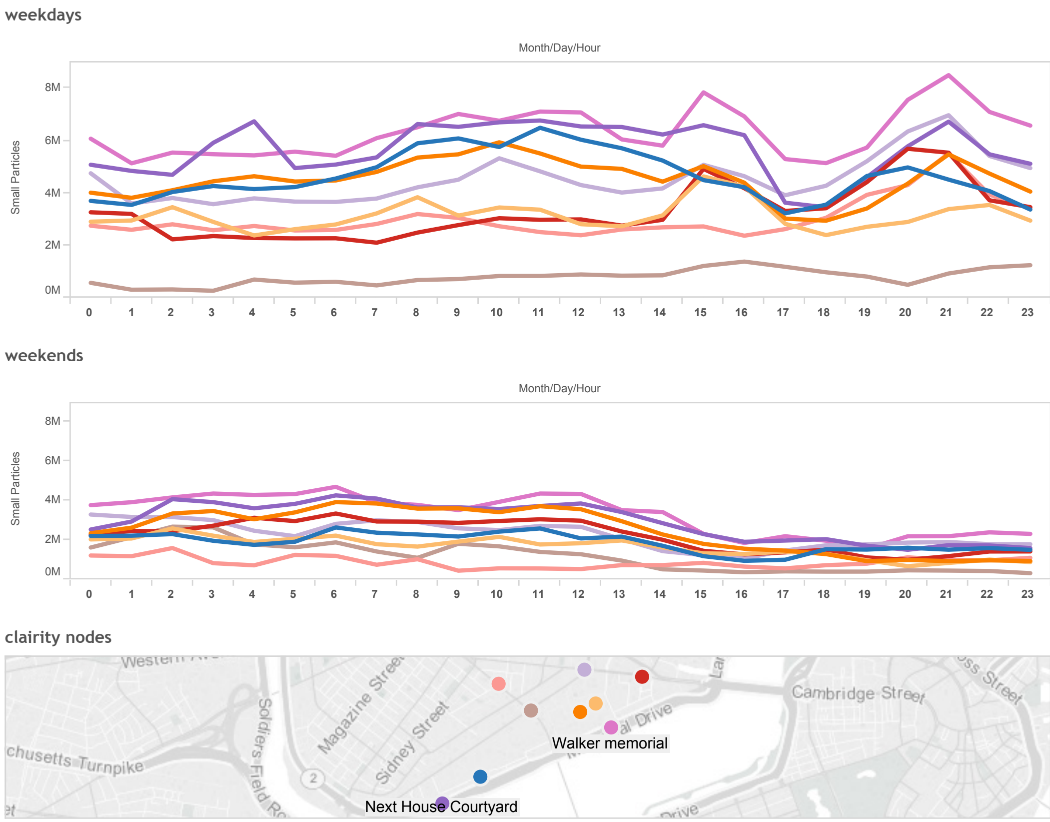


Figure 5-9
Temporal variation analysis of air quality (small particles) data of May 2014 weekdays and weekends (averaged). The overtime variation is linked to the different hourly condition, which can be related to the different emissions by car mobility. Source: authors’ elaboration from Clairity data.

Having high-temporal and spatial resolution data allows another study, focusing on specific days with spikes in pollutant concentration, and analyzing the decrease in the following days/hours for dispersion patterns within the area.

While the objective of this work is not a fluid dynamic study, but an exploration of the potential aspects emerging from a local sensing network, some considerations can be made about concentration peaks and dispersion.

The air quality over the month of May showed in the first figures (5.3-4-5-6)showed a peak on May 9th, both detected by the governmental network and the local network, and likely connected to low wind conditions.
Thanks to the temporal resolution offered by Clairity, it is possible to focus on the specific day May 9th (Friday) and explore the increase and decrease throughout the day.
Figure 5-10 shows the same data at a higher resolution, therefore detecting that the increase in small particles concentration on that day was prevalent on May 9th and in particular around 2:00 pm. During that timeframe, the spatial analysis reveals that some nodes reacted more than others in their peak in concentration, such as the "Walker Memorial" (located on a high-traffic road; dark line is the average data line).

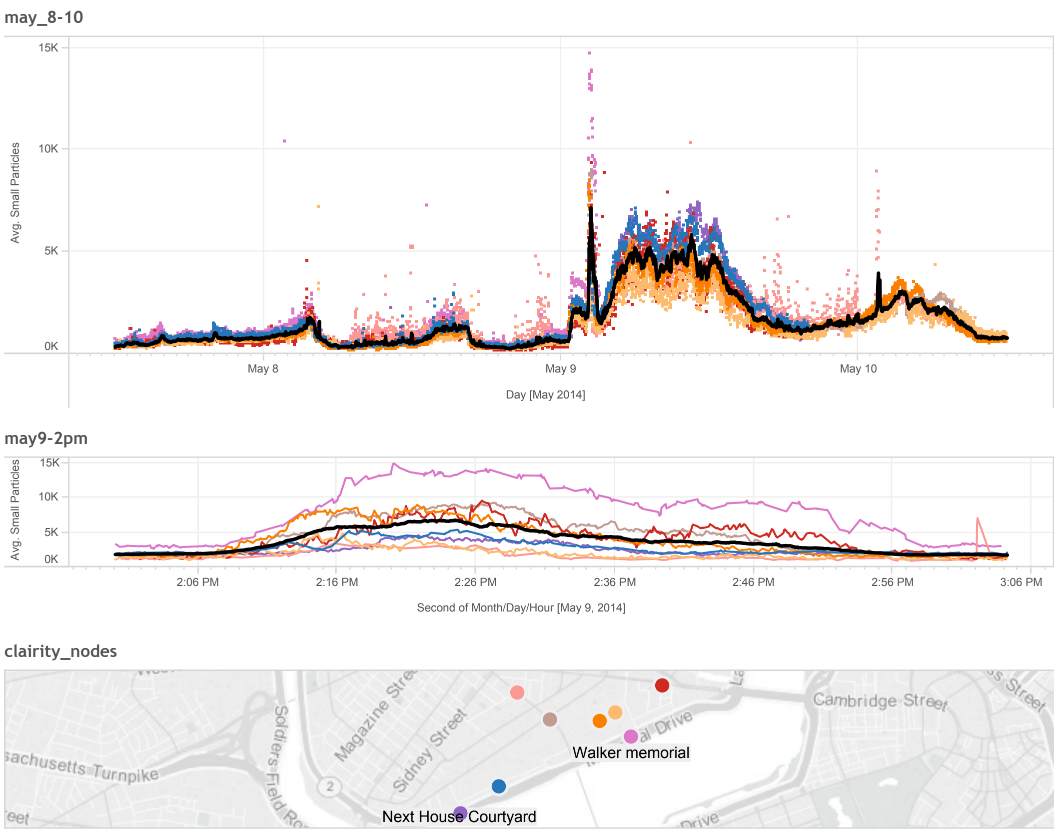


Figure 5-10
High temporal resolution data displaying the variation around May 9th. Thanks to the temporal resolution of Clairity data, it is possible to track spikes in their shape, formation and dispersion; this kind of analyses are not possible using traditional monitoring station data. Source: authors' elaboration from Clairity data.

The high-resolution in the data timeframe, covering also a few seconds, as seen here, is useful to detect spikes that would have been averaged and hidden on an hourly or daily basis. However, as will be explained in detail in § 5.3.B, the increased resolution emphasizes the peak in concentration in a small timeframe (such as 2 pm in the case above), which it is not necessary to be considered problematic. In fact, even if the fine particulate concentration is higher than the defined thresholds, the health effect on the human body might not be as harmful as expected, since the thresholds are defined according to studies that considers a larger timeframe (24-hr for PM2.5). (see § 5.3.B).
Therefore, while being a strength of the local network, the high-time resolution needs careful consideration in interpreting the results.

Indoor/outdoor relationship

Other analyses can be conducted comparing fine and coarse particles, or particles and gases concentration, in order to explore correlations and detecting different sources, such as local emissions from cars (recognizable by local NOx concentration) and large-scale pollution (such as PM2.5 at a certain extend).

Again, because the interest in this work is to explore the strengths and challenges of such a sensing network, limited analysis is presented here.

Comparing indoor and outdoor concentration is also an interesting analysis aimed at understanding possible interrelationships. Figure 5-11 shows the monthly variation of small particle concentration from two nodes positioned nearby at an indoor ("next house dining", a dormitory restaurant only open for breakfast and dinner) and outdoor location ("next house courtyard", right outside the dormitory). Low concentration on the outdoor location around May 4-6, seems to be connected to indoor location concentration. However, focusing on a specific day, for instance May 29th, the concentration reveals different patterns: the indoor location has lower values and less fluctuation than the outdoor node. Similar concentration can be linked to high ventilation of the indoor space, because of ventilation system or doors opening. Focusing on all month but dividing the data at an hourly base, the indoor location shows instead a high fluctuation. This can be related to early morning and dinner times, when meals are prepared and small particulates are released to the indoor area.

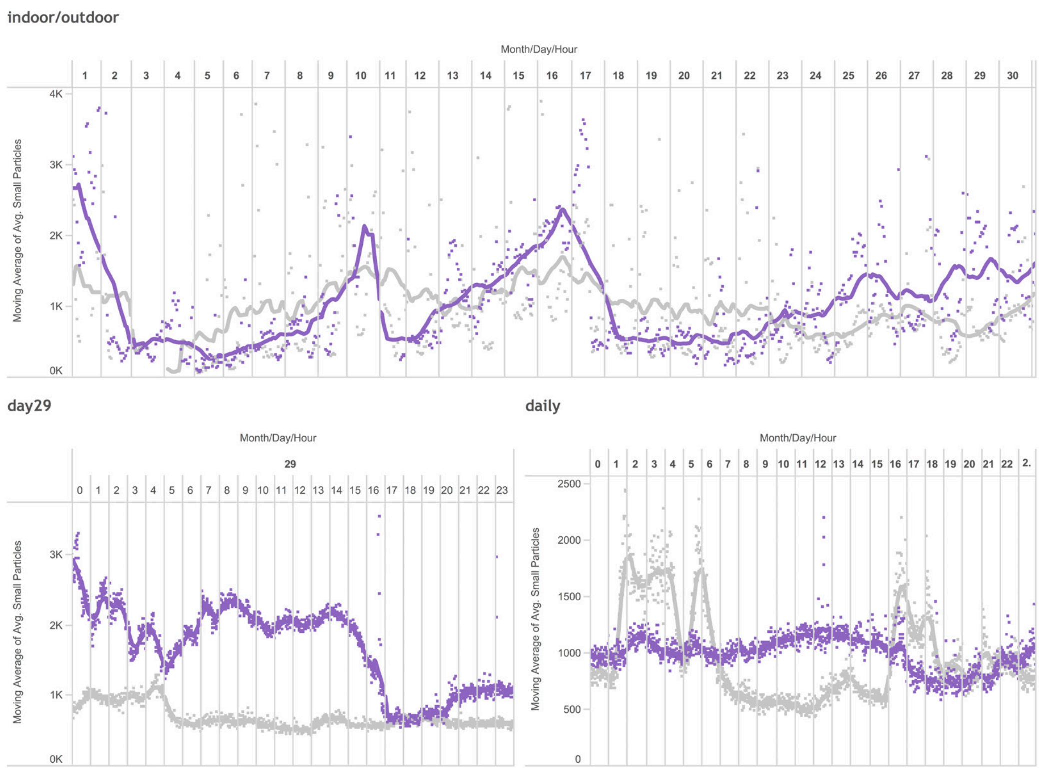


Figure 5-11
Comparison between indoor and outdoor data (small particles) coming from two nodes positioned nearby at an indoor ("next house dining", in grey) and outdoor location ("next house courtyard", in purple). Pictured at top: the monthly variation of daily data from the two nodes. Pictured at bottom-left: the variation on day May 29th, where outdoor measurements are higher than indoor ones. Pictured at bottom-right: the hourly variation of the monthly data, showing the different pattern connected to the different emission sources (likely to be connected to indoor cooking and outdoor car mobility). Source: authors' elaboration from Clairity data.

5.2. DATA ANALYSIS FROM THE HIGH-RESOLUTION MOBILE SENSING FIELDWORK

As described in § 4.2, after the long process of review, the fieldwork was designed and planned according to air sensing guidelines (United States Environmental Protection Agency, 2014). The process required considering the air sensor technical characteristics (such as accuracy, bias, precision, calibration, response time, detection limits – see Glossary) and the measurement characteristics (duration, frequency, data grouping).
This section presents selected results from the mobile sensing fieldwork conducted in April-May-June 2014 at the MIT campus, using different sensors, among which the "Sensaris EcoPM v.3".

5.2.A – Mapping air pollution hot-spots
5.2.B – Mapping urban climate hot-spots

5.2.A - MAPPING AIR POLLUTION HOT-SPOTS

- Particulates (PM2.5 and PM10)
- Gases
- Interpolation and overlapping with Clairity

Particulates (PM2.5 and PM10)

As anticipated in ch. 4, while the path included some indoor tracts (in red in Figure 5-12), the data presented in the following sections are the indoor locations. Since the mobile device does not have a way to detect indoor/outdoor ambient air, it was necessary to take notes of the time corresponding to each switch indoor/outdoor and outdoor/indoor. This was a first limitation of the mobile sensing fieldwork, others will be described later on.

Figure 5-12
Mobile sensing path within the MIT campus. Red lines represent indoor paths while green lines represent outdoor paths. The overall path pass by all Clairity nodes and all main streets and outdoor areas (squares, parks). Source: author's elaboration.

Data was therefore collected from the mobile device while walking along the planned path, and data was streamed online through a mobile phone connected to both the device (via Bluetooth) and the web (via MIT wifi). The location of each entry monitored by the devices, with a time resolution of about a second, was retrieved thanks to the GPS sensor integrated in the smartphone used during the fieldwork. The double connections required, and the battery life were limitations for the execution of the fieldwork, and required careful advance planning.
Figure 5-13 shows the results for a day selected on the basis of the previous analyses, where a high difference among the locations was detected in the previous analysis (May 30th).
As evident from the figure, mapping air quality with mobile sensing seems to be an effective tool to detect differences within the urban environment, and potential pollutants concentration can be spotted. In particular, the map reveals lower PM2.5 concentration in all east campus compared to the west campus. Among the reasons of this difference, the building density and activity density can be underlined. In fact, the sky view factor, a factor contributing in the ventilation at the local level, is different in the east and west campus: while the east campus has less density and more compact buildings, the west campus locates many smaller buildings with a high density, ultimately resulting in a variety of “canyons” with low sky view factor (see § 1.1.A).
In addition, small pockets of pollutants are displayed by mapping air quality using the mobile sensor: hotspots in the inner part within the west campus can be easily spotted, and the reason for their higher concentration certainly depends on local urban characteristics.

Similar to the analyses on Clairity data, future exploration might correlate urban morphology indicators to the pollutants data, in addition to anthropogenic emission sources, such as car mobility, in order to better study the causes of the pollution concentration increase in some locations at a fine grained scale.
However, for the purpose of this work, the potential of mobile sensing for monitoring at a high resolution is manifested.

A particularly delicate aspect of mapping air quality with such a fine resolution is the communication of the information and the transparency of data provided. Figure 5-13 showed a qualitative map using traditional heatmap colors (dark green/light green/yellow/orange/red) for each point of the fieldwork, representing the differences of the indicator, PM2.5 concentration.

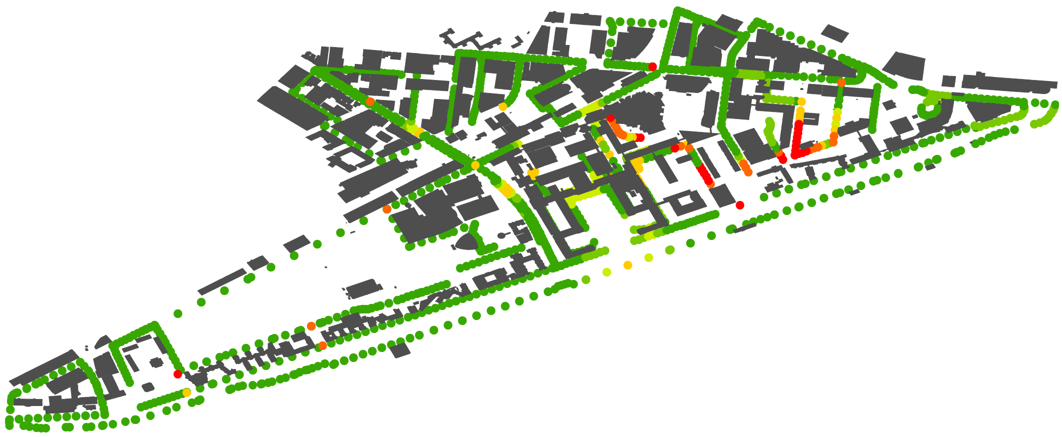


Figure 5-13
Mapping air quality using data from the mobile sensing fieldwork. Qualitative example of small particles data about May 30th. Each point represents a record coming from the sensor readings, according to the level of pollutant measured (red=high, green=low level). Source: author's elaboration.

However, using different distribution ranges (in order to differentiate the values from 0 to 500 µg/m3), such as the statistical "natural breaks" or "equal intervals" ranges, the results can vary in terms of visualization. In order to better communicate the results, the US-EPA Air Quality Index (AQI) was therefore used for the distribution range, based on the classification made for PM.2.5. Figure 5-14 shows the same map with the US-AQI range.

Figure 5-14
Mapping air quality using data from the mobile sensing fieldwork, example of small particles data about May 30th. PM2.5 concentration expressed in µg/m3 unit, as coming from the sensor raw readings. Source: author's elaboration.

Using the AQI, other critical areas emerge in the map, such as the upper part of Massachusetts Avenue (the high-traffic street dividing the east campus from the west campus). The colored points provide a consistently high concentration in the immediate surroundings, demonstrating the ability of the sensor to detect pollutants while moving in space. Since the sensor used is a light scattering device, in addition to the instant value of the concentration, a 30 second peak is automatically provided by the device, in order to acknowledge the normal fluctuation of the air within the sensor that might lead to punctual instant underestimation. As explained by the manufacturer and confirmed in the data analysis, the PM2.5 “30s peak” data is a more stable measurement value (compared to the PM2.5), and is used in the maps.

Because of this communication issue, and others further explained in detail in § 5.3, the maps presented here cannot lead to robust consideration about the health risk of people at the MIT outdoor campus areas. For instance, the PM concentration provided by the sensor is automatically converted to mass concentration, based on internal studies conducted by the manufacturer, and this process, as later explained, requires specific local studies. In addition, while the health risks associated with the AQI to the concentration defining the thresholds are related to data averaged on 24 hours, the mobile sensing data is not.

However, considering the limitations better explained in the next section, the maps have a strong impact in providing a good idea of the small particles distribution across the campus, with an unprecedented resolution.

The same mapping process was followed for PM10 concentration; Figure 5-15 shows the results of the big particles distribution across the campus, using the US-EPA AQI for 24-hour average thresholds of PM10 mass concentration. The results show how the distribution of small and big particles is overlapping on most of the campus, with some exceptions. The east campus confirms to have healthier outdoor air in comparison to the west campus, and some hotspots are detected in addition the ones identified for PM2.5, such as the entrance of MIT in the mid part of Massachusetts Avenue, and a north west part of the campus (Kendal square). In both places, traffic lights regulate the flow in two large intersections between two high-traffic roads and the pedestrian flow; the large waiting time for cars in the presence of masses of people crossing the road might have influenced the sensor readings of PM10 from car idling. In fact, PM10 is a heavier pollutant travelling less than PM2.5, and is less distributed in the air, therefore observable closer to the emitting locations (such as cars idling at the traffic light) compared to the more diffused PM2.5 concentration (see §.1.2).

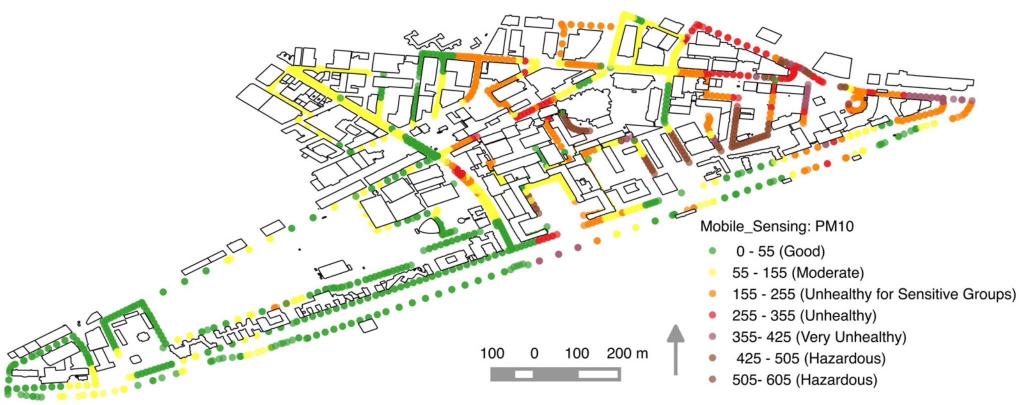


Figure 5-15
Mapping air quality using data from the mobile sensing fieldwork, example of small particles data about May 30th. PM10 concentration expressed in µg/m3 unit, as coming from the sensor raw readings. Source: author’s elaboration.

Future exploration of both PM2.5 and PM10 might correlate to anthropogenic emission sources, such as car mobility and idling, urban morphology indicators and other variables to the pollutant concentrations data, thanks to the high-resolution of the maps. However, for the purpose of this work, the potential of mobile sensing for monitoring at a high resolution is evident, together with its challenging limitations.

Gases

Since the sensor used for the mobile sensing fieldwork included a gas sensor (VOCs), some consideration can be made after mapping the data collected.

As introduced in § 1.2 and in the glossary, VOCs are an air pollutant and exposure to VOCs might lead to respiratory, allergic, or immune effects. However, VOCs standard is not included in US-EPA AQI and its limits values are not defined for outdoor air quality, while regulations applies to indoor air and to major emitting sources (such as paint industry). Since VOCs are varied and ubiquitous and include both anthropogenic, and naturally occurring chemical compounds, results are not easily interpretable. In addition, VOCs sensors have technology limitations and are mostly addressed for indoor measurements (Herberger and Ulmer, 2012).

Figure 5-16 shows the VOC concentration (in ppm) across the campus, with higher values in correspondence to the southern part of Massachusetts Avenue, with the possibility of a relationship to vehicle emissions on this high-traffic road. As mentioned, other considerations can be made, but require further analysis of local conditions and fall outside the interest of this research.

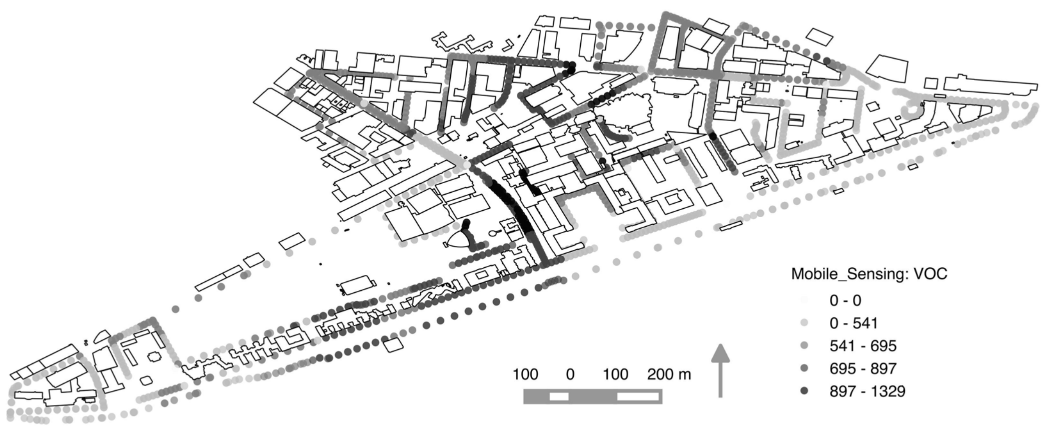


Figure 5-16
Mapping air quality using data from the mobile sensing fieldwork, example of small particles data about May 30th. VOC concentration expressed in ppm unit, as coming from the sensor raw readings. Source: author's elaboration.

Interpolation and overlapping with Clairity

Interpolating data from mobile sensing can be useful to draw maps about air quality at a local scale with high-resolution. Figure 5-17 shows a qualitative interpolation map generated from the data extract of the previous sections (May 30th). Two main considerations can be made from the map. Firstly, while the map is "static", it is clear that the data is "dynamic", in the sense that each point is representative of a reading made in a particular moment (second, hour of the day). Therefore, the map is representative of a mix readings throughout the day (morning to afternoon, in the case analyzed). Secondly, using interpolation and kriging techniques, fine-grained heatmaps can be drawn, displaying the presence of "hot-sposts". However, the measurements scale and statistical range can affect the map proprieties, underrating or overrating and emphasizing the spatial difference in the measurements.

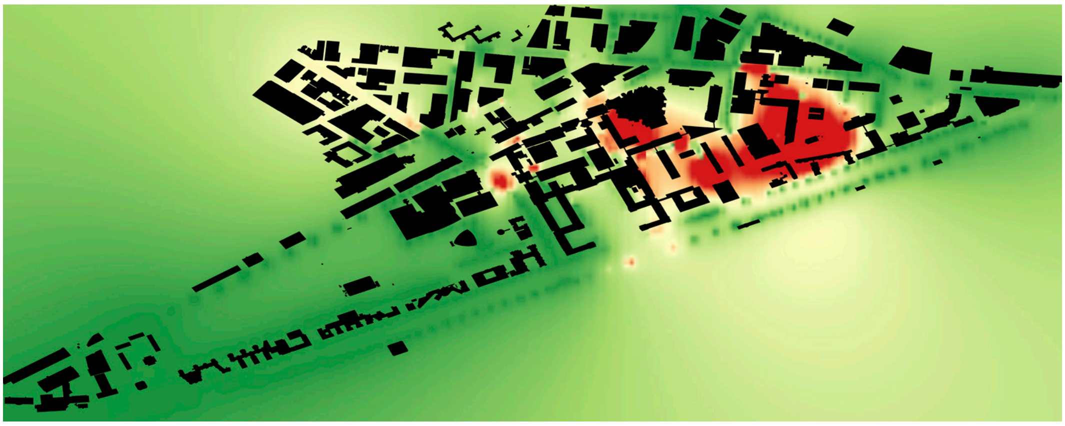


Figure 5-17
Mapping air quality using data from the mobile sensing fieldwork. Qualitative example of PM2.5 data about May 30th. Each color represents the interpolation from all records coming from the sensor readings, according to the level of pollutant measured (red=high, green=low level). Source: author's elaboration.

In order to assess in a qualitative way the pollution level and health risk using the mobile sensing reading from the fieldwork, Figure 5-18 displays the same results using the US-AQI index previously mentioned. It is evident how the results can be visually interpreted in a different way, with a higher coverage of the campus at a "health risk" condition (west and north side of the campus, the more urban dense areas of the campus). However, as anticipated, the AQI relates to 24-hour averaged data, while the map relates to readings throughout a day, but each reading is relative to a specific second/minute/hour of that day (see more on §5.3.B).

Overlapping air quality using data from the local sensing network (Clairity) and the mobile sensing fieldwork is challenging. As mentioned, Clairity nodes raw data are expressed in number of particles while the sensor device used provides data expressed in µg/m3 concentration. As described in § 5.3.B, the conversation from the two measurements is possible, but required further investigation.

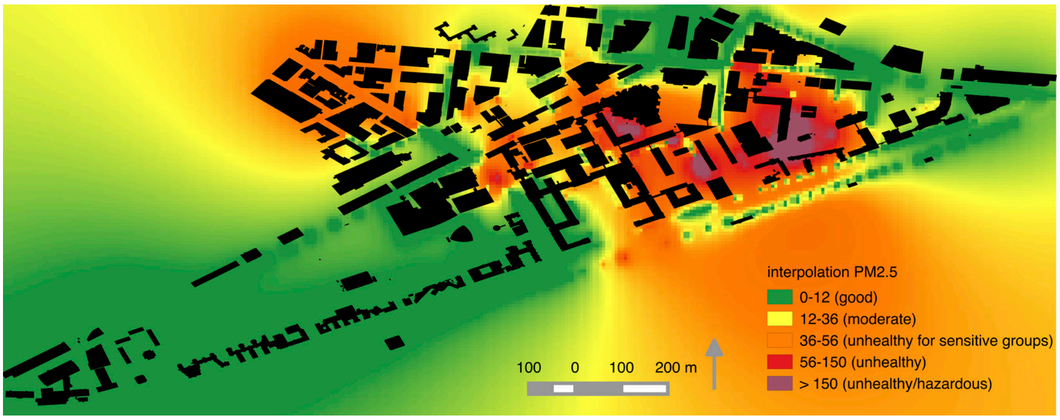


Figure 5-18
Mapping air quality using data from the mobile sensing fieldwork. Interpolation map about PM2.5 concentration (expressed in µg/m3 unit, as coming from the sensor raw readings), using US-AQI air quality index. Source: author's elaboration.

Figure 5-19 therefore represents the overlapping of the two datasets using a qualitative heatmap. In order to interpolate data relative to the same timeframe in the two datasets, and algorithm was created to extract data from each Clairity node in the same timeframe of the mobile sensing passing by it. Every time the mobile sensing device was passing by a Clairity node during the fieldwork, the algorithm extract a corresponding averaged data over 30 minutes from the Clarity node datasets (multiple times, according to the designed path).

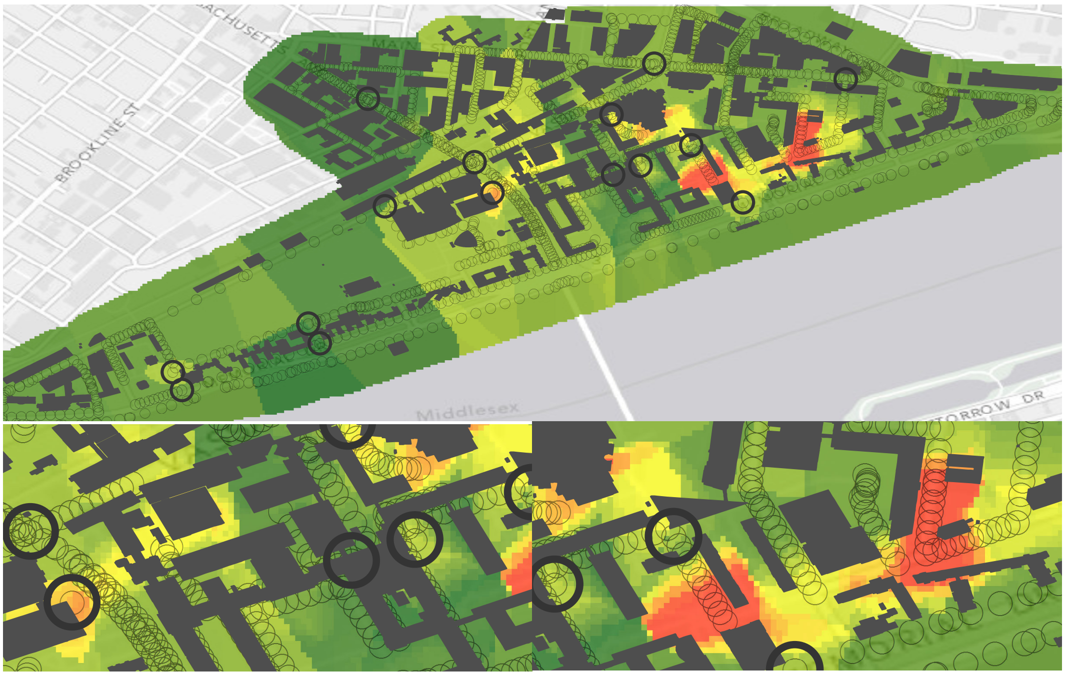


Figure 5-19
Pictured at top: overlapping air quality using data from the local sensing network (Clairity) and the mobile sensing fieldwork. Qualitative example of small particles data about May 30th. Each color represents the interpolation from all records coming from the sensor readings, according to the level of pollutant measured (red=high, green=low level). Pictured at bottom: two close-view maps showing the mobile readings (small circles), Clairity nodes (big circles), hot spots and campus buildings. Source: author's elaboration.

5.2.B - MAPPING URBAN CLIMATE HOT-SPOTS

- *Temperature*
- *Humidity*
- *Notes about the limitation of the fieldwork*

Temperature

As explained in ch. 4, urban climate data, such as temperature and humidity, were monitored by the local network but revealed data only representative of air inside the nodes (i.e. with altered temperature because of the electronics component inside).

Therefore, data is not communicated on the websites, and not analyzed in the previous section. Weather data used in the analysis was taken from a weather station located on the rooftop of a building within the campus, and was the only available information available.

However, the fieldwork planned and conducted using a mobile sensing device, was able to monitor air temperature and humidity along the path.

Figure 5-20 shows the temperature distribution along the campus, collected by the sensors as it was moving at a reduced speed. Section 4.2 described the resolution of the data planned to be gathered and the corresponding speed of the data.

More about the representativeness of data (for each point) will be explored in the next section.

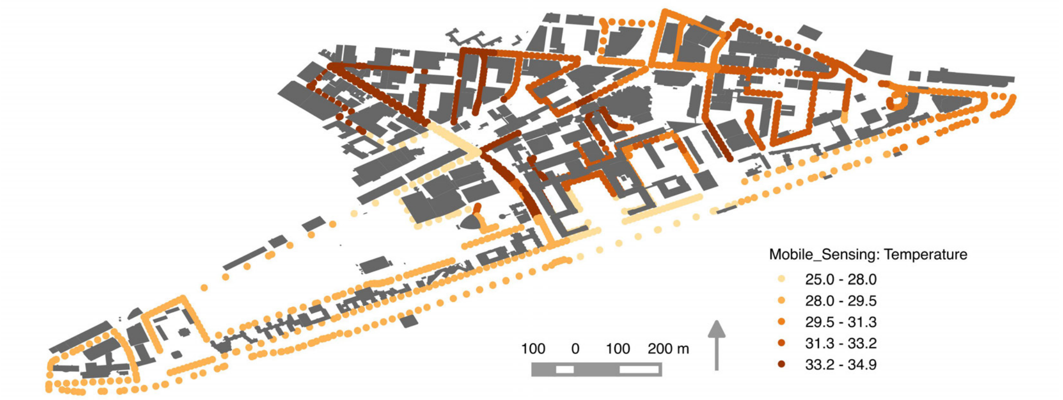


Figure 5-20
Mapping urban climate using data from the mobile sensing fieldwork, example of temperature data about May 30th. Temperature expressed in °C, as coming from the sensor raw readings. Source: author's elaboration.

As evident from the figure, mapping temperature with mobile sensing is able to detect differences within the urban environment, and potential heat concentration can be spotted, while absolute values can appear less significant. In particular, the areas closer to the river (south) have lower temperature then the inner part of the campus. A possible explanation is the contribution of the water in the later heat component of the energy balance (see § 2.1.A), together with a possible higher wind speed because of lack of building obstruction along the river.

In addition, it is evident how less granularity is required for open field while more granularity is necessary for dense built areas; this consideration relates the representativeness of data, which will be further explored in the next section.

Another consideration evident from the map is the lower temperature in all east campus compared to the west campus. Among the reasons for this difference, two of the main factors are largely due to anomalies on the campus. The first example is the presence of large greenfields in the east campus, where sport activities are located. The latent heat from vegetation is able to trap some heat from the energy balance, resulting in a lowered sensible heat, and temperature monitored by the sensor. Secondly, the sky view factor, a factor contributing to the radiation balance, is different in the east and west campus: while the east campus has less density and more compact buildings, the west campus locates many smaller buildings with a high density, ultimately resulting in a variety of "canyons" with low sky view factor.

Similar to the analyses on Clairity data, future exploration might correlate urban morphology indicators to the temperature data, in addition to anthropogenic emission source, such as car mobility, in order to better study the causes of the temperature increase in some locations at a fine grained scale.
However, for the purpose of this work, the potential of mobile sensing for monitoring at a high resolution is manifested.

Humidity

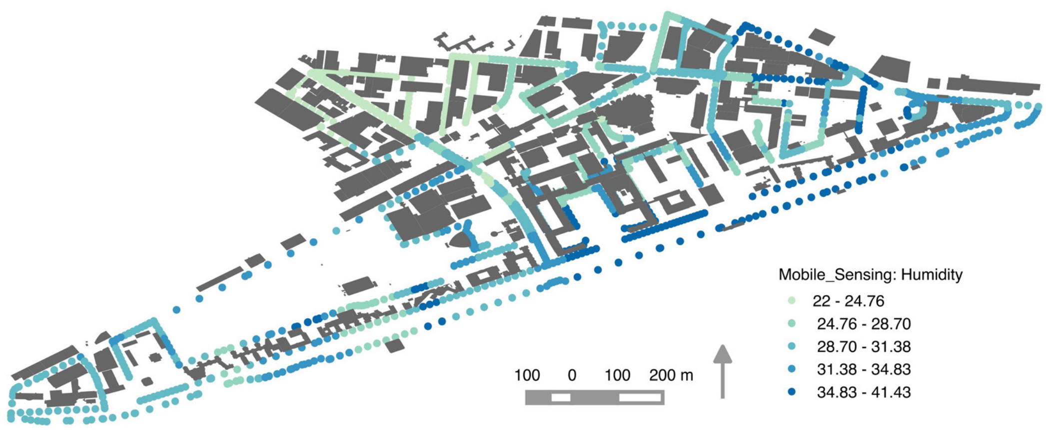


Figure 5-21
Mapping urban climate using data from the mobile sensing fieldwork, example of humidity data about May 30th. Relative humidity expressed in %RH, as coming from the sensor raw readings. Source: author's elaboration.

Notes about the limitation of the fieldwork

Some technical limitations of the fieldwork can be here described.
Firstly, the fieldwork was conducted in different days during April-May-June 2014, but only data about May 30th were here analyzed and presented. In fact, in other situations, different variables interfered, both external (i.e. rain) and internal (i.e. malfunctioning of the sensor), creating gaps or generating data with particular representativeness. Secondly, because the sensor is measuring as moving in space with a defined speed, the readings can be shifted according to the response time. This issue was overpassed opting for a slow speed (walking pace) for day May 30th, while other data at higher and at variable speed (running and biking) need further investigation.
Another remark related to the mentioned challenges in representing in a map data coming from different timeframe. Real-time maps technology and video visualization are better in visualizing and interpreting such kind of sensing data.
A final remark related to the sensor technology, which appears to be at a young but promising stage. After the comparison of different devices and the selection of the ones used in the fieldwork (as described in § 4.2.B and Annex 2), the same challenges seem to occur and alter the fieldwork execution. Power management was a limiting factor in collecting data, because both the phone and the device's batteries needed to be operative in order to avoid gaps in the readings. In addition, for data streaming two connection processes are required: a stable and constant Bluetooth connection between the device and the smartphone, and a stable and constant internet connection from the smartphone to the server platform. Several attempts were therefore needed before conducting a proper fieldwork, as described in this section.

For a more detailed analysis and discussion of the limitation of sensing as emerged from both the fieldwork and the case studies, such as accuracy and interpretation/communication of results, see § 5.3.B.

5.3. FINDINGS AS EMERGED FROM CASE STUDIES AND FIELDWORK ANALYSIS

This section reviews opportunities and limits as emerged from the literature review of sensing projects (ch 2) and sensors (ch. 4), the analysis of the case studies (Clairity and sensing projects at SCL) and the analysis of the mobile sensing fieldwork, as specifically addressed in the research goals (ch. 3).

5.3.A – Strengths of mapping by sensing
5.3.B - Limits of mapping by sensing

5.3.A - STRENGTHS OF MAPPING BY SENSING

- A "proper" scale and resolution for mapping urban climate and air quality
- Increased mapping representativeness
- Opportunity of participation, citizen science, and increased awareness

A "proper" scale and resolution for mapping urban climate and air quality

As introduced in § 1.3 sensing has the advantage of improving both scale and resolution in mapping urban climate and air quality. In fact, exploring this potential was a declared research goal of this work.
§ 5.1 explored the opportunities offered by local scale sensing in mapping air quality: spatial and temporal studies at an unusual high resolution is available for research addressing several aspects, such as spikes in a limited amount of time, and dispersion over space. In addition, since the network provides data at the local level, exposure studies can benefit from this improved scale, contributing to increased epidemiological research at the people's level. Outdoor exposure, in fact, can be deduced from both the air pollution data provided by Clairity and people presence within the campus, by estimation or phone tracking.

In addition, the increased spatial resolution allows unprecedented mapping of heat and air pollutant concentration within the urban environment. § 5.2 demonstrated how it is possible to map urban climate and air pollution indicators and identifying hot-spots, areas with sensitive urban-climatic and environmental problems determined by high-concentration of heat and pollutants. In the case of MIT campus, areas with high-density of building volumes and surfaces and distant from the river in the east campus show higher concentration than the east campus. As shown, spatial differences can be higher than temporal differences, and while a governmental station may monitor a fair quality of air, often the average is hiding health risks in selected areas, either close to emission sources or areas where air is stagnant. Thanks to the fine-grained mapping provided by air sensing, an analysis of causing factors can help to better understand hotspot formation. In the fieldwork mapping, it was shown how calculating urban morphology and other parameters such as wind intensity at the local scale, might provide insights on hotspot generation, and suggest urban planning and design interventions.

Increased mapping representativeness

A relevant aspect that emerged from the analysis is the different representativeness of the sensing data according to the spatial and temporal resolution. From an urban structure point of view, large areas with similar characteristics might require less resolution in air sensing. In fact, the maps in § 5.2 shows how low-density areas with similar green area proportion, such as the west MIT campus, require much less resolution than areas in the west campus, where heat and pollution consistently vary over space.

For this reason, some attempts have been made in order to define the minimum "proper" resolution required, in both time interval and distance from measurements (dependent on the velocity of the mobile sensing campaign). However, because of the severe accuracy concerns of low-cost devices (see next section), and the doubtful process of measuring the complexity of air phenomena occurring around the sensors itself, further research is needed. Waiting for advances in sensor technology, the optimal density of measurement points should be explored, in order to save sensor's energy and data management, while still maintaining data representativeness.

In addition, further exploration of the "proper" scale and resolution, which as emerged, is linked to the characteristics of the site (physical, geographical and meteorological), and a final analysis was conducted at SCL.

Mapping air quality from the fieldwork mobile sensing data, for instance, it is possible to aggregate the data at different higher scales, with smaller resolution, and assess the error made in the estimation. Figure 5-22 shows an example of maps of PM10 at the MIT campus at different size grid cells from 500m x 500m to 25m x 25m, then calculated the average PM10 measurement in each grid cell.

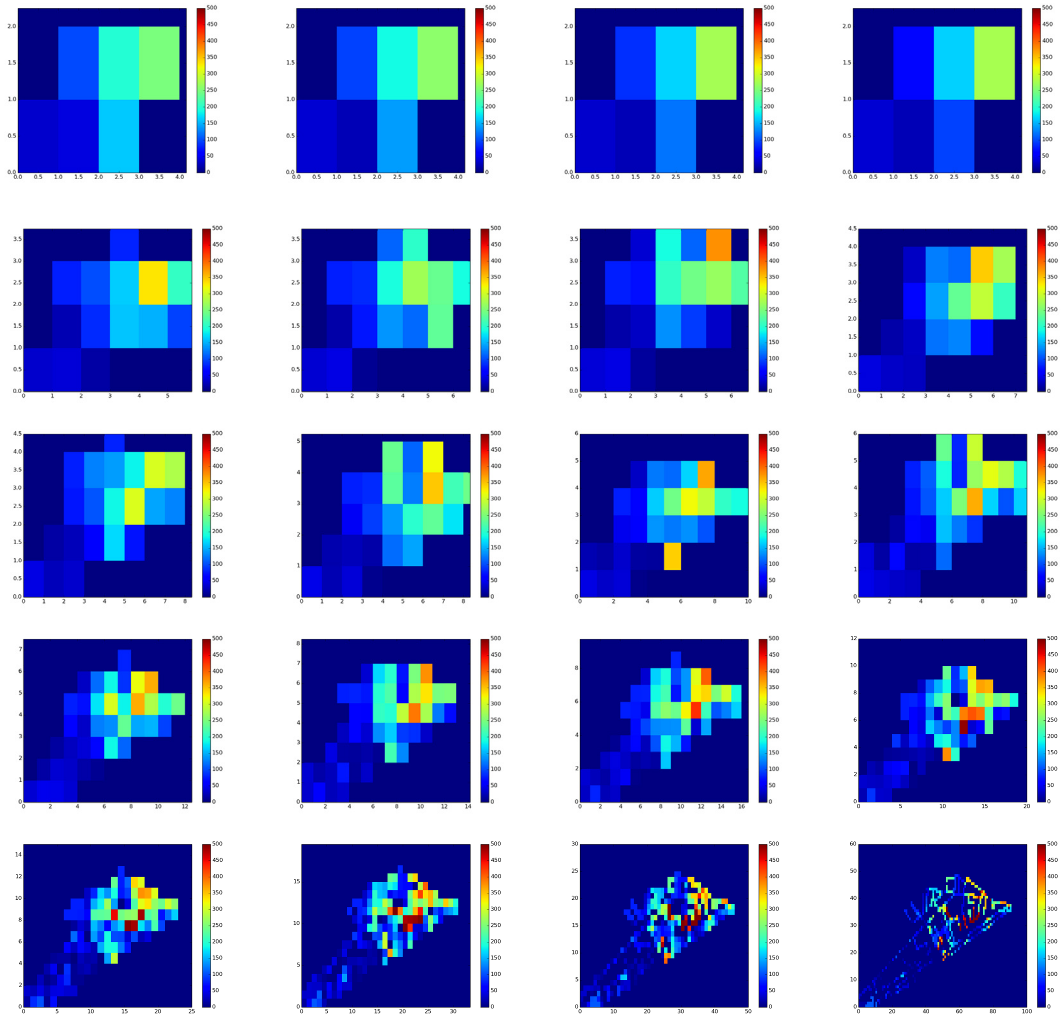


Figure 5-22
Plots of PM10 at the MIT campus at different size grid cells in meters (first raw: 500x500, 475x475, 450x450, 425x425; second raw: 400x400, 375x375, 350x350, 325x325; third raw: 300x300, 275x275, 250x250, 225x225; forth raw: 200x200, 175x175, 150x150, 125x125; last raw: 100x100, 75x75, 50x50, 25x25), with the calculated average PM10 value in each grid cell. Source: elaboration done at MIT-SCL.

As shown, the average error made in estimating the measurement is higher for the west campus compared to the east part of the campus, where a more homogenous concentration of particles seems to occur, and less observation would be needed.

In order to quantitatively assess the different representativeness of a measurement over scales, a comparison between the value of a point and the averaged values calculates at increasing scales was calculated. Considering random selected points across the campus, the representativeness of the PM10 concentration in those points varies with scales in a different way.

Figure 5-23 shows that points in the east campus, such as n. 9, 11, and 12, have less significant variations over scale than others, and their representativeness is higher than points in the west campus (1, 13, 16). For this reason, fewer recordings might be sufficient to describe air quality at certain conditions, and further research and fieldwork plans should include these consideration in the fieldwork design.

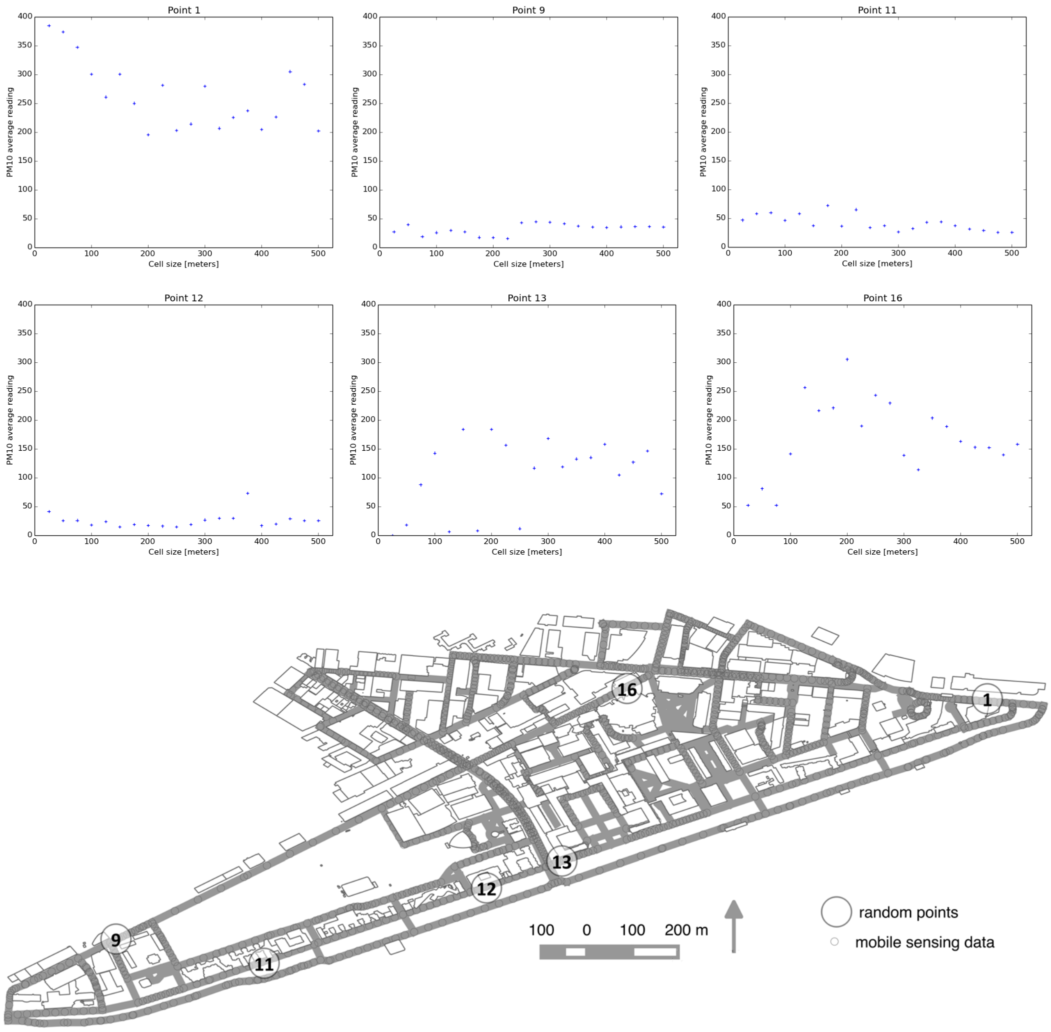


Figure 5-23
PM10 levels for the six random points pictured at bottom. The estimate of the PM10 level (y-axis) varies according to the grid cell size (x-axis) as calculated in Figure 5-22. Source: elaboration done at MIT-SCL.

Opportunity of participation, citizen science, and increased awareness

Since Clairity network and the fieldwork did not involve a participatory sensing component, some evidence from the sensing projects described in ch. 2 can be emphasized in the opportunity emerged from participation in mapping by sensing.

In fact, participatory sensing is the fundamental component of many of the air quality mapping projects recently emerging at a global scale. Involving individuals in sensing processes can be done in several ways, by providing sensors (i.e. AirCasting surverys in New York by HabitatMap no-profit organization) or by creating crowd-funding campaigns (i.e. kickstarter for AirBeams, TZOA, etc.) and making available low-cost devices in the market. Apart from business interest (i.e. Sensodrone, by Sensocorn private company), and academic research (i.e. Envboard/TECO by KIT University) most of the projects aim to increase the participation of citizens in the air quality discourse. From a technical point of view, a vast amount of data coming from volunteer sensing increases the quality of low-cost data and the spatial and temporal coverage, allowing a better fine-grained air quality mapping. See **Annex 2** for more details about the nature of the different sensing projects.

One of the most successful examples of participatory sensing for air quality mapping is the international challenge organized by Everyaware EU project, in four European cities as a form of a web-game ("AirProbe International Challenge," n.d.). The results was a total over 6 million geolocalised data points, with an additional 3 million without geolocation. Both coverage and pollution levels measured indicated a tendency to monitor familiar areas, with a search for highly polluted spots. Within the same project a participatory sensing initiative was also organized involving high-school students in Collegno (Turin, IT) for three weeks, in monitoring their home-school paths and competing to find the most and the least polluted paths in their city. The event has been a proof of concept for an innovative learning scheme, more problem-oriented and curiosity driven. In both the challenge and the smaller initiative, the project's results claim to have reached a progressive learning process of the users involved (Everyaware Project, 2014, pp. 23–24).

However, the opportunity offered by this novelty sensing approach deals with data from a large number of devices, randomly distributed in space and time (according to user usage), un-calibrated and low-cost (therefore less reliable) and carried by non-skilled individuals, as compared to the practice of mapping by limited sensing campaign or by using governmental stationary highly controlled stations, with data collection systems based on expensive high-quality measurement instruments. See next section for more about this.

Involving citizen's science seems to be a fruitful opportunity in both increasing awareness and increasing data for mapping air quality. Community and web-based self-organized sensing initiatives are therefore bottom-up approaches that seem to prove the potential for being integrated in traditional top-down sensing for governmental purposes and international law compliance.

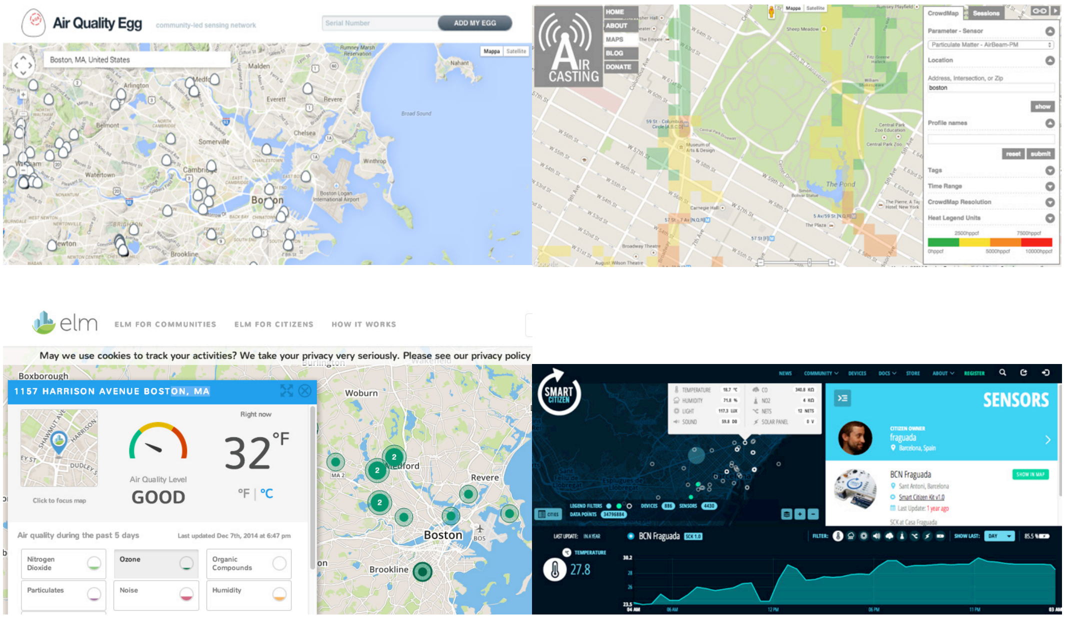


Figure 5-24
Four examples of crowd-sourced air quality projects (mentioned in § 2.2.B) and data shared by the community. From top-left to bottom-right: AirQualityEgg ("Air Quality Egg," n.d.), AirCasting ("AirCasting," n.d.), Elm PerlinElmer ("Elm Air Quality Sensor Network | PerkinElmer," n.d.) , and SmartCitizen ("Smart Citizen : Citizen Science Platform for participatory processes of the people in the cities," n.d.).

5.3.B - LIMITS OF MAPPING BY SENSING

- Cost, technology, usability and data quality
- Communication, transparency and misinterpretation
- Privacy ethic management

Cost, technology, usability and data quality

As seen in both Clairity and the fieldwork, and in some air sensing projects struggling to advance (i.e. CitySense in Cambridre, US, or Smartsantander), technology problems are frequent and seem to be an obstacle to the current diffusion of sensing for urban climate and air quality mapping.
In fact the complexity of factors involved in the measurements, such as power management, observation process, data storage, data streaming and platform operation, and the eventuality of failure of one component, increase the probability of altered measurements. For instance, in Clairity, frequent malfunctioning of nodes created data gap of hours or even days. In the case of the fieldwork, in order to get data from the sensor device, two connection processes are required: a stable and constant Bluetooth connection between the device and the smartphone, and a stable and constant internet connection from the smartphone to the server platform. This is not always possible in specific situations with no connectivity. In addition, since GPS measurements are energy consuming, existing technology for current smartphones do not allow continuous usage for several hours, increasing the limitation of voluntary participation to a sensing project.

Technology is obviously connected to cost: the more sophisticated technology the higher the cost of the device. However, besides the aforementioned issues, most of the existing sensors analyzed in order to plan the fieldwork share the same challenges related to data quality.
The new generation of low-cost air quality sensors is providing an exciting opportunity for research communities to use this technology to map urban climate and air quality beyond traditional regulatory monitoring, and many sensing projects are being implemented, such as AirCasting, AirQualityEgg (see ch. 2).
However, as seen in the case studies and the literature review (§ 4.2.B), air sensors are still in an early stage of technology development, and their characteristics and performance have not yet been evaluated.
Issues occur in accuracy, precision, bias, and in data comparability. Both the Clairity data analysis and the fieldwork data analysis showed the potential for future research and implementation, while it seems that the currents challenges of the devices limits their diffusion for rigorous scientific studies.

<u>Monitoring Urban climate</u>
Most of the sensing project and sensor devices include microclimate estimation, mainly for calibration purposes. Clairity project measurements about temperature and humidity are not considered to be representative of the

outdoor ambient climate and were excluded from the analysis. On the contrary, the fieldwork analysis proved the potential for detecting heat hot-spots (UHI) with a low-cost sensor. While climatologists use higher accuracy instrumentation and generally reject low-cost sensing studies, the potential for a diffused network of stationary and mobile sensor for urban climate seem to be realistic.
A very different situation related to air quality mapping, where sensor technology and cost need further improvement.

Monitoring Particulates

As anticipated, one of the main issues of low-cost sensing for particulates is the challenging conversion from number (count of particles) to mass (concentration). The relationship between aerosol light scattering and fine mass seems to be a well studied argument in the air quality research community. Co-location and correlation statistics have been used for comparative studies since the 90's (“Relationship between Aerosol Light Scattering and Fine Mass,” n.d.), and continue to be explored proving high correlation between particle counters and mass- measuring instruments (Tittarelli et al., 2008).
Nevertheless, there have been studies that suggested that the number rather than the mass per unit volume of fine particles in the air might be more closely correlated with adverse health effects (Wichmann et al., 2000).
While US-EPA continuously releases methods for measuring ambient concentrations of specified air pollutants, designated as "reference methods" or "equivalent methods" (sometimes combining light scattering instruments), particulate counters have in fact, been extensively used in research and in mobile monitoring (“Approved 19" Rack Environmental Dust Monitor, Model EDM 180 - GRIMM Aerosol Technik - Master in Real-Time Aerosol and Dust Monitoring,” n.d., “DUSTTRAK II Aerosol Monitor 8532;Area Aerosol Monitors,” n.d., “Indoor Portable Particle Counter GT-321 | Met One Instruments,” n.d.).
With the availability of low-cost light scattering devices, such as the Dylos, several studies have used inexpensive particle monitors for published research studies (Dacunto et al., 2013; Semple et al., 2013).
Furthermore, some studies have attempted to provide an equation for best fit curve between Dylos measurements and a reference light scattering instrument, for example (Northcross et al., 2013); they tried to identify an algorithm to transform particle numbers into mass, assuming particles are spherical and with a given density (it has been noticed that the Dylos has a non-linear response becoming less responsive to an increase in PM levels when concentration increases, so that a polynomial curve was identified).

However, the correlation between the Dylos particulate counts and mass is challenging, and in the Clairity project the measurements are not directly comparable with governmental concentration data (see § 5.1.A).
In addition, as detailed more in the § 5.3.B, the issue with conversion determines the impossibility of a direct equivalence between air quality index (EP AQI) and the threshold for the colors selected for Clarity communication of results, creating potential misinterpretation with the public.

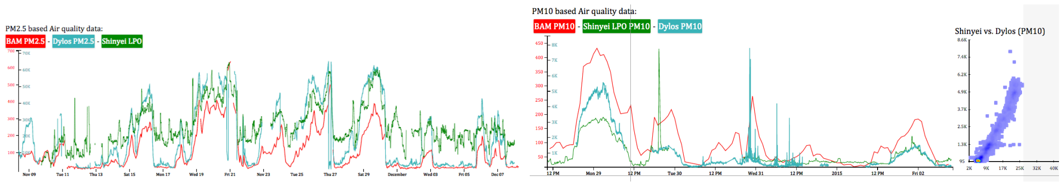


Figure 5-25
Comparison between Dylos, Shinyei (used in EcoPM) and BAM (a professional reference system for standard monitoring). Source: Beijing experiment ("The Shinyei experiment: Real-time Air Quality readings from Beijing," n.d.).

Monitoring Gases

Similar challenges occur in comparing data from gas sensors to governmental concentration. With this specific aim, both the US EPA and the European Union (JRC) are testing and comparing sensors for potential future use within a regulatory framework, such as NO2 and Ozone (Gerboles and Buzica, 2009; United States Environmental Protection Agency, 2013).
See also the US-EPA "Next Generation Air Measuring" research (United States Environmental Protection Agency, n.d.) and the "European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability"(EuNetAir) (European Cooperation in the field of Scientific and Technical Research, 2011) for more information about this topic.

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A final consideration relates to the relationship between accuracy and quantity of data. Increasing the density of data in local areas, for instance by a repeated fieldwork campaign, or better yet, a campaign using multiple sensors simultaneously, ensures a higher quality of the data. The same approach related to air sensing for mapping at a reliable accuracy: repeated measurements increase the opportunity for statistical analysis and the improvement of data quality. In other cases, increasing sensing data allows higher coverage and resolution, and decreases the approximation process with data coming from remote stations. Participatory sensing is usually engaged with the aim of collecting a high amount of data, sacrificing data accuracy for data quantity. With the help of big data analysis tools, and machine learning process, it is possible to extract meaningful information from un-calibrated sensors from participants. While this approach is shared by most of platforms already mentioned (AirCasting, SmartCitizens, AirQualityEggs, etc. see Annex 2) and lead to many attempts to increase the amount of air quality measurements (i.e. using low-cost sensors on pigeons, see ("Pigeonblog," n.d.)), acceptable sensor quality and calibration procedures are both necessary for scientific results, aimed at going beyond educational purposes.

Communication, transparency and misinterpretation

The communication used in the Clairity project, as many other air quality sensing projects, faces challenges in delivering the correct information to the public, and in the transparency of the process.

The main problem arises with defining the colors and description of a heat-map for air quality mapping, which are helpful to make it easier to understand the risk from outdoor pollutants exposure.

For this purpose, the US-EPA air quality index (AQI), for instance, has assigned a specific color to each AQI category to make it easier for people to understand quickly whether air pollution is reaching unhealthy levels in their communities. For example, the color orange means that conditions are "unhealthy for sensitive groups," while red means that conditions may be "unhealthy for everyone," and so on ("Air Quality Index (AQI) - A Guide to Air Quality and Your Health," n.d.).

Many maps from sensing projects uses the same approach, by mapping spatial variation of air quality with heatmaps with corresponding colors.

O3 (ppb) (8-hr)	O3 (ppb) (1-hr)	PM2.5 (µg/m3) (24-hr)	PM10 (µg/m3) (24-hr)	CO (ppm) (8-hr)	NO2 (ppb) (1-hr)	AQI
0-59	-	0.0-12.0	0-54	0.0-4.4	0-53	Good
60-75	-	12.1-35.4	55-154	4.5-9.4	54-100	Moderate
76-95	125-164	35.5-55.4	155-254	9.5-12.4	101-360	Unhealthy for Sensitive Groups
96-115	165-204	55.5-150.4	255-354	12.5-15.4	361-649	Unhealthy
116-374	205-404	150.5-250.4	355-424	15.5-30.4	650-1249	Very Unhealthy
-	405-504	250.5-350.4	425-504	30.5-40.4	1250-1649	Hazardous
-	505-604	350.5-500.4	505-604	40.5-50.4	1650-2049	Hazardous

Figure 5-26
US-EPA AQI with selected pollutants. Source: author's elaboration from US-EPA website calculation tool ("Air Quality Index (AQI) - A Guide to Air Quality and Your Health," n.d.).

However, relevant concerns arise in this process.

In fact, AQI indices (US-EPA or other equivalent governmental air quality index), are based on air pollution concentration according to the definition of air pollution standards (see § 1.2.A) and to the measurements provided by monitoring stations following specific protocols.

Two issues therefore apply to mapping by sensing projects with low-cost technology.

Firstly, as seen with the Clairity project, especially with particulate matter, the conversion factor from low-cost observations to standard measurements is often significant and requires large approximation. Indirect measurements provide data not directly comparable to air quality standards, and communicating their health risk with the same approach as with AQI is inappropriate and can lead to misinterpretation.

Secondly, AQI and air quality standards are based on air pollution data that is averaged over 1, 8, or 24 hours, while many sensing projects, including Clairity, provide short-time measurement.

Therefore, another concern about mapping by sensing is less evident but extremely important. In fact, the pollutant limits and standards are designed according to the pollutant and its different way to affect the human body. For example, SO2 affects the parts of lungs that communicate with the central nervous system, triggering a reflex response, and can cause difficulty breathing and respiratory symptoms such as coughing, wheezing, and chest tightness within 5 minutes of exposure. On the contrary, the respiratory effect of O3 can happen in one hour or even the next day, because of the specific way that O3 affects the body (Ozone can also inflame and damage the lining of the lung, but this effect may not be most obvious until the day after exposure, comparable to the inflammatory effect of sunburn on the skin) (United States Environmental Protection Agency, 2014, p. 16). While governmental data and maps follow AQI principles, many mapping by sensing projects use the same approach for real-time data or data not aggregated in time intervals.

Citizen scientists or the general public may therefore become concerned if they read levels of a pollutant higher than the health thresholds defined.

In fact, the increasing use of sensors provides high-resolution data in both spatial and temporal scale that can even reach one reading per second. As seen in the Clairity example, for instance, real-time sensing allows tracking minute-by-minute changes in pollution levels, and identifying short-term, peak levels of some pollutants (see § 5.1).

In fact, the AQI used in Clairity to communicate the results on the website, is updated for each node every 10 seconds, and uses the colors showed in Figure 5-27:

	Fine Particles (particles/0.01ft^3)	Carbon Monoxide (ppb)	Ozone (ppb)
Good	0-600	0-4500	0-64
Moderate	601-2100	4501-9500	65-164
Unhealthy	2101+	9501+	165+

Figure 5-27
Clairity Air Quality Index. Source: Clairity project report (Clairity, 2014).

In order to define the 2 thresholds separating “moderate” and “unhealthy” characteristics, Clairity considers the 8-hour threshold from Ozone and the 1-hour threshold for CO, from UD-EPA standards.

However, the actual health effects of very short term elevated levels of most pollutants are not well understood and governmental standards (such as by WHO, EPA, EU), are established based on larger temporal scales with little information on short-term pollutant exposures. For example, the ozone 8-hour standard suggested by the WHO is 100 µg/m3, 120 by EU and 150 by US-EPA (=75ppb) (see § 1.2.A) and theretofore, because the standard is based on the average of hourly monitoring measurements over a 8-hour period, it does not mean that a single measurement taken over a few minutes, or even hours, above the threshold is a cause for immediate concern.

As shown in Figure 5-27, because in Clairity AQI three pollutants are combined in the AQI visualization, the color instantaneously showed on the website relates to the worst performing pollutant among the three. Coarse particles, NO2, and NO are being monitored but are not included in the AQI colors, therefore not being communicated even if they reach severe concentration.
In order to define the 2 thresholds separating "moderate" and "unhealthy" characteristics, Clairity considers the 8-hour threshold from Ozone and the 1-hour threshold for CO, raising concerns as already explained. Additionally, there is subjectivity in the definition of the values, since they do not match with the US-EPA AQI (see Figure 5-26).
Additionally the threshold considered for fine particles comes from Dylos specification, as declared by the manufacturer, with no comparison to official standards. It is clear that a comparison with US-EPA standards for PM2.5 needs to be explored, in order not to provide miscommunication of air quality status.

As emerged from this brief description, besides common issues in monitoring air pollution, communicating the results in relation to the quality of air and the potential health risk associates to the exposure, is challenging.
Transparency in the data communicated is therefore essential, in order to raise awareness without inducing misinterpretation of results.

Privacy ethic management

Considering all the existing sensing projects, briefly described in ch. 2, such as AirCasting or AirQualityEgg, it emerges that none of them actively deal with privacy and security concerns. Some of them developed simple systems to fully hide or share the measurements publicly by an access control feature (i.e. AirQualityEgg). Since most of the data comes from mobile sensing with GPS coordinates, one of the main concern can be the possibility of tracking users' movements.
However, some expedients can be used in order to face privacy issues in participatory sensing. For example, in the maps created within the Everyaware projects, presented in § 2.2.B, air pollution is mapped adding noise to data, using a fine-grained control system. Another expedient can be the possibility for a user to have the phone app process the data and only stream aggregated statistics. Current devices and apps, however, seem to stream the raw data to the platform, like in the fieldwork case, and geolocated tags are added.

Personal sensing examples have similar issues, even if they often do not include publicity of the data. However, they are usually associated with exposure

monitoring, by collecting health indicators, such as heart rate, blood oxygen levels, and the data is stored on a platform.
The problem pertains to the general debate about big data and privacy: personal data, social media data has not always managed to protect users' privacy. In addition, in some projects, such as work similar to "Urban centrality", opportunistic sensing provides user data (such as bank transactions) with no explicit consents, or doubtful privacy management.
Mobile phone tracking, via triangulation and multi-lateration of radio signals between radio towers, or via Bluetooth sensors (Louvre museum example) or simply via GPS (most of the sensing App), touch upon delicate privacy issues, since potentially enables someone to check the location and movement of a user without an informed, explicit consent.

Other sensing projects, such as Underworlds, also described in § 4.2.B, face an even larger privacy issue, since it is dealing with public health data. The risk of data leak or misuse of data for purposes other than the project might raise challenging privacy and security concerns.

Conclusion

This chapter presented a detailed data analysis and interpretation of results from the sensing experiments conducted using the local sensing network (Clairity) and the fieldwork conducted by author in April-June 2014.
In general, the potential of sensing emerged to be very high, but more for future elaboration than today implementation.

Strong and unexpected findings were underlined in the data analysis and interpretation.
On one hand, building a local sensing network, such as Clairity, is innovative and forward thinking but still struggles with issues connected to recent sensor technology. In addition, being a stationary network, data representativeness is challenging and designing the location of the sensing nodes requires further research. Communication and transparency challenges were as found to be underrated but essential to avoid the misinterpretation currently ongoing in many sensing projects.
On the other hand, the mobile sensing shared some technology issues, with the extra challenges of sensing in mobility (i.e. air flow, connectivity). However, it showed the best potential for an unprecedented resolution in mapping urban climate and air quality parameters within the urban environment. It allowed hot-spot mapping in both urban climate and air quality.
Therefore, mobile sensing emerged as a feasible option and the only way to gain a proper representativeness and increase resolution. However, it needs to be framed in a context where calibration and reference to official data is conducted, otherwise the qualitative approach can lead to unreliable results. Including the sensing data in a platform can be problematic too, but machine learning techniques are helpful to increase data quality coming from different low-cost sensors.

While these findings suggest the challenges of this recent technology, rapid development are occurring, and it is likely that sensors will improve in data quality and be ready to be implemented at a large scale for urban mapping.
Urban planning, therefore, should be ready and profit from this opportunity, as it will change the future of urban climate and air quality in our cities. In addition, participatory sensing scenarios are beneficial for both increasing data quality and enhancing awareness on environmental and health topics.
The next and final chapter expands more about this.

References

Air Quality Egg. (n.d.). Retrieved December 29, 2014, from http://airqualityegg.com/

Air Quality Index (AQI) - A Guide to Air Quality and Your Health. (n.d.). Retrieved January 02, 2015, from http://www.airnow.gov/index.cfm?action=aqibasics.aqi

AirCasting. (n.d.). Retrieved December 29, 2014, from http://aircasting.org/

AirProbe International Challenge. (n.d.). Retrieved December 08, 2014, from http://www.everyaware.eu/APIC/

Approved 19" Rack Environmental Dust Monitor, Model EDM 180 - GRIMM Aerosol Technik - Master in Real-Time Aerosol and Dust Monitoring. (n.d.). Retrieved December 06, 2014, from http://www.grimm-aerosol.com/en/environmental-dust-monitors/103-approved-19-rack-environmental-dust-monitor-model-edm-180.html#ad-image-0

Clairity. (2014). *An Air Quality Sensor Network for MIT ' s Campus* (p. 74). Retrieved from http://clairity.mit.edu/site/documents/report.pdf

CLAIRITY: MIT's Air Quality Network. (n.d.). Retrieved December 29, 2014, from http://clairity.mit.edu/site/html/

Dacunto, P. J., Cheng, K. C., Acevedo-Bolton, V., Klepeis, N. E., Repace, J. L., Ott, W. R., & Hildemann, L. M. (2013). Identifying and quantifying secondhand smoke in multiunit homes with tobacco smoke odor complaints. *Atmospheric Environment*, *71*, 399–407. doi:10.1016/j.atmosenv.2013.02.018

DUSTTRAK II Aerosol Monitor 8532;Area Aerosol Monitors. (n.d.). Retrieved December 06, 2014, from http://www.tsi.com/dusttrak-ii-aerosol-monitor-8532/

Elm Air Quality Sensor Network | PerkinElmer. (n.d.). Retrieved January 02, 2015, from http://elm.perkinelmer.com/map/

European Cooperation in the field of Scientific and Technical Research. (2011). *European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability - EuNetAir* (pp. 1–66). Retrieved from http://w3.cost.eu/fileadmin/domain_files/ESSEM/Action_TD1105/mou/TD1105-e.pdf

Everyaware Project. (2014). *Everyaware Project - Final Report Period* (p. 56). Turin, IT. Retrieved from http://www.everyaware.eu/resources/deliverables/D7.3.pdf

Gerboles, M., & Buzica, D. (2009). *Evaluation of micro-sensors to monitor ozone in ambient air*. Ispra (VA), Italy. doi:10.2788/5978

Herberger, S., & Ulmer, H. (2012). New IAQ sensor for demand controlled ventilation: REHVA. *HVAC Journal*, *04*(August), 37–40. Retrieved from http://www.rehva.eu/publications-and-resources/hvac-journal/2012/042012/new-iaq-sensor-for-demand-controlled-ventilation/?L=0%2527%2520and%2520char%2528124%2529%2520user%2520char%252

Indoor Portable Particle Counter GT-321 | Met One Instruments. (n.d.). Retrieved December 06, 2014, from http://www.metone.com/particulate-gt321.php

MassDEP:: Air & Climate :: Air Quality & Monitoring :: MassAir version 1.5. (n.d.). Retrieved December 06, 2014, from http://public.dep.state.ma.us/MassAir/Pages/MapCurrent.aspx?pm=88502&ht=1&hi=102

Northcross, A. L., Edwards, R. J., Johnson, M. A., Wang, Z.-M., Zhu, K., Allen, T., & Smith, K. R. (2013). A low-cost particle counter as a realtime fine-particle mass monitor. *Environmental Science: Processes and Impacts*, *15*, 433. doi:10.1039/c2em30568b

Personal Weather Station: KMACAMBR9 by Wunderground.com. (n.d.). Retrieved January 01, 2015, from http://www.wunderground.com/personal-weather-station/dashboard?ID=KMACAMBR9

Pigeonblog. (n.d.). Retrieved December 08, 2014, from http://realtimecities.wikispaces.com/Pigeonblog

Relationship between Aerosol Light Scattering and Fine Mass. (n.d.). Retrieved December 06, 2014, from http://capita.wustl.edu/CAPITA/CapitaReports/BScatFMRelation/BSCATFM.HTML#content

Semple, S., Apsley, A., & MacCalman, L. (2013). An inexpensive particle monitor for smoker behaviour modification in homes. *Tobacco Control*, *22*(5), 295–8. doi:10.1136/tobaccocontrol-2011-050401

Smart Citizen : Citizen Science Platform for participatory processes of the people in the cities. (n.d.). Retrieved January 02, 2015, from https://www.smartcitizen.me/

The Shinyei experiment: Real-time Air Quality readings from Beijing. (n.d.). Retrieved from http://aqicn.org/sensor/shinyei/

Tittarelli, A., Borgini, A., Bertoldi, M., Desaeger, E., Ruprecht, A., Stefanoni, R., … Crosignani, P. (2008). Estimation of particle mass concentration in ambient air using a particle counter. *Atmospheric Environment*, *42*(36), 8543–8548. doi:10.1016/j.atmosenv.2008.07.056

United States Environmental Protection Agency. (n.d.). Next Generation Air Measuring. Retrieved December 07, 2014, from http://www.epa.gov/airscience/next-generation-air-measuring.htm

United States Environmental Protection Agency. (2013). *Roadmap for Next Generation Air Monitoring*.

United States Environmental Protection Agency. (2014). *Air Sensors Guidebook* (p. 73). Research Triangle Park, NC: US Environmental Protection Agency. Retrieved from ww.epa.gov.ord

Wichmann, H. E., Spix, C., Tuch, T., Wölke, G., Peters, A., Heinrich, J., … Heyder, J. (2000). Daily mortality and fine and ultrafine particles in Erfurt, Germany part I: role of particle number and particle mass. *Research Report (Health Effects Institute)*, (98), 5–86; discussion 87–94. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11918089

CHAPTER 6

6. FINAL CONSIDERATIONS | RECOMMENDATIONS FOR URBAN PLANNING

Introduction

What the research shows? What can be recommended to urban planning?

Chapter 5 included all findings that emerged from the data analysis and interpretation of results, on the basis of the fieldwork execution and the data gathered from both the experiment and the collaboration with mapping by sensing projects at SCL-MIT.

While most of the findings outlined in the previous chapter underlined the challenges of recent sensing technology, rapid development are occurring, and it is likely that low-cost sensors will improve in data quality and be ready to be implemented at a large scale for urban mapping.

This chapter, therefore, includes recommendations for urban planning, with the aim of contributing to the process of making urban planning ready and profit from the fruitful opportunities offered by sensing, as it has the potential to change the future of urban climate and air quality in our cities. For example, participatory sensing scenarios are beneficial for both increasing data quality and enhancing awareness on environmental and health topics.

In particular, the three sections of this chapter address recommendations for urban planning on three levels, on the basis of the findings outlined from this work.

The first section (§ 6.1) envisions a future where urban planning is more and more focused on governing health and well-being at the people's level, by mapping urban climate and air quality profiting from new (sensing) tools and integrating sectorial knowledge. However, the panoptic top-down concern should be tackled by bottom-up "smartness": promoting crowdsourcing and people-centric sensing will enhance urban sensing in an integrated perspective, both increasing data quality and citizens participation and awareness.

The second section (§ 6.2) provides detailed recommendations in profiting from the opportunities and in dealing with the limitations of using sensing. Urban planning should profit from sensing pervasiveness, its scale and resolution improvement, while at the same time, should overcome barriers, such as data quality and transparency of mapping.

The last conclusive section (§ 6.3) wraps up the overall findings and recommendations, in a project proposal to be applied in the case of Milan. Sensing will integrate modeling in the final aim of mapping urban climate and air quality in the city of Milan.

6.1. ENVISIONING A CHANGING ROLE FOR URBAN PLANNING

On the basis of the findings outlined from this work, from the literature review to the fieldwork in the field of mapping urban climate and air quality by sensing, this section frames the overall expected future role of urban planning. Considering the emerging trend with attention on environment and health, it seems likely to envision a future where urban planning is more and more focused on health and well-being, and on governing them at the people's level.
Mapping by (innovative) air sensing can be a way of transferring the climatic and environmental knowledge into planning languages, bridging the gap between urban climatology, meteorology, air studies, city planning and urban design.
However, the panoptic top-down concern arising from recent "smart city" ICT-driven projects, should be tackled by bottom-up "smartness" promoting crowdsourcing and participatory sensing.
In fact, as seen in the case studies, humans seem to be more and more the focus of urban science, and enhancing people-centric sensing in an integrated modeling/sensing perspective, is helpful in both increasing data quality and citizen participation and awareness.

6.1.A – Governing health and well-being, environment and climate change
6.1.B – Sensing, being smart, but not top-down and tech-oriented

6.1.A - GOVERNING HEALTH AND WELL-BEING, ENVIRONMENT AND CLIMATE CHANGE

- Back to govern health and well-being
- Governing climate change and profiting from climate awareness
- Governing by improved knowledge: mapping urban climate and air quality

Back to govern health and well-being

The history of urban planning and design for health and well-being for liveable urban conditions traces back to traditional vernacular practices and theories, such as Greek-Roman city principles or Chinese feng shui. Urban climate and air quality in cities was mostly controlled by natural ventilation, relying on wind and thermal buoyancy as driving forces. Urban planning has used these driving forces throughout history to build cities with the desired thermal environment, according to its geographic location, and to transport away undesired pollutants. Although principles such as orienting buildings towards the sun or prevailing wind were followed for two thousand years, urban climatology was set on a solid scientific base around the nineteenth and mid twentieth century, with the aforementioned seminal works of Luke Howard, Albert Kratzer, and Tony Chandler (Chandler, 1965; Howard, 1818; Kratzer, 1956). Since then, applied climatology appeared to hold great promise for implementing urban planning and design practices, which meanwhile had to deal with new urban conditions,

such as unprecedented high buildings and skyscrapers, and their impact on air turbulence and shading, and new pollutants emission within the urban environment, such as car mobility and urban industry. A new field of research was born, and innumerable studies used numerical modeling and sensing techniques, such as remote sensing, balloon mounted sensors, and sensing stations in order to understand energy exchanges and air flow within the urban environment.
However, while urban climatology has progressed and has been developing since its first studies, such as the work by Oke, its practical application has not. Landsberg's Metutopia city criteria (H. E. Landsberg, 1973) still seems to not be addressed in urban planning practices, and the lack of atmospheric and climate principles in settlement planning (Oke, 1984) remains evident in current planning processes.

The reasons why urban planning and design removed traditional air-related principles, with few exceptions, such as Stuttgart city later mentioned, and failed in integrating new knowledge coming from the advances in urban climatology are complex.
Issues in communication between urban climatology, environmental science and urban planning seem a predominant factor (Oke, 2006). The raise of air conditioning might have its role, while the rise of car mobility, urban sprawl and the last decades of nefarious soil sealing, asphalt use, and tree removal, all contributed to the new challenges for urban planning, in facing exacerbation of outdoor temperature extremes and air pollution concentration.
Probably because of the complexity and interdisciplinary nature of the subject, there still seems to be a lack of integration with the large body of knowledge concerning urban climate and air pollution into planning processes.
In particular, while best practices are proposed at the building scale, where these potential barriers have not prevented application of knowledge from climate, energy and environmental disciplines by planners, architects and engineers, this is not generally valid for the neighborhood scale. Yet the neighborhood scale is the scale of communities, of living public outdoor spaces, where air quality and urban climate have their main effects.

Governing health and well-being

However, health and well-being are priorities for the billions of people living in stagnant air neighborhoods, and urban planning has a big role in potentially improving urban condition, for both microclimate comfort and air pollutant removal.
As explored in this work, the complexity of the factors involved in heat and pollutant accumulation within urban environment requires studies and urban measures at the local scale.
Urban planning should therefore embrace more attention to health and well-being at the neighborhood level, somehow as stressed by New Urbanism movement, with an emphasis on people's scale and quality of life, but profiting from emerging technologies that allow more understanding of the local scale.

In fact, there is a recent emerging role for planners in urban heat and air pollution debate (Stone, 2005), and recent sustainable urbanism concepts and design practices are promoting health and well-being for sustainable, walkable neighborhoods (Duany et al., 2009, Chapter 6; Farr, 2012, Chapter 7). Recent protocols, such as the Ecodistricts protocol (http://ecodistricts.org), and rating systems, such as LEED-ND (United States Green Building Council, 2014), likely to increase in their diffusion, have specifically addressed neighborhood health-well-being, and outdoor climate and air quality is one of their main components.

Governing climate change and profiting from climate awareness

Besides the here mentioned barriers in complexity, scale and communication that urban planning should overcome in order to improve urban health and well-being, climate change is posing new challenges for cities.

In fact, climate change causes added stress on neighborhoods, such as heatwaves exacerbating UHI in some urban areas, threatening the health of inhabitants. Increased heat can generate increase pollutants formation, such as secondary ozone during hot summer, causing respiratory illness. Several actions are being taken by urban planning, and "renewable cites" (Droege, 2006); "low carbon" cities and regions (Treville and Dosi, 2012), include mitigation measures, while adaptation measures are being included in "climate plans", with synergies to health improvement: adapting to UHI harmful effects, especially in the case of heatwaves, is an adaptation strategy that increases urban resilience and climate action plans can enforce it (Stone et al., 2012).

However, while climate considerations have galvanized urban planning, and many cities have adopted some form of climate plan, city planners' awareness of urban climate and air quality issues is generally lacking, or leading to unsuccessful practices. In fact, as emerged from a recent study "Climate change and cities" (Rosenzweig et al., 2011), urban planning seems to struggle in acting towards climate change's low-frequent and high-impact hazards. One of the main reasons can be traced to the unusual temporal and spatial scale adopted: the remote temporal horizon of climate plans is somehow unusual for urban planning, and the global models downscaled at smaller scale usually have a coarse resolution of 12 kilometers square pixels, whish is unusual for urban planning interventions (Hebbert and Webb, 2012). In fact, in the climate change discourse there is little about high-frequency and micro-scale phenomena, such as spatial patterns of shade, shelter from wind and rain, UHI, local air circulation, pollutant accumulation and dispersion, and similar factors of significance at the people's scale, for their everyday health and liveability.

As evidenced by this research, these effects are complex and hardly downscaled and modeled, while direct observations are required for a local scale and fine resolution. Existing urban planning tools, like INDEX, Climate-Neighbor and I-PLACE3S, are more and more including climate change considerations (Condon et

al., 2009), and urban design tools, like Envimet, Solweig, and Rayman are being incrementally used for improving modeling air conditions at the microscale.
Emerging sensing techniques are being pervasively used and explored, thanks to advances in air sensor technology, and new opportunities are available for city planners.
In fact, air sensing, as explored in this research, has the potential to increase knowledge to an unprecedented level, for both environmental science and urban planning, and can provide existing integrated tools with better decision-making processes.
Mapping urban climate and air quality should then be viewed as a promising example, and urban planning should be prepared to benefit from maps at high-resolution and local scale, since air mapping availability is likely to increase in the coming years.

It seems therefore likely to envision the future urban planning landscape which is increasingly focused on governing health and well-being at the people's level.

Governing by improved knowledge: mapping urban climate and air quality

In order to better govern cities, urban planning should increase knowledge, by quantitative and qualitative data about urban social, economic and environmental phenomena, by mapping and sharing data and analyses.
In the field of health and well-being, mapping urban climate and air quality can be beneficial. Progressing from successful but limited experiences in mapping urban climate and air pollution for defining local measures, future urban planning should be ready to incorporate climate and pollutant considerations in its process.
Stuttgart planning is a valuable and famous experience of a city that deliberately studied the behavior of its local air system and learned how to map and manage urban planning; today, its "urban climatology and environmental pollution unit" of ten scientists remains outstanding in Germany and the greater world (Hebbert and Webb, 2012). Mapping is intended as a knowledge transfer mechanism, as the cross-disciplinary connection and cooperation between climatology, environmental science and urban planning. Mapping urban climate and air quality for urban planning has the ability to translate complicated pollution and climatology data into a spatial pattern that is comprehensible for city planners and non-experts.

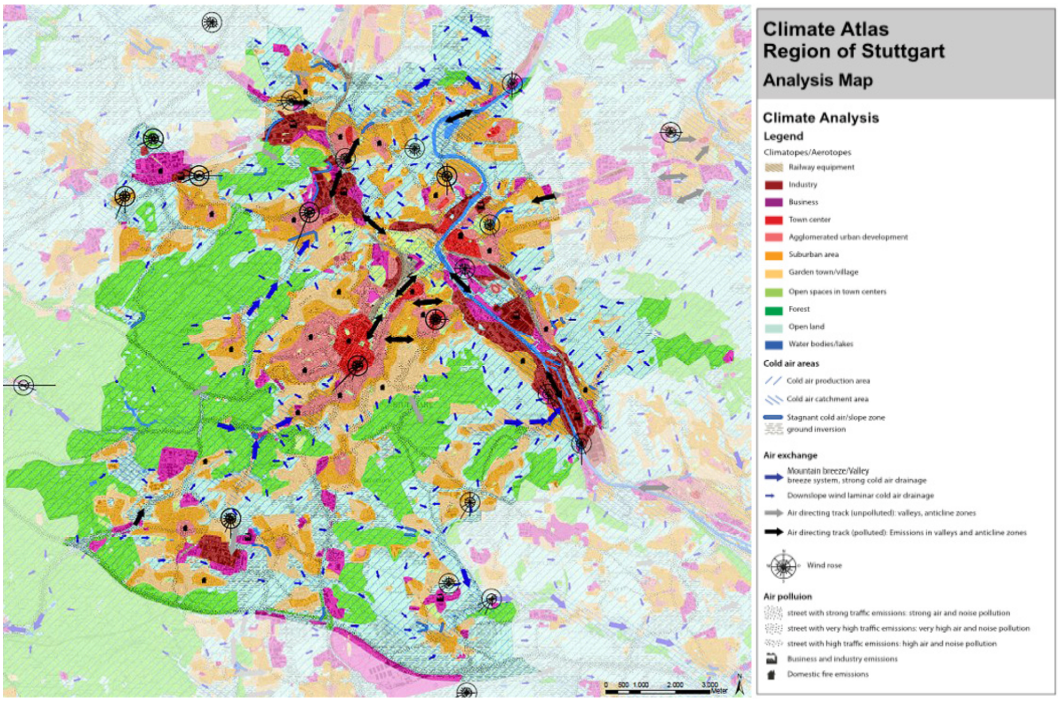


Figure 6-1
Climate Atlas, Region of Stuttgart, analysis map. Source: Stuttgart Climate Atlas 2008 ("Climate Atlas Region Stuttgart 2008," n.d.)

In addition, mapping is meant for informing and providing the basis for decision-making processes. In the case of Stuttgart, practical recommendations and applications for urban planning and design are implemented (i.e. regulatory requirements for green roofs and facades, building height limitation, measures to mitigate harmful effects of highway pollution on residents, such as traffic calming schemes, traffic separation zones, dense planting), all of them based on the city's Climate Booklet for Urban Development (Ministry of Transport and Infrastructure of Baden-Württemberg, 2012, para. 6) following goals for climate-friendly spatial planning:

- Improvement of habitat conditions with regard to comfort/bioclimate
- Improved aeration of settlement areas
- Increase of fresh air supply through local wind systems
- Reduced emission of air pollutants and greenhouse gases
- Determination and appropriate evaluation of existing and expected pollution
- Appropriate reaction to pollution situations through adaptation of use concepts

According to the same booklet, and as evident from the principles and the overall perspective of the work, the term climate "*is used not merely to describe meteorological influences in the narrow sense of climatology, but also air quality components in the sense of the urban climatology. These include the investigation and rating of air pollution impacts (immissions), studies of pollution dispersal (transmission), and measures for the reduction of pollutant releases (emissions)*".

Going beyond traditional urban climate zones (Oke, 2004; Stewart and Oke, 2012; Stewart, 2013) focuses on climatology work, the more comprehensive approach developed in Stuttgart Klimaatlas (Figure 6-1), seem to be followed by several cities in the last years in developing their "urban climatic maps". A recent review (Ren et al., 2011) confirms the virtue of the technique of mapping urban climate and air quality in providing recommendations for urban planning. In fact, the spatial medium of cartography (in a multi-layer GIS model) of an urban climatic map generally combines three analytical aspects:

- Ventilation and the wind environment (i.e. mapping wind tunnels)
- Thermal environment and heat stress (mapping UHI)
- Air quality (mapping pollution concentration).

In order to map each aspect, such as the thermal environment, multiple layers of data are collected, from geographical data to sensing data gathered with direct observation, such as traverse mobile sensing measurements. Figure 6-2shows an example of thermal map produced for the city of Kaohsiung, Taiwan (Ren, Lau, Yiu, and Ng, 2013).

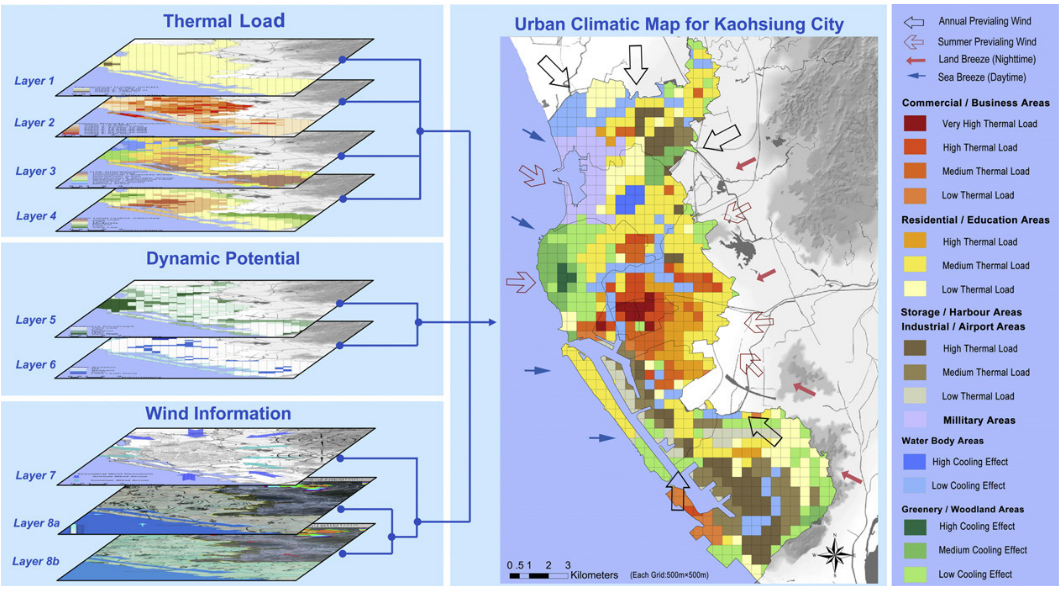


Figure 6-2
Structure of the urban climatic map construction for Kaohsiung, Taiwan. The map uses a 500x500 meter grid. (Ren et al., 2013, p. 12)

Recent experiences are embracing the opportunities offered by mapping urban climate and air quality, following Stuttgart honorable example, integrating their recommendations for urban planning and design, such as Seoul (Eum, Scherer, Fehrenbach, Köppel, and Woo, 2013), Hong Kong (L. Chen and Ng, 2011), and many other cities across more than 15 countries in the world (i.e. Tokyo, Japan; Arnhem, Netherlands), recent increasing interest in this type of mapping, according to the mentioned Ren's review (Ren et al., 2011)

Mapping urban climate and air quality is therefore the information basis for cross-disciplinary study and practice, and the opportunities for urban planning and design to use it for improving health and well-being are vast. UHI and

pollutant concentration and sensitive areas can be visualized by colors and graphics presented with spatial information in maps, in a way that urban planning can profit from this evaluation tool and implement local actions.
Both sensing and modeling are required for mapping urban climate and air quality; however modeling heavily relies on sensing, on local observation and monitoring sensor networks. Because of the lack of sensing due to the cost of the surveys, their limited spatial-temporal validity, and the cost of the sensing infrastructure networks, their maintenance and their limitation in representativeness, there has been a large spread of modeling studies generated in the past few decades while sensing studies are only very recent.
However, recent enhancement and innovation in sensor technology is shifting this paradigm: from urban modeling to urban sensing (see § 6.2.B).

The opportunities for urban planning in having maps at the local scale and high resolution on urban climate and air quality are vast (see § 6.2.A). Here instead, some limitations of mapping for improving health and well-being can be mentioned, together with synthetic solutions mixed with advantages (Ren et al., 2011):

- Lack of homogeneity and comparability among maps: standardization procedures should be developed in order to share knowledge and compare applied measured and ascertain the improvement effect on urban liveability;
- The necessary use of GIS and digital expertise: different scales and resolution should be maintained and updated for a flexible planning integration;
- Data based on limited observations: data from sensing (i.e. mobile traverse temperature) should be included in modeling and better explored.

Next section § 6.1.B deals with recommendations to overcame limitations in mapping by sensing, while § 6.2 introduces recommendations to profit from the opportunities of mapping urban climate and air pollution by sensing.

Urban planning should be prepared, in benefiting form mapping air quality and urban climate at high-resolution local scale, since air mapping availability is likely to increase in the coming years.

It seems therefore likely to envision a future where urban planning is more and more focused on governing health and well-being at the people’s level, by mapping urban climate and air quality profiting of new tools and integrating sectorial knowledge.

6.1.B - SENSING, BEING SMART, BUT NOT TOP-DOWN AND TECH-ORIENTED

- Smart city and the panoptic top-down ICT concern
- New science of cities: humans as the focus of urban science
- Bottom-up smartness: pluralistic models, DIY urbanism, crowdsourcing

Smart city and the panoptic top-down ICT concern

We live in a predominantly urban and digitally connected world. According to the last UN prospect, 54% of the world's population reside in urban areas in 2014, and by 2050 the urban global population is projected to reach 66% (United Nations, 2014). ICT is growing worldwide, especially in urban areas, and societies at every level of development and wealth category are adopting mobile devices and internet-enabled computers, the two dominant forms of information and communications technology (Heeks, 2008).

Proponents of the vision of "smart cities" elevate ICTs as an important new force shaping their form and organization, whether in grand plans for new cities or the transformation of existing ones, asserting that it will enhance some advantages or mitigate some problems traditionally ascribed to cities.

However, the ICT component, and more generally the adjective "smart", clearly imply some kind of positive urban-based technological innovation, underlying a self-congratulatory tendency which hides numerous unspoken assumptions (Hollands, 2008). In fact, as mentioned in § 2.3, urban technological innovation, via ICTs, are found in literature with a positive connotation: the "city of bits", the "virtual cities" (Dodge et al., 1998), the "computable city" (Batty, 1997), the "ubiquitous city" (Jang and Suh, 2010; H. Lee et al., 2008), the "geocomputation revolution" making cities grow and evolve (Diappi, 2004), the "real-time city" (Calabrese and Ratti, 2006), and "city sensing" (Borga, 2014) are all ICT-driven concepts and approach.

However, while today's "smart city" concept, adopted in many cities for self-promotional purposes, assumes positive impact of ICT on the urban form, it hides a lack of definition and precision, rhetorical aspects and a lack of principles which would make them more progressive and inclusive (Hollands, 2008).

Advantages are evident and discussed in this work, since ICT (air sensing networks in this research), allows improving knowledge for traditional and more recent urban problems, such as exposure to heat and pollutants concentration within cities.

Nevertheless, the ICT-driven idea of smart city designed as "open air computers", to address current efficiency (and only sometimes sustainability) concerns, follows the traditional paradigm of top-down and technocratic approach, and almost always leave citizens as an afterthought. In classic examples, like Masdar City, smart cities systematically address maximum resource efficiency through design and top-down management, and seem not to reflect on how these systems are accepted and involved in communities.

In fact, this top-down narrative enjoys the support of the world's largest software services and hardware corporations poised to build such systems through exclusive government contracts, such as IBM, Cisco, or Siemens. The

danger of the “corporatization of city governance and a technological lock-in” is a current critique about smart city being too technocratic in nature and being captured and overtly shaped by corporate interests for large, long-term market potential for their products (Kitchin, 2014, p. 10). Examples included in this work, such as SmartSandander, are not exempt from these concerns.
Technology asking for more technology might go against ecological principles and forget people’s needs at the same time. For example, installing an invasive and energy-consuming air-sensor network could lead to intrinsic contradictions, with the intent of improving citizens’ air quality and life, while contributing to its pollution and altering urban environment. However, projects like Citivan (see chh. 3-4) are founded on a citizen’s living condition, and sensing technology is directly addressing their needs and improving life quality and health.
In cases such the New Songdo City, South Korea, a massive smart city or “ubiquitous city” (Jang and Suh, 2010; H. Lee et al., 2008) designed from scratch including ICT in the early master planning and infrastructure design, some attempts to address quality of citizens life and environmental sustainability (“u-eco-city”) are being made, but with inherent contradictions, mixed results and adverse effects, making it a doubtful model for replication (Shwayri, 2013)

Beyond the fear of the creation of top-down smart cities as “panoptic cities” (Kitchin, 2014), a pluralistic model focused more on a bottom-up approach in urban government is now also emerging. Integrating the idea that citizens are “the ultimate actuators” of the smart city, urban planners are facing more democratic bottom-up approaches, thanks to the potential of “collective intelligence” to be integrated in the smart city vision.

New science of cities: humans as the focus of urban science

The shift from urban modeling (Batty, 1976) to city sensing, in the context of the smart city discourse, was introduced in § 2.3. As anticipated, the sensing component for the ”real-time city” and “wiki-city” (Calabrese et al., 2008), the “sentient city” (Shepard, 2011), and the “responsive city” (Goldsmith and Crawford, 2014) can be both seen as a top-down and a bottom-up approach.
From one side, a smart control system for a city acts as human cerebellum, understanding and intelligently responding to uncertain environments in real-time, according to hierarchies and feedback loops. Central to the top-down narrative of smart cities is the idea that cities can be modeled, built, and operated as real-time control through data generated by individuals, institutions, and sensors. For example, by monitoring the localized phone activity in a city (provided by a mobile operator) (Manfredini et al., 2012; C Ratti, Pulselli, and Williams, 2006), or the movement of buses (provided by a transit agency), a system could identify mismatches and make cities more efficient, safe, and healthy.

As the analytical tools to handle big data have grown more sophisticated over the last two decades, scientists have applied a diverse mix of modeling approaches originating from different fields, such as mathematics, economics, and physics, and sensing data analyses coming from human activities, such as social networks, in order to explain fundamental dynamics of cities. Complexity sciences, social physics, urban economics, transportation theory, regional science, and urban geography are examples of merging fields used to study citizens' behavior and how cities function. Streams of computational social science and "urban metabolism" studies scale metaphors for the city; for instance, the pace of social life (e.g. crimes, patents) was found to relate exponentially to the size of cities, by nearly the same degree as an animal's metabolism relates to its body size (Bettencourt, Lobo, Helbing, Kühnert, and West, 2007). Michael Batty summarizes these approaches as a New Science of Cities (Batty, 2013), which also includes biological patterns of cell growth, gravity studies and fractal geometry, suggesting that cities are not simply places in space but complex systems of networks and flows where relevance for future research and planning is on collective action. Humans are the focus of urban science today, and in order to understand and improve cities, humans' interactions, flows and networks need to be explored. The collaboration with MIT Underwords project conducted under this research (see chh. 3-4) showed this emerging trend in urban studies, where sensing technology meets urban metabolism for improving citizens' health.
Cities are not seen as a machine, which a "controller steered […] cybernetically toward a future desired state", but as complex systems like "biological organisms evolving in a Darwinian fitness landscape", and small interventions can have massive, counterintuitive consequences, making cities almost impossible to control. In urban planning field, this discovery is devastating: "monumental top-down plans, which dominated most of 20th-century city planning, are a recipe for failure" (M. Szell, 2014).

However, questions arise: how do we design cities, smart cities, from principles and findings of the "new science of cities"? In the absence of a purely top-down model of how cities operate, what kinds of sensing technologies should urban planners be promoting and testing? How should we foster collective intelligence and bottom-up smartness?

Bottom-up smartness: pluralistic models, DIY urbanism, crowdsourcing

While city science is exploring new comprehensive models to explain how cities work, a movement of citizen scientists, researchers, activists, and entrepreneurs has been reshaping urban spaces in a bottom-up way, using ICT to connect and mobilize communities, and applying digital technologies directly to enable new forms of urbanism.

This "do-it-yourself urbanism" (DIY-urbanism) broadly encompasses such diverse and colorfully named activities as: flash mobs, guerilla gardening, timebanking, empty spaces movements to occupy abandoned buildings, bartering schemes, open data hacking (Iveson, 2013). They all have in common is the use of ICT interfaces to directly engage citizens about unobserved processes in the city, such as emerging subcultures, new mediums of exchange and sharing, and as specifically explored in this research, new practices in sensing and surveillance urban air quality. To this regard, sec. 2.3 mentioned the natural surveillance from citizens on their neighborhood, under certain circumstances, though "almost unconscious" (Jacobs, 1961, pp. 32–35), compared to more directly engaged urban activism with the bottom up and self-organizing energy fostered and catalyzed by ICT and social networks, "Leak the knowledge of the neighborhood into codified systems – like a wikileak" (Sassen, 2014).

Crowdsourcing and crowd funding were mentioned in this work in relation to several successful projects for crowd-sourced participatory sensing in cities, specifically for air quality surveillance, in the context of the so-called "volunteered geographic information" (VGI) (Goodchild, 2007). A new view of people-centric urban sensing is emerging, where people are no longer just consumers of sensed data, but rather they participate in the new role as producers of data. (Campbell et al., 2006).

Yet therein lies a dilemma; to what extent do bottom-up small-scale "DIY urbanism" (informal/illegal or formalized/politicized) practices constitute a democratic urban politics that might give birth to a larger picture improvement? How do we profit from such practices to scale up to the level of entire cities? (Iveson, 2013). While software may be easily shared and spread across a wide user base, other requirements are not so easily scalable: human capital (developers, designers, data analysts, coordinators, etc.), regulatory compliance, physical infrastructure, and access to centralized, protected databases. In the case of crowd-sourced sensing, mentioned in this research in the field of air quality, most effective practices succeed when they eventually become standardized, aggregated, accessible and integrated to formalize city systems. In order to enhance quantity, quality and credibility of community-gathered data, it is necessary to build a new architecture for participatory sensing that systemize existing methodology (Burke et al., 2006).

Ultimately, urban planning should become adept at designing systems that mediate between large-scale, enterprise-type structures of city government and the local tacit knowledge and innovation that bubbles up from citizens. As Ratti and Townsend write, noticing the “social nexus” of the Arab spring form of intelligence resulting from coordinated human activity though internet and ubiquitous mobile phones: *“truly smart cities will emerge as inhabitants and their many electronic devices are recruited as real-time sensors of daily life. Networking the ubiquitous sensors and linking them to government databases can enhance a city's inventiveness, efficiency and services”* (Carlo Ratti and Townsend, 2011).

The research contribution of this work is conducted towards this direction (in the field of air quality): urban planning should profit from both top-down sensing networks and bottom-up approach, and design systems, tools and governance structures that mediate the two levels in order to enhance smart, sustainable, and inclusive communities and cities.

6.2. RECOMMENDATIONS FOR URBAN PLANNING TO PROFIT FROM SENSING IN MAPPING URBAN CLIMATE AND AIR QUALITY

This section summarizes and generalizes the findings outlined in this work, based on the fieldwork and case studies analysis. Urban planning should profit from the paradigm shift from modeling to sensing, as emerged in this work. Sensing pervasiveness, its scale and resolution improvement can lead to a new mapping paradigm, where instead of using data from scarce governmental stations, diffusive sensors will map urban climate and air quality in real-time and at an unprecedented fine grained resolution.
However, urban planning should be ready to face and overcome barriers already evident from this work at this stage: data quality and transparency of mapping can lead to misinterpretation and bring to incorrect decision making processes.

6.2.A – Profiting from the paradigm shift: from modeling to sensing
6.2.B – Improving sensing challenges and limits (data quality, communication, privacy), and enhancing bottom-up awareness

6.2.A - PROFITING FROM THE PARADIGM SHIFT: FROM MODELING TO SENSING

Considering the reality of the idea of an "electronic skin" on our cities (Gross, 1999), and that "Everyware" vision (Greenfield, 2006) became reality, from "ubiquitous computing" the research attention in the last decade shifted to "pervasive sensing".
The paradigm shift from modeling to sensing was largely discussed in this work, as a result of the diffusion of ICT and sensing technologies that enhanced the smart city concept as "senseable" city (see ch. 2). In fact pervasive sensing has recently become feasible and affordable, and the knowledge about our environment can be enriched thanks to the availability of diffused fine-grained and real-time information layers.
Considering ICT development and its related effect on urban studies discussed in the previous section, the focus here is on the consequences of the availability of sensors becoming smaller, more accurate and networked, leading to the idea of a "smart dust".

- Use sensing for supplement modeling and governmental monitor networks
- Use sensing for improving scale and resolution
- Defining urban planning actions for UHI and air pollution

Use sensing for supplement modeling and governmental monitor networks

In the field of air quality and urban climate, thanks to recent availability of technology, and the diffusion of pervasive sensing, a new paradigm in urban air studies can be leveraged; a number of sensors within the urban environment can unveil the spatial pattern of air pollutant and heat concentration, and improve scientific knowledge for urban planning and design (both spatial planning and environmental planning), ultimately posing urban planning as the reference platform for urban exposure studies, turbulence and mechanic studies, climatology, and environmental science.

In fact, historical approaches for monitoring air characteristics, such as climate and pollution phenomena, generally use complex, expensive, stationary scarce monitoring stations, which limits the quantity of data, the representativeness, the coverage, and the actors involved in collecting data and making it available.

However, as explored in this work, characteristics such as outdoor ambient temperature and pollutants have much higher spatial (and temporal) variability than data available through governmental monitoring networks.

For this reason, in order to map air quality and urban climate within the urban environment, at the people's scale, urban planning should profit from emerging low-cost sensing technologies and supplement routine governmental data. Collaboration with environmental authorities could lead to installing low-invasive small sensors throughout the city, or implementing portable sensors in a city network providing real-time estimates of the spatial and temporal variability of air pollutants and temperature, for immediate access to the general public. In fact, data from such networks could support traditional ambient modeling, as demonstrated in several large-scale projects discussed in this work (i.e. crowdsourced network, such as Wunderground, used in the fieldwork), and at a local scale, as demonstrated from the potential of Clairity case study, which can potentially supplement US-EPA data coming for distant stations. In addition, the real-time aspect is especially important for pollutants such as particulate matter, one of the most important pollutants that should be communicated to citizens for estimating exposure and consequently suggesting limiting outdoor activities in unhealthy conditions. In the current traditional practice, samples are collected in the field at the monitoring station location (i.e. every 24h), and brought to a laboratory at a later date, resulting in data validation taking a month or more (Snyder et al., 2013, p. 11369).

However, since currently no low-cost sensor meets the requirements established by governmental regulation (such as US-EPA NAAQS for FRM and FEM, or EU "Airbases" and air quality directives), emerging sensors need to be thoroughly validated to ensure that their performance specifications meet designated objectives, such as: precision, accuracy, sensitivity, interferences, etc. Nevertheless, both US-EPA and EU-JRC are investing in next generation air monitoring, are testing low-cost sensors against recognized designated sensors, and are providing recommendations for their proper use avoiding bias (such as co-location, calibration) (Gerboles and Buzica, 2009; United States Environmental Protection Agency, 2013).
See US-EPA "Air Sensor Airbook" (United States Environmental Protection Agency, 2014) and dedicated websites: US-EPA "Next Generation Air Measuring" research (United States Environmental Protection Agency, n.d.) and the

"European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability"(EuNetAir) (European Cooperation in the field of Scientific and Technical Research, 2011) for recommendations on emerging air sensing technology.

Use sensing for improving mapping scale and resolution

One of the most crucial and evident potential benefits of sensing for mapping air quality and urban climate is in improving scale and resolution. Since the importance of a proper scale and resolution was a research premise of this work, and it is largely discussed throughout the chapters, only a few considerations are discussed here.

§ 1.3.A discussed the responsibility of urban planning in urban climate and air quality of cities, and the need for mapping at a local scale for defining local actions. § 2.3.B presented different possible scales and resolution obtainable with of sensing, while § 3.1.A thoroughly discussed the reasons why local scale and a high resolution are needed in urban air studies, mentioning the high intra-urban air differences within cities and the consequent misleading underestimated exposure coming from large scale data (Barrett et al., 2008). A better spatial resolution is recommended in both climate studies, such as UHI magnitude quantification (Stewart, 2011) and air pollution and exposure research (Stroh et al., 2007), and in order to cover more representativeness, a larger number of observations need to be made. Improved scale and representativeness opportunities from sensing were therefore presented in both the case study (§ 4.1.A) and fieldwork (§ 4.2.A), and overall ch. 5 explored results coming from data analysis.

A basic recommendation comes from the Clairity case study: when studying local air quality phenomena, local sensing networks should be implemented, and when representativeness is compromised by high variability, such as within the urban environment, high-resolution data should be gathered. A "proper" scale and resolution is context-specific, and the example of the MIT campus, with its urban structure variability, suggested different spatial and temporal scale for different pollutants and areas of the campus. Urban planning and environmental studies should profit from the opportunities offered by local scale sensing in mapping air quality: spatial and temporal studies at an unusual high resolution is available for research addressing several aspects, such as spikes in a limited amount of time, and dispersion over space. In addition, since the network provides data at the local level, exposure studies can benefit from this improved scale, contributing to increased epidemiological research at the people's level. Outdoor exposure, in fact, can be deduced from both the air pollution data provided by Clairity and people presence within the campus, by estimation or phone tracking.

The fieldwork demonstrated how effectively and effortlessly mobile sensing can collect fine grained data, thanks to the use of mobile sensors, or stationary sensors installed in mobile vehicles, covering larger areas with high spatial and temporal resolution according to the logging settings. In addition, mobile sensing was helpful at identifying urban hotspots, areas with sensitive urban-climatic and environmental problems determined by high-concentration of heat and pollutants, within the urban environment with unprecedented resolution. In the case of MIT campus, areas with higher-density of building volumes/surfaces further from the river showed higher concentration.

Urban planning and environmental studies should therefore profit from the increased spatial resolution allowed by sensing in identifying hot-spots, since spatial differences can be higher than temporal differences, and while a governmental station may monitor a fair quality air, often the average is hiding health risks in selected areas, either close to emission sources or in areas where air is stagnant.

In addition, urban planning, and in particular urban design, can profit from fine-grained mapping provided by air sensing, for analysis of causing factors, such as urban morphology, in order to understand hotspot formation and suggest localized interventions.

With the development of new technologies, such as unmanned aerial vehicles (UAVs), smartphones, low-cost portable devices, and weareables, unprecedented opportunities to improve resolution of mapping urban climate and air pollution studies are offered and should be engaged.

As mentioned, issues about data accuracy are relevant, because of the low-cost technology involved, potential lack of calibration, and the heterogeneous measurement conditions that may occur. Despite the limits of low-cost sensors measurements, such as data overload and great error in accuracy, these can be potentially reduced with big data analysis, with the help of statistics and machine learning processes that detect patterns in data and adjust results accordingly. In the case of Clairity and the fieldwork, outliers and anomalies were detected and analyzed; since sensing devices and networks produce big data, they can be used to “decode” urban climate and air quality, as well as decoding the city with the “power of big data” (Offenhuber and Ratti, 2014).

Within the same approach, large real-time extensive datasets can be mined or opportunistically collected, in order to infer spatially dense air pollution levels even without the need for directly collecting air data. For instance, potentially available datasets from sources such as traffic flows, meteorology, road network structures, energy consumption for heating, can be combined and used to infer air pollution levels in high resolution. Additionally, combining datasets from mobile phone tracking, could allow estimating the day-night variation of people’s presence in within urban areas, and potentially assess their exposure throughout the day.

The predictive capabilities of this approach, combined with mobile sensing, can be an alternative to time and computationally intensive air pollution models that are currently used. Therefore, high-resolution spatial-temporal air pollution estimates can be utilized for personal and population exposure studies on a larger urban scale than previously thought possible.

A final consideration regards the potential uses of sensing in countries with limited resources and fast developing pattern. As mentioned for the Cape Town project, the low-cost component of emerging air sensing paradigm, opens doors to vast implementation for improving everyday activities and quality of life (i.e. mobility, security, air quality and health).
Of course the complexity of the local situation need to be tackled, and technology itself cannot be a solution without the appropriate framework conditions.

In particular with regard to air sensing, many countries do not have governmental monitoring stations to measure health-related pollutants, such as fine particulate matter (PM2.5). In fact, nearly 70 percent of the air monitoring stations are disproportionately located in wealthy countries, and especially in Africa, Southeast Asia, and South America, there are major gaps in monitoring (Hsu and Zomer, 2014). At the same time, many of these countries are quickly industrializing and urbanizing (United Nations, 2014), but still lack of routine ambient air monitoring networks or, in the case of India, the lack of AQI and tools to communicate to citizens the exposure and health risks associated with outdoor activities.

The opportunity for diffusion of low-cost air sensing, in its different context, scale, resolution, and components, from opportunistic to crowd-sourced, are promising and should be further studied and implemented

Defining urban planning actions for UHI and air pollution

Directly connected to the recommendations to profit from sensing and improve scale and resolution in mapping urban climate and air pollution is the recommendation for urban planning and design to use the local scale and high-resolution maps available in order to define strategies, policies, actions, and measures.

§ 1.3 introduced the reason why mapping is needed for both spatial planning and environmental planning, since it increases qualitative and quantitative fine-grained knowledge of the urban environment.

There is an emerging role for planners in urban heat and air pollution debate, and urban literature and regulations on defining local measures is growing (Eliasson, 2000; Oke, 1984; Stone and Rodgers, 2001; Stone, 2005). The lack of mapping and studies at the local scale, the neighborhood scale can be overcome thanks to the sensing strategy explored in this research.

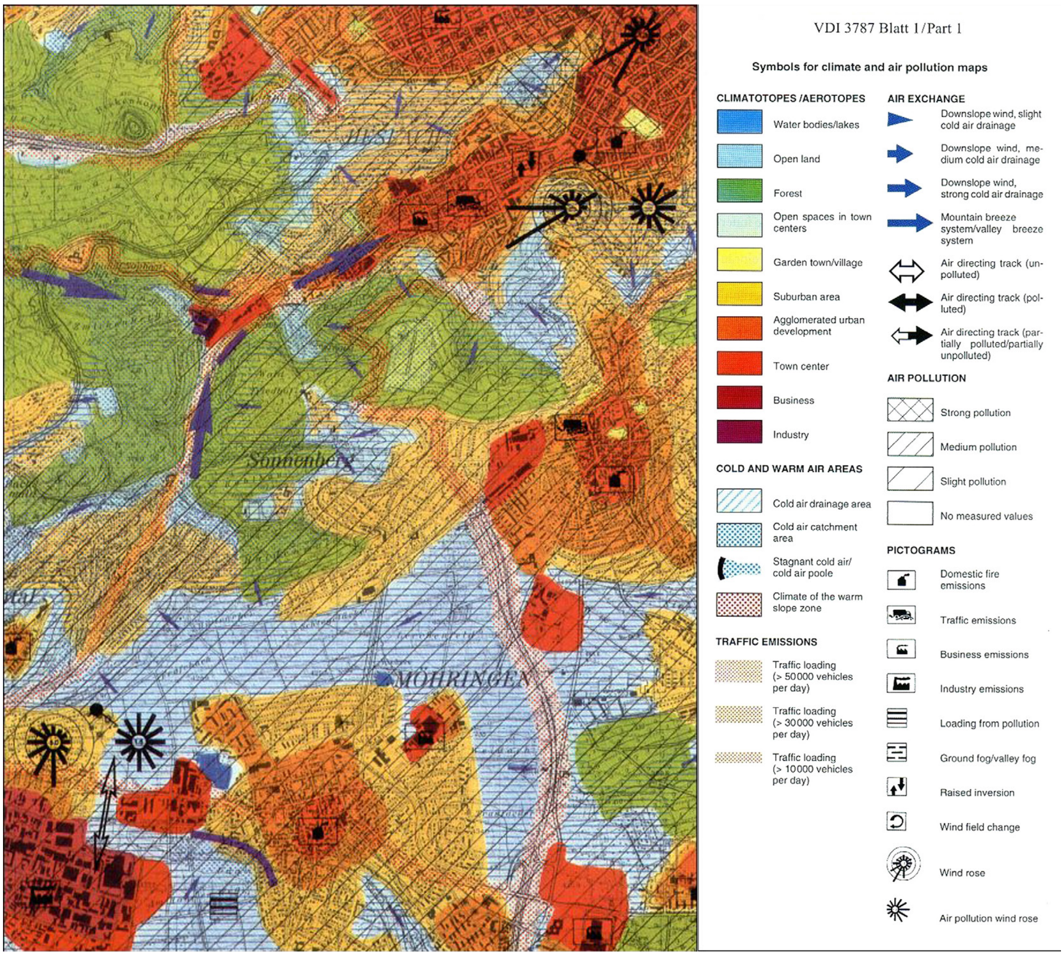


Figure 6-3
Climate Analysis Map of the City of Stuttgart, extract (XIII, 8). Source: Climate Atlas (neighborhood association Stuttgart) 1992 ("Stadtklima Stuttgart | Climate analysis maps," n.d.).

The aforementioned example of Stuttgart maps should be replicated in its ability to inform urban planning and provide recommendations. "Urban climatic recommendation maps" (UC-ReMap, where the climatic adjective include air pollution, as explained in the previous section) should be elaborated on the basis of the fine-grained maps provided by air sensing. While Stuttgart climate map and UC-ReMap (see Figure 6-3 and Figure 6-4) represent a model for urban planning recommendations in the field of urban planning and air quality, and have proved to be effective (i.e. determined the revision of the existing land use plan by planners, changing buildable land to private and public greenery for ventilation, see Figure 6-5), they are not based on fine-grained sensing data, and could be further improved in their resolution. In fact, while their scale and resolution are extremely valuable and helpful in defining local actions, they specifically postpone to local scale detailed studies and assessment.

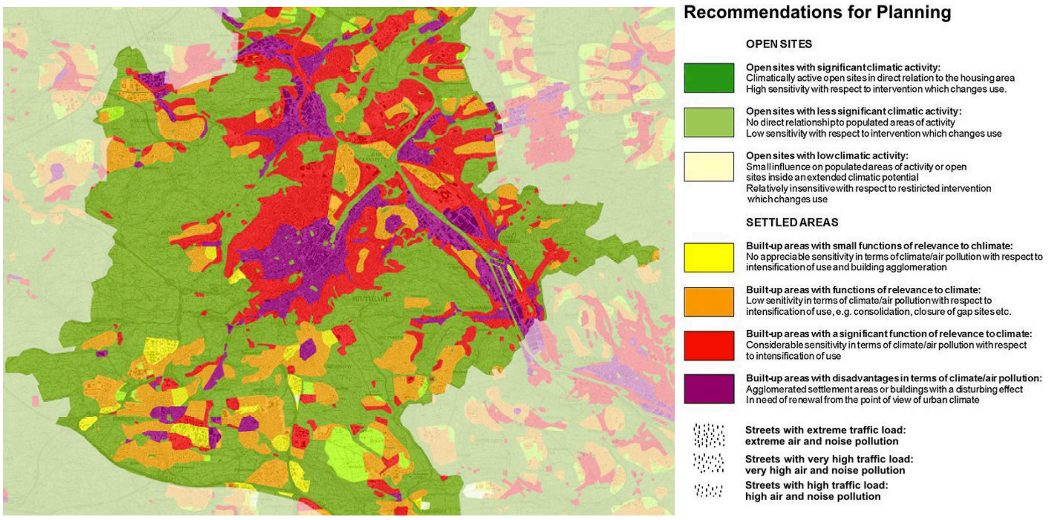


Figure 6-4
Maps with indications for the planning for the Stuttgart area. Climate Atlas (neighbourhood association Stuttgart) ("Climate Atlas Region Stuttgart 2008," n.d.)

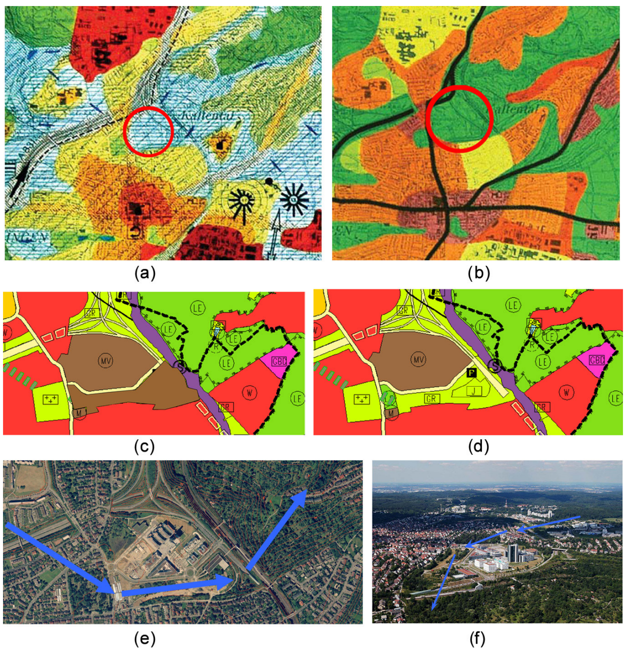


Figure 6-5
Successful implementation examples of Stuttgart UCMap study: (a) UCAnMap of Stuttgart, (b) UCReMap, (c) original land use plan, (d) revised land use plan, (e) air path and (f) ventilation zone (Ren et al., 2011)

The role and responsibility of urban planning and design in urban climate and air quality, was introduced in § 1.3.A, in four components: urban cover, urban metabolism, urban fabric, urban structure (Oke, 2004). Several measures that urban planning can implement are proposed by different studies mentioned in this work, such as site layout (Littlefair et al., 2000, pp. 50–53), interventions on the urban materials (i.e. albedo enhancements, such as cool pavements, cool roofs) (United States Environmental Protection Agency, 2008) and green roofs installation (United States Environmental Protection Agency, 2008, Chapter 3), tree planning and vegetation cover (Ng et al., 2012; Taha, 1997; United States Environmental Protection Agency, 2008, Chapter 2; Zhou and Shepherd, 2009), and on the urban geometry (i.e. increasing the sky view factor, modifying the H/W ratio), etc. (Stone et al., 2012). An overall framework of measures to specifically mitigate UHI is provided in Yamamoto's paper (2006), and a recent paper review (Gago et al., 2013).

Although these proposals suggest efficient measures for improving urban climate and air quality conditions, they focus mainly on detailed planning measures and urban design elements without a comprehensive understanding of air conditions within the urban environment in the entire city. Hence, they generally do not incorporate urban climate and air quality information into basic urban development strategies. As already explained, this is partly due to the lack of comprehensive information for planning purposes. Because spatially distributed information coming from sensing can allow fine- grained mapping, urban planning should now develop tools to integrate urban climatic/pollutant factors with urban planning considerations, and presenting air phenomena and hotspots in the form of spatial maps would be beneficial for both short-term measures and long-term strategies.

In the case of Seoul, urban climate consideration were included in urban master plans using spatially distributed information on air quality and thermal situation, and the combined effect of ventilation (Eum et al., 2013). A selection of recommendations for planning measures, among those listed in Table 6-1, was proposed for different areas with different targets and priorities. This process makes the measures contextualized and more effective, and when dealing with air phenomena in urban environment, as explored in this work, a local scale is needed instead of measures generically valid for the overall urban area.

Table 6-1. Example of planning measures that urban planning can define based on the local condition. Example table from Soul case, from cited source (Eum et al., 2013).

Target	Implementation measures
Ventilation (A)	
A1	• Maintain the ratio of parks, green areas and unoccupied areas
	• Restrict the building height and density
	• Avoid extensive construction
	• Align road developments with prevailing direction of the urban air exchange
	• Avoid attached building developments and planting of trees in settlement boundaries
	• Avoid new constructions causing significant barriers to ventilation
	• Align unavoidable constructions, which could cause barriers to ventilation, with the prevailing

	direction of the air flow or lay them out permeably
	• Avoid the establishment of closed forests
A2	• Implement measures to maintain urban ventilation (planning objective A1)
	• Increase the ratio of parks, green areas and unoccupied areas
	• Reduce the building height and density
	• Lay out settlement areas permeably by securing the ventilation path
	• Lay out settlement boundaries permeably
	• Reduce barrier effects caused by existing barriers to ventilation
A3	• Do not keep vacant lots in settlements; rather plant trees to function as wind barriers
	• Make constructional arrangements against wind disadvantages
	• Implement measures of wind protection along traffic routes
	• Plant trees to protect crop fields from wind and to reduce erosion
	• Implement measures concerning forest establishment to avoid or reduce windbreak risks
Air quality (B)	
B1	• Implement measures to maintain the urban ventilation (planning objective A1)
	• Avoid road constructions causing significant traffic loads
	• Avoid settlements causing significant emissions of air pollutants
	• Restrict the building height and density
	• Implement measures to improve compensatory effects of air flow on air pollution loads (planning objective B2) in case of unavoidable road constructions or settlements
B2	• Implement measures to maintain or improve urban ventilation (planning objectives A1 and A2)
	• Implement measures to maintain compensatory effects of air flow to air pollution loads (planning objective B1)
	• Implement measures to avoid and reduce risks of air pollution in areas of potentially poor air exchange (planning objective B3)
B3	• Implement measures to maintain or improve compensation effects of air flow to air pollution loads (planning objectives B1 and B2)
	• Implement measures to avoid and reduce emissions caused by traffic and industry
	• Facilitate use of regenerative energy (e.g. solar and geothermal energy) to provide low-emission local heat supply
	• Facilitate access of residential areas to remote heat supply, unless low-emission local heat supply is possible
	• Implement measures to avoid and reduce industry-related emissions
	• Arrange for the displacements of factories and industrial plants causing high and irreducible emissions, so that they are relocated to less sensitive locations
	• Carry out detailed analyses of air quality before planning constructions that may reduce air quality, e.g. residential areas
	• Reduce air pollution by planting trees
Thermal situation (C)	
C1	• Implement measures to maintain the urban ventilation (planning objective A1)
	• Preserve areas of cold air production
	• Avoid settlements causing significant waste heat
C2	• Implement measures to maintain or improve urban ventilation (planning objectives A1 and A2)
	• Implement measures to maintain compensatory effects of air flow on thermal stress (planning objective C1)
	• Implement measures to improve cold air transport in areas of cold air stagnation
	• Implement measures to avoid and reduce risks of thermal stress in potential areas of poor air exchange (planning objective C3)
C3	• Implement measures to improve urban ventilation (planning objective A2)
	• Implement measures to maintain or improve compensatory effects of air flow on thermal stress (planning objectives C1 and C2)
	• Enhance greening in residential areas including streets by facilitating roadside trees, planting in gardens, green facades and roofs
	• Enable the establishment of shadows when designing new buildings, e.g. arcades
	• Reduce the sealing ratio
	• Implement technical measures to reduce the production of waste heat
	• Examine displacements of manufacturing and industrial plants with waste heat-intensive processes
C4	• Avoid cultivation of crops susceptible to frost
	• Implement measures to improve cold air transport in areas of cold air stagnation
	• Avoid extensive enlargement of residential areas
	• Condense residential areas with constructions, if it causes no other climatic or air quality problems
	• Support initiatives by owners/occupants to reduce the heat loss of buildings

Local scale recommendations coming from fine-grained air mapping, is found in the aforementioned Kaohsiung city case, Taiwan, as example of high-density city in developing economy context (Ren et al., 2013). Figure 6-2 anticipated the comprehensive approach followed for the elaboration of the UC-MAP, where climatopes where defined based on topography, land use, population, UHI, natural landscape, bodies of water, wind, urban morphology. Working with planners, detailed recommendations were provided in three levels of planning actions at different scales, following the German guidelines coming from Stuttgart example, but adding coastal wind information, not fully taken into account in the German context. Figure 6-6 shows an example of planning recommendations for the “greenery” component.

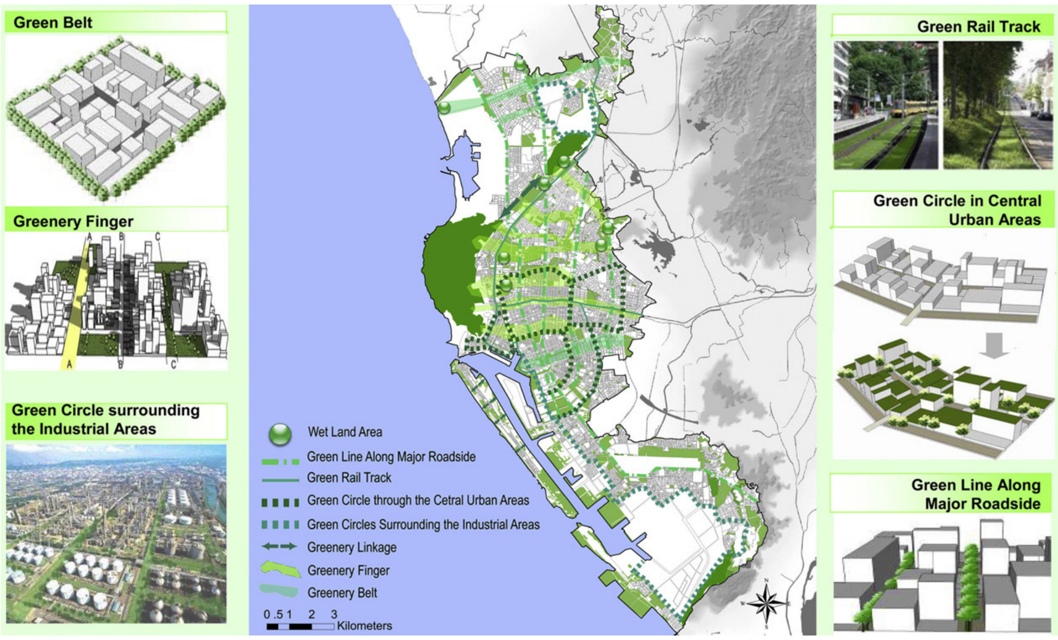


Figure 6-6
Example of detailed recommendations that urban planning can define based on local condition. Example from the greenery aspect for Kaohsiung, Taiwan (Ren et al., 2013, p. 14).

Both Seoul and Kaohsiung examples of recommendations for urban planning are based in mapping urban climate and air quality at a fine-grained level but from modeling with an integration of local observations.

As explored in this work, next generation sensing it allows for the improvement of such mapping, and urban planning should be therefore prepared to take advantage of this opportunity. Instead of expensive models and mapping, it will be possible to obtain local scale and high-resolution maps in both small scale and large cities, in both developed and developing contexts, and therefore urban planning should be ready and explore how to use this unprecedented knowledge for improving cities and citizens’ air, health and quality of life.

From urban planning to urban management

Urban planning should therefore profit from this opportunity, and use this unprecedented knowledge for improving neighborhood scale inhabitants' problems, such as UHI and air pollution concentration, which, when overlaid with people's presence and exposure, ultimately determines the health risk of citizens. In fact, as reminded in this work, this unprecedented level of definition allows for mapping not simply heat or pollutants levels but instead the surpassing of specific thresholds in the "hot-spots", areas where heat or pollutants exceed health limits, as defined by epidemiological and health studies. Urban planning and design should therefore concentrate its efforts in addressing specific solution for these localized areas.

In addition, as a strategic and emergency measure, alert systems can be implemented by city management, with indications to avoid outdoor activities in certain areas where pollutants surpass thresholds for a limited amount of time (such as PM2.5 level based on AQI), or more comprehensive response plans in coordination with municipal and community services.

In the case of heat concentration surpassing health-thresholds, examples of heat alert systems exist, and the case of Toronto was mentioned (Figure 1-13) in its ability to profit from local scale mapping of municipal and community heat-related services ("cooling centers", community conditioned centers, parks, libraries, hospital services) and locate them where they are needed most, on the basis of a local scale mapping of heat concentration (outdoor temperature) and sensitive people (isolated seniors, homeless, etc.).

Recommendations for urban planning: field of intervention and examples		
	fine-grained mapping for reducing emissions and impact	*fine-grained mapping for reducing sensitivity and increasing adaptive capacity*
Urban Policies	Mobility (i.e increasing local public transportation), Energy (i.e. promoting district heating), Land use (i.e. relocating pollutant urban functions)	Mobility (i.e. increasing pedestrian areas, modifying car accessibility), Energy (i.e. improving buildings isolation performances), Land use (i.e. relocating target groups from a high polluted areas to cleaner air area)
Urban Design	Morphology (i.e. improving ventilation by modifying urban geometry), Fabrics (i.e. increasing green arees)	Increase adaptation capacity to UHI (i.e. improving latent heat from water bodies and vegetation), and pollutants concentration (i.e. barriers from local sources)
Urban Practices	Citizens behavior and lifestyle (i.e. reducing private car transportation)	Citizens behavior and lifestyle (i.e. increasing awareness in outdoor activities)

Table 6-2
The three fields where urban planning should profit from the paradigm shift from modeling to sensing in air quality and urban climate studies. Source: author's elaboration.

6.2.B - IMPROVING SENSING CHALLENGES AND LIMITS (DATA QUALITY, COMMUNICATION, PRIVACY), AND ENHANCING BOTTOM-UP AWARENESS

This section illustrates recommendations to overcome limits and barriers of the sensing approach explored in this research. In fact, while its potential was presented as an opportunity for urban planning, several issues and challenges occurred.
Both the case studies analysis and the fieldwork explored in detail the most common problems found in mapping urban climate and air quality using air sensing. Three main categories of challenges were identified, and some recommendations to overcome them are proposed.

- *Improve sensing in data quality*
- *Improve sensing in communication, transparency, privacy*
- *Improve sensing by expanding the conversation with citizens and communities*

Improve sensing in data quality

As seen in both Clairity and the fieldwork, and in some air sensing projects struggling to advance, technology problems are frequent. In fact the complexity of factors involved in the measurements, such as power management, observation process, data storage, data streaming and platform operation, and the eventuality of failure of one component, increase the probability of altered measurements.
However, the main issue of next generation sensing is data quality, since low-cost sensing is based on less sophisticated technology in order to allow a lower cost of the sensor. As emerged from the case studies and the literature review (§ 4.2.B, § 5.3.B), air sensors are still in an early stage of technology development, and their characteristics and performance have not yet been evaluated by rigorous scientific studies, and their long-term reliability is also unknown. Issues occur in accuracy, precision, bias, and in data comparability.
A general recommendation is therefore to meticulously assess sensing performance before using data, since their interpretation for urban planning might mislead to inappropriate decisions.
In addition, in order to improve data quality in collecting data from sensors, it is necessary to scrupulously follow available guidelines and avoid measurements bias, such as following the recent US-EPA "Air Sensor Guidebook" (United States Environmental Protection Agency, 2014)

This research explored in detail the currently available affordable (low-cost) sensing technology in the field of urban climate and air pollution.
In the former field, sensors have reached a high level of development, and seem to provide acceptable performances (accuracy, response time). They are therefore "recommendable" for the purpose of mapping urban climate, with all the premises, expedients and precautions largely presented in this work. However, they are generally rejected by climatologists, which use higher

accuracy instrumentations based on WMO standards. Even monitoring stations with higher cost (around 1000$) and performance comparable to WMO standards used by climate enthusiasts and organizations are generally neglected by governmental and official institutions (see § 6.3, in the case of Milan).
In the latter field, sensor technology is more recent, and since the phenomena involved are more complex than temperature and humidity monitoring, indirect processes are usually measured. In the case of particulate matter, optical light scattering devices are used instead of sensors measuring the weight and size of particulates. It is therefore recommended to consider from the early state of sensing design the challenging issue of the conversion from number (count of particles) to mass (concentration). In fact, as explored in Clairity case, the measurements are not directly comparable with governmental concentration data, and the level of health risk coming from the concentration is unknown, or based on manufacturer information.
Similar challenges occur in comparing data from gas sensors to governmental concentration, even though both the US EPA and the European Union (JRC) are testing and comparing sensors for potential future use in regulatory framework, such as NO2 and Ozone (Gerboles and Buzica, 2009; United States Environmental Protection Agency, 2013).

Given the fact that sensor packages with acceptable performance for a given application are being developed, while not all monitoring objectives (e.g., US National Ambient Air Quality Standards (NAAQS) compliance monitoring) can be met with current sensing technology, some monitoring objectives can or likely will be achievable in the near future (Snyder et al., 2013, p. 11370).
Further basic recommendations to improve data quality using low-cost sensors can be listed, based on this research:

- knowing in advance the uncertainty and other performance specifications (i.e. accuracy, response time) and selecting the device according to the desired characteristics;
- calibrating, co-location, and referencing them to the more robust monitors, such as the governmental monitor stations data, following specific protocols and guidelines, in order to avoid the three typical issues: precision, accuracy, measurement bias;
- deploying a large number so that confidence in the measurement is improved due to big data coming from the measurements

In this regard, a final recommendation relates to the relationship between accuracy and quantity of data. Increasing the density of data in a local area, for instance through a repeated fieldwork campaign, or better yet, a campaign using multiple sensors simultaneously, ensures a higher quality of data. In other cases, increasing sensing data allows higher coverage and resolution, and decreases the approximation, interpolation and kriging processes with sparse data coming from remote stations.

As seen in many participatory sensing platforms, collecting a high amount of data is pursued by sacrificing data accuracy for data quantity. With the help of big data analysis tools and machine learning process, it is possible to extract meaningful information via un-calibrated sensors from participants.

Improve sensing in communication, transparency, privacy

Other large challenges that need to be further explored in using sensing for mapping air quality related to data management, communication and transparency, and the general concern of privacy shared in all cases when data is collected with opportunistic or crowd sourced sensing.

While data quality can be improved, thanks also to the technology development, and the big data accumulation seems not to be easily storage able (if anything, leading to "data obesity"), data management in assessing, using, improving, monitoring, and maintenance, processing, and visualization are major challenges that still require considerable effort (Snyder et al., 2013, p. 11375; Subramanian, 2012).
As seen in the fieldwork, and specifically in the case study, Clairity nodes provide data that is representative of the different characteristics of each node: location, height, indoor/outdoor, air obstacles around the sensor (i.e. being installed in a pole or under a balcony) are information that need to be included in the dataset. In fact, the descriptive information associated with the collected data, called metadata, is required for correctly conducting data analysis and interpretation.
A recommendation is therefore to carefully collect all necessary metadata together with the sensor readings, in both stationary and mobile sensing (i.e. the indoor/outdoor info added in the fieldwork).

Transparency in the data collected is needed also for the communication process, in order to raise awareness of heat/pollutant exposure effects, without inducing misinterpretation of results, in both cases, when data is collected by the general public or comes from stationary sensors.
In fact, as demonstrated by the data analysis in this research, communicating the results in relation to the quality of air and the potential health risk associates to the exposure is very challenging. Air pollution health impacts are a result of both the concentration and duration of exposure, and governmental thresholds based on WHO standards reflect both of these aspects of exposure. The concentration record measured by an air sensor with its timestamp at a specific point may be below or above the defined thresholds, but it may not reflect the duration of exposure (i.e. PM2.5 is based on 24-hr exposures). In fact, the actual health effects of very short-term elevated levels of most pollutants are not well understood and governmental standards (such as by WHO, EPA, EU), are

established based on larger temporal scales with little information on short-term pollutant exposure.
Hence, when dealing with communicating sensing data in mapping air quality, extreme caution should be given to the visualization and interpretation of data, following the examples of AQI color maps detailed for different combinations of pollutants and thresholds.
It is recommended to pay high attention to delivering the mapping results to the public with the right level of transparency and information, since most of the projects mentioned in this research neglected to engage in a thoughtful communication strategy.

Privacy and surveillance

“You imagine, as does everybody else for that matter, that our organization has for many years been preparing the greatest document center ever conceived, an archive that will bring together and catalogue everything that is known about every person, animal and thing…a centralized archive of humankind” Italo Calvino, World Memory, 1996

One of the biggest concerns of sensing is data privacy and the ethics behind every sensing project that required collecting data from humans. The panoptic and surveillance concern, introduced in the previous section, follows the privacy issue that arise in collecting users’ data, ultimately resulting in a vast database containing detailed information about users’ behavior. Analogous to what Italo Calvino describes in his novel “World Memory” (Calvino, 1995), the level of secrecy and the uncertainty of users’ reaction if they would know being tracked, are both challenging elements to consider.
As evidenced by this research, none of the existing air sensing projects considered actively deal with privacy and security concerns. Some of them developed simple systems to fully hide or share the measurements publicly by an access control feature. However, because most of the data comes from mobile sensing with GPS coordinates, users’ movements are being tracked together with the measurements records.
Even when GPS geotagged data are not provided, mobile phone tracking is possible via triangulation with radio towers, or via detection of a phones’ Wi-Fi or even just Bluetooth signal, potentially enabling to check the location and movement of a user without an informed, explicit consent. Other sensing projects collect personal sensing data, in relation to personal health status (i.e. heart rate, blood oxygen levels); the risk of adverse usage of data, or the eventuality of data leakage might raise challenging privacy and security concerns.
Finally, other projects analyzed in this research are treating personal data, social media data, bank transaction data, and have not always managed to protect a user’s privacy, since opportunistic sensing provides data with no explicit user consent.

However, collecting big data is double-sided, being both “civic” and “threatening”: the first, because of the valuable insights offered to research studies, makes them “an integral part of public space”, while the second face is obscure but “on closer inspection, the totalizing idea of data turns to be a myth”, since data coverage is limited and unequal (Offenhuber and Ratti, 2014, pp. 15–16)

Nevertheless, a recommendation when working with people’s data collection, such an air sensing project with participatory component, should be to provide maximum transparency on data collection and usage to the users, in order to inform and give the ability to control any data that concern his/her life. For example, some expedients can be included, such as adding noise to data, using a fine-grained control system, phone apps that process the data and only stream aggregated statistics. In some cases, the users should even be given the option of trading data in exchange of services (i.e. exposure study) or money.

A final remark comes again from Calvino’s story: the historical and cultural dimension of data collected and its lasting privacy management. The duration of data lifecycle should be limited, in order to avoid perpetual digital memory of regrettable humankind information at a large scale. In fact, as in Calvino’s story, managing a “centralized archive of humankind” ultimately leads to subjectivity and contradictions in selection, interpretation, analysis, and ultimately to death.

Improve sensing by expanding the conversation with citizens and communities

Public participation in environmental decision-making was pushed as a result of the Rio Declaration on Environment and Development (United Nations, 1992), and in country-specific documents, such as the European UNECE Convention on “Access to Information, Public Participation in Decision-making and Access to Justice in Environmental Matters”, usually known as the Aarhus Convention (United Nations Economic Commission for Europe, 1998). However, environmental data, particularly in the field of urban climate and air quality, currently relies heavily on a ‘top-down’ approach, in which governmental authorities collect the data and publish and communicate it to the public. Citizens should not only consume but also be able to generate their own environmental data in a mechanism that could lead to learning about current environmental issues, and to increased awareness and potential to behavioral change towards an improvement of their own environment.

In fact, participatory sensing should be based on simple apps running on citizens’ mobile devices, gathering and sharing basic statistics on ambient air quality at regular intervals, possibly joining data-collection campaigns in a community, in order to collaboratively generate city-scale analysis therefore developing potential for important, accessible planning tools for communities of all sizes (Burke et al., 2006). In this regard, examples of projects were presented in this research mostly connected to a global scale, collecting a vast amount of data coming from volunteer sensing, therefore increasing the quality of low-cost data and the spatial and temporal coverage, ultimately allowing a better fine-grained air quality mapping.

Involving individuals in sensing processes can be done in several ways, such as by providing sensors in specific campaigns (i.e. AirCasting surverys in New York, SensingCity in Christchurch, New Zeeland) or by creating crowd-funding campaigns (i.e. AirBeams, SmartCitizen) and making low-cost devices affordable and available in the market.

Furthermore, this process may serve to encourage more citizens to participate in environmental decision making in urban planning participation mechanisms, as demonstrated in recent research in several locations in the field of noise sensing (Becker et al., 2013), and in an air quality sensing project called “Everyaware” (Everyaware Project, 2014). Examples in the field of urban climate have also proved to be successful in engaging individuals in sharing data from personal weather stations (i.e. Wundergound, Citizen Weather Observer Program).

Involving “citizen science” seems to be a fruitful opportunity in both increasing awareness and increasing data for mapping air quality, and it should be better addressed by urban planning participatory practices. While data quality may be a concern, and specific recommendations need to be taken into consideration, as illustrated in the previous section, these activities demonstrate the interest and potential for citizen scientists to increase air monitoring data collection (Snyder et al., 2013, p. 11373). Community and web-based self-organized sensing initiatives are therefore bottom-up approaches that should be integrated in traditional top-down sensing for governmental purposes and international law compliance.

6.3. RECOMMENDATIONS FOR FUTURE WORK IN MAPPING URBAN CLIMATE AND AIR QUALITY IN MILAN

Profiting from the research results, and the recommendations for urban planning in mapping urban climate and air quality, an example for the case of Milan is proposed. It combines both a modeling and sensing component, as emerged from the research conducted at Laboratorio di Simulazione Urbana (Politecnico di Milano) and at Senseable City Laboratory (Massachusetts institute of Technology).

6.3.A – A proposal for modeling and smart real-time air sensing in Milan
6.3.B - Recommendations for scale and resolution, cost and technology, participation and awareness

6.3.A - A PROPOSAL FOR MODELING AND SMART REAL-TIME AIR SENSING IN MILAN

- The context: air quality and fine particles pollution in Milan
- The context: urban climate and UHI in Milan
- The project proposal: mapping urban climate and air pollution

The context: air quality and fine particles pollution in Milan

Milan, a city with a population of 1.3 million people covering an overall area of 182 km2, in a metropolitan area of 3.2 million inhabitants, is facing challenges in air pollution and urban climate. Its geographical characteristics and urbanization processes determine its worst air quality and strongest UHI in Italy, both among the most extreme in Europe.

In the field of air quality, because of both its geographical condition and urbanization processes, Milan air pollution is an environmental issue of great concern, especially in relation to the concentration of particulate matter within the urban environment. In addition, being located in Italy's most industrialized region, air quality standards for suspended particulate matter are frequently exceeded in Milan and in its metropolitan area. Highly dense residential and commercial areas correlates to high volume of vehicular traffic; moreover, many industries, including power plants, refineries, incinerators, chemical and metallurgical factories are located in its outskirts, and consequently its PM2.5 and PM10 reach level of concern.
As described in sect. 1.2, while particle concentration might depend on local sources, a regional contribution is relevant especially for pollutants traveling over kilometers, such as fine particles, the most dangerous in relation to health effects but also due to their long residence time in atmosphere. In this regard, a PM2.5 and PM10 study confirmed this pattern in the case of Milan: fine particles can be created or transported far away fostering accumulation processes because of their reduced removal in case of persistent atmospheric stability and

lack of advection processes or rainy days. Therefore, the concentrations of PM2.5 can be affected both by local emissions and by contributions of mesoscale origin (Marcazzan, Vaccaro, Valli, and Vecchi, 2001). According to another study focused on particulates in Milan, 50% of the PM10 observed in urban environment is caused by traffic emissions, of which a 4–40% share is estimated to come directly from the exhaust, whereas the remaining share derives from non-exhaust emissions and resuspension of soil dust (Lonati, Giugliano, and Cernuschi, 2006).

Because the PM10 daily average concentration limits have been exceeded in Milan more than 35 times (see Figure 6-7), implementation of strategies, such as traffic restrictions to control the acute pollution events, are currently enforced.

However, as emerged from this research, monitoring stations, such as the European AirBase network used for calculating PM concentration and enforcing limits based on epidemiological studies, are often not representative of the urban environment, since high variability can occur (see sect. 3.1 for more detailed discussion about the need of local scale and high dense air data).

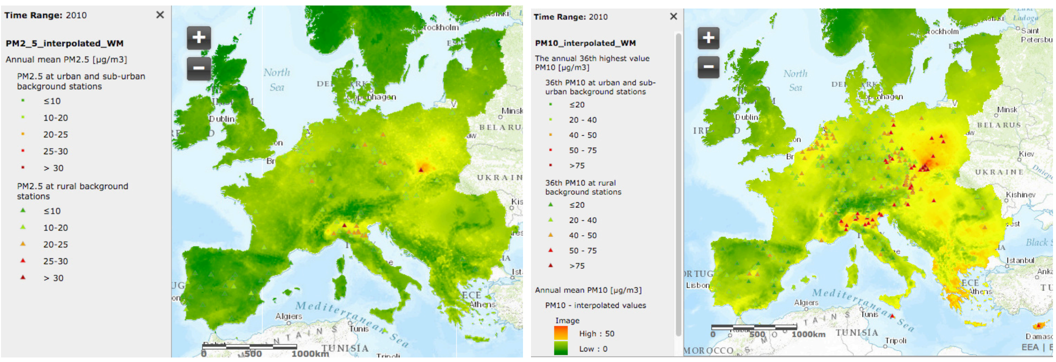


Figure 6-7
Maps derived for 2007, 2008 and 2010 primarily from Airbase background station monitoring data, few EMEP station monitoring data, supplemented with altitude, meteorological ECMWF data and EMEP concentration modeling data. Source: European Environment Agency (EEA) PM2.5 (left) and PM10 (right) maps ("PM10 interpolated maps — European Environment Agency (EEA)," n.d., "PM2.5 interpolated maps — European Environment Agency (EEA)," n.d.).

The context: urban climate and UHI in Milan

In the field of urban climate Milan also shows problematic conditions, especially in relation to the UHI phenomena in hot summers.

In fact, very similar to heat concentration and UHI formation, because of both its geographical condition and urbanization processes, Milan air pollution is an environmental issue of great concern.

In fact, UHI in Milan has been observed and studied for several years. Studies evaluated UHI phenomena using ground temperature series, comparing the UHI trend with the growth of the city radius (Bacci and Maugeri, 1992) and observed a difference in temperature of up to 8°C between the city center and the nearby rural lands in extreme condition, during early morning and after sunset in the summer (Borghi, Corbetta, and Biase, 2000). Recent studies confirmed UHI

occurrence in Milan, and analyzed the CLHI temporal variability over Milan (Pichierri, Bonafoni, and Biondi, 2012).
In a recent dossier about climate and cities (Osservatorio Meteorologico di Milano Duomo, 2014) based on historical 30-year data as recommended by WMO (1960-1991, 1971-2000, 2001-2012), it was calculated that Milan and Bologna show the highest increase in temperature over the periods considered in Italy, mostly connected to summer anomalies. In particular, considering UHI occurrence when the maximum day temperature is higher than 35°C and the minimum night temperature is higher than 25°C, Figure 6-8 shows how after year 2000, UHI phenomena in Milan are evident and likely to increase in relations to climate change and heatvawes.

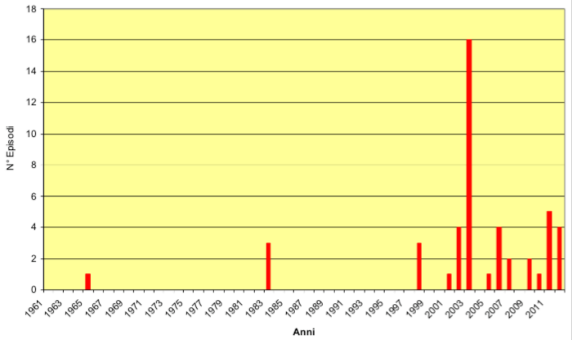


Figure 6-8
Number of hot days (maximum temperature >35°C and minimum temperature >25°C) in Milan. Source: (Osservatorio Meteorologico di Milano Duomo, 2014, p. 33)

Moreover, during 2003 European summer heatwaves, in Milan the greatest excess in mortality was observed in Italy (+23%, together with Turin) (Michelozzi et al., 2005). Impact on building energy demand, generated by UHI in Milan was also calculated to be relevant (Poli et al., 2009).
Figure 6-9 shows the estimated number of combined tropical nights (> 20C) and hot days (>35C) in 2021-2050, with Milan being among in a region likely to experience challenges, also because of its low share of public green spaces.

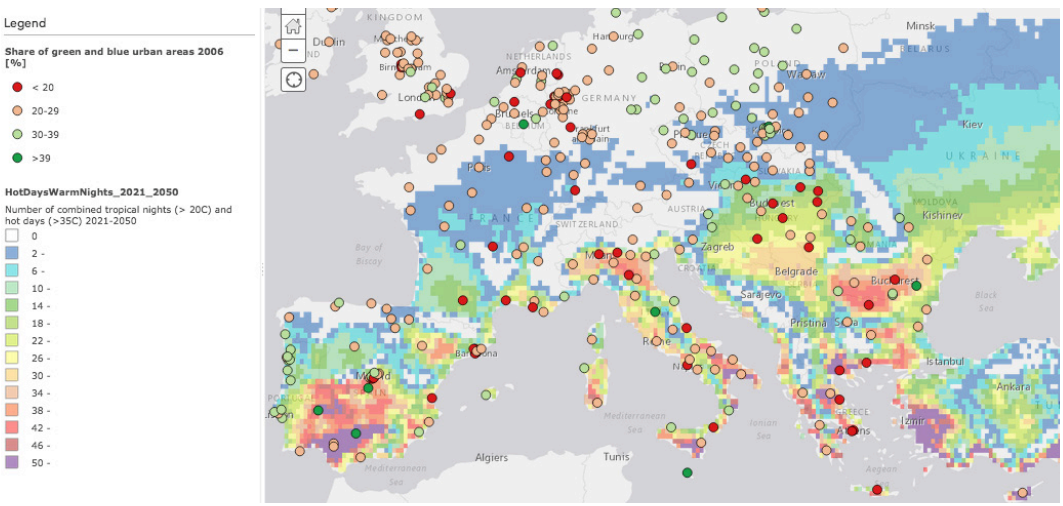


Figure 6-9
Estimated number of combined tropical nights (> 20C) and hot days (>35C) in 2021-2050. Source: European Environment Agency, EEA ("Heat wave risk of European cities," n.d.)

Data used for analysis generally comes from limited urban meteorological stations, such as a non-profit organization station (Osservatorio Meteorologico di Milano Duomo), two military aeronautical stations (Milano Linate and Mapensa airports), and a few regional EPA stations collecting weather data (ARPA Lombardia), and extensive modeling is required to model UHI in Milan (Borghi et al., 2000). Other services, such as the Epson Center in Milan, use elaborated modeling processes, based on satellite observation in order to determine temperature forecast.
However, a new sensing approach is emerging in the field of urban climate, also in the context of Milan. A non-profit organization of volunteers, Centro Meteorologico Lombardo, CML ("Centro Meteorologico Lombardo," n.d.) provides data from a collection of 400 weather stations (46 in Milan area) installed in individuals locations, in a sensing network aimed at contributing to the urban climate and UHI research. While issues in such sensing approach occur, as discussed in ch. 5, such as luck of calibration, un-validated data procedure, challenging comparison between stations located at different urban conditions (such as a house balcony), the invaluable resource from this form of participatory sensing is evident and should be better acknowledged in urban climate research studies.

The project proposal: mapping urban climate and air pollution

As emerged from the brief context description, Milan faces both urban climate and air pollution issues, which translates in UHI, heat and pollutant concentration within the urban environment.

In addition, as emerged form this research, air sensing seems to have the potential of supplementing governmental monitor network, therefore supplementing modeling for improving scale and resolution. Participation scenarios were also discussed as being beneficial outcomes of a planned sensing project.

The idea of the project is therefore to collect urban climate and air quality data at the street level, integrating official data, through a mobile participatory smart real-time sensor network, based on personal and participatory sensing. The network will supplement official data, and will be the main source for identifying and understanding "urban hot-spots" through the collection and monitoring of extreme temperature data and pollutants concentrations over defined thresholds.

If well planned, a project with these characteristics has the potential to produce high spatial and temporal resolution measures of climate and air quality level which could contribute to scientific understanding, as well as addressing economic, policy and regulatory issues spanning climate change, air pollution and human exposure (and health) responses.

As seen in ch. 1 and 2, besides indirect measurements (i.e. remote sensing), direct observation through mobile sensing devices is certainly the most promising technique, thanks to the availability of cheaper sensors and pervasive network systems, with increasing participatory sensing and user-generated content aggregators. Both US EPA and EU are investing in the "next generation air monitoring", developing, evaluating, and applying low-cost reliable portable devices.

The opportunity for the case of Milan is unique: the city is in fact in 2013 started promoting a “smart city” approach for its development, following six pillars: Smart Economy, Smart Living, Smart Environment, Smart Mobility, Smart People, Smart Governance (“Smart City MIlano,” n.d.). Several projects are being financed and implemented, in the framework of "Smart Cities and Smart Communities and Social Innovation".

In addition, Milan will host the Universal Exhibition in 2015, EXPO 2015, around the theme “Feeding the Planet, Energy for Life”, therefore focusing on environmental sustainability and technology innovation (“Expo Milano 2015 - Feeding the Planet, Energy for Life,” n.d.).

The project proposal, therefore, profits from a smart infrastructure currently functioning in Milan, the bike sharing system, in order to implement an innovative participatory sensing project, which could be the first leading example worldwide. The novelty consists in potentially being the first working and useful

network for urban climate and air quality mapping that combines data coming from different sources (including official measurements stations for reference data ad calibration) with a single but open data management backend (heterogeneous mixture of sensor platforms generating a coherent map).
Additionally, the smart information platform thus created could be a novel platform for interdisciplinary communication and collaboration between meteorologists and climatology, the environmental community and the urban planning decision makers.
It could be the first real-time climate and pollution mapping (i.e. for a city like Milan), and the first smart public data network integrated with the bike sharing data, a system that promotes a green and smart image of a city, and is increasing worldwide in usage, thanks also to recent bike-oriented mobility policies.
It could put the base for environmental (personal and participatory) sensing, creating a local sensing community (see Figure 6-10).

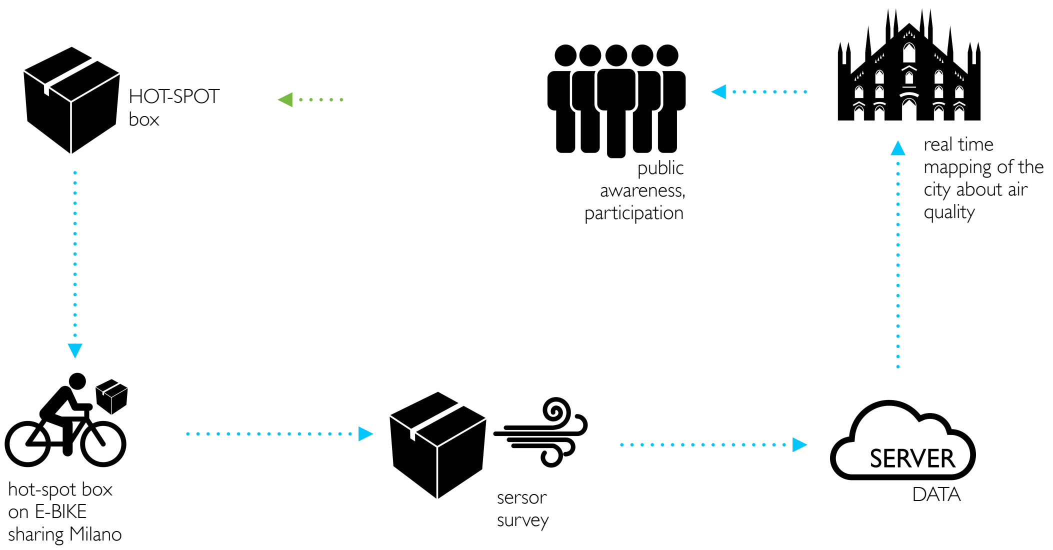


Figure 6-10
Conceptual framework of the project proposal. Source: author's elaboration.

Therefore, the main main objectives are:

- mapping real-time air quality using big-data coming from low-cost sensors (identifying HotSpots)
- understanding concentration of pollutants/temperature and of people (exposure and health concerns)
- understanding factors involved in Hotspots creations (urban morphology, land use, mobility, cooling/heating)
- proposing solutions for alleviating HotSpots (urban design, land use planning, mobility, people's behaviour change)
- increasing public awareness, participation, top-down and bottom-up cooperation in air quality improvement

See next section for recommendations in developing such a project, based on evidences emerged from this research.

6.3.B - RECOMMENDATIONS FOR SCALE AND RESOLUTION, COST AND TECHNOLOGY, PARTICIPATION AND AWARENESS

- The modeling component: GIS model and data analysis
- The sensing component: mobile sensor devices and bike sensing
- Expected results: increase knowledge and integration with existing planning

The modeling component: GIS model and data analysis

Section § 3.2.A introduced the modeling component explored at the Laboratorio di Simulazione Urbana, Politecnico di Milano.
The modeling component is related to a data platform to be implemented for the case of Milan city: indicators were previously selected:

Data	Source	Notes	type
Data included in the model			
Topographic Geo-Database	municipal administration	covers whole surface with land use data, volume data, building type, surface type	GIS based
D.E.M.	Laboratorio di Simulazione Urbana	covers all building volumes	TIFF images
Public Green System database	municipal administration	covers all green areas, including trees details (species, dimension, age	GIS based
3D Model of the city center	Laboratorio di Simulazione Urbana	which covers all building volumes of the city center with accurate details (1:1000)	CAD based
Urban Climate Data	local EPA , a local NGO ("Centro Meteorologico Lombardo," n.d.), Politecnico di Milan sensing station	urban climate data (temperature, humidity, wind)	datasheets
Air Quality data	local EPA	air pollutants concentration (PM2.5, PM10, …)	datasheets
Other Databases	various	(energy consumption for heating/cooling/lightening, mobility fluxes)	various
Modeling tools used in the model			
ArcGIS	("ArcGIS," n.d.)	data aggregation, interpolation, kriging	GIS based
Matlab	("MATLAB," n.d.)	image processing, urban morphology parameters calculations	code based
Envi-met	(Bruse, 2004)	estimation of thermal and environmental parameters at the local scale	software interface
Solveig	(Lindberg et al., 2008; "The SOLWEIG-model," n.d.)	estimation of thermal and environmental parameters at the local scale	software interface
urban energy balance models	(Mariani and Pangallo, 2005), various	estimation of urban heat fluxes (latent heat, sensible heat, ..)	various

Table 6-3
Data and models included in the project based in Milan. Source: author's elaboration.

The idea is to combine multiple sources, integrating air sensing data with a bottom-up approach. The increased scale and resolution, will allow the City of Milan to implement local measure, ultimately fostering a responsive city process (Figure 6-11).

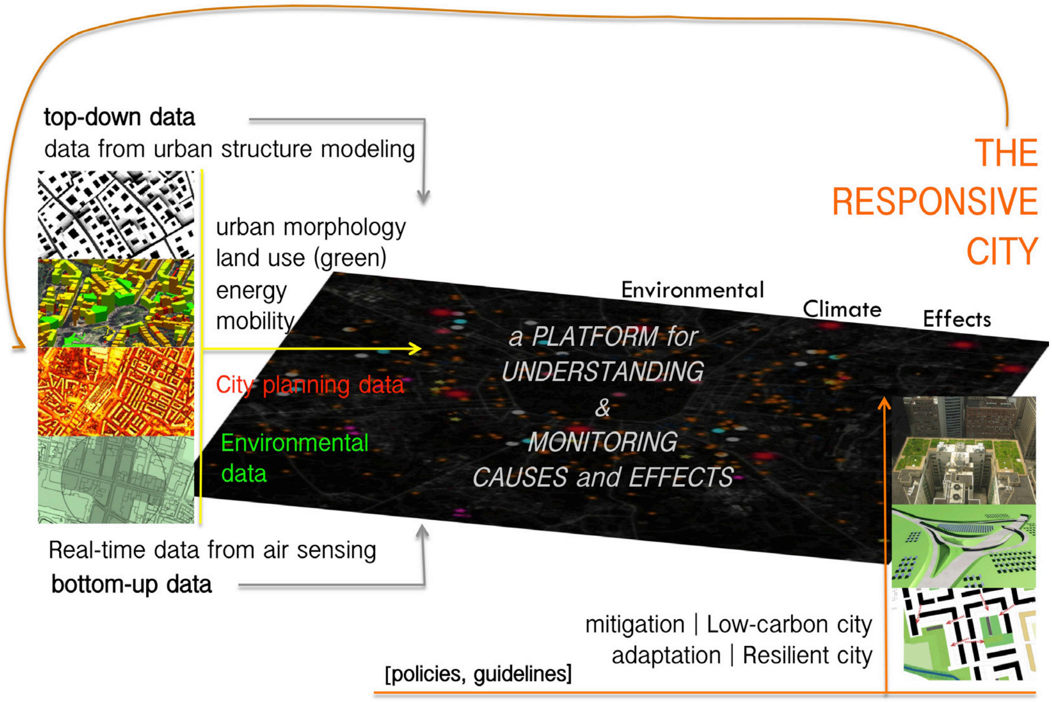


Figure 6-11
Conceptual framework for the modeling/sensing components and the local measures. Source: author's elaboration.

See § 3.2.A for modeling maps about indicators collected and proposed.

The sensing component: mobile sensor devices and bike sensing

The proposed project could benefit from using mobile sensor devices: though low-cost air quality sensing network is not a novelty, as emerged from this research, only recent technologies and studies demonstrate that they are now feasible and quite reliable for widespread use of monitoring at environmental levels, complementing other measurement technologies, and are now rapidly emerging as a feasible measurement technique for inclusion in air quality monitoring and regulation, source attribution and human exposure studies.
An example of a device that could be used in the project, to be installed on the bikes, is the sensor used in the mobile sensing fieldwork (§ 5.2), featuring PM10, PM2.5, humidity and temperature sensors. As emerged in the research, several issues occur in using low-cost sensors, and planning their use requires awareness of their limitation. As explored in ch. 5, technology problems might alter results'

accuracy, but a large quantity of data collectively can provide accurate data, at least in qualitative terms (such as detecting hotspots).
A specifically designed mobile phone app available to the public, could let citizens participate in the network and show data in augmented reality. The app could also be useful for citizens and tourists in suggesting most comfortable areas and routes (i.e. highlighting green areas, shaded areas, better microclimate pedestrian/biking streets, etc.).
A dedicated server and a web-based platform can display urban visualization with real-time data after a process of harmonization and calibration of data coming from different sources (mobile devices from bike sharing, mobile devices from citizens, EPA stations, university monitoring station, volunteer association station, etc.).
In addition, the GIS-based model previously described, could elaborate, mesh, and render the processed real-time data with the indicators coming from the urban data already calculated; morphology (i.e. sky view factor), land use (i.e. green areas), buildings density, anthropogenic waste heat and air emissions estimates (i.e. mobility, energy consumption).

Why using bikes?

Bikes are low cost, convenient, increasingly popular, environmental friendly means of transportation. They suit particularly well in air quality sensing projects, because of their agility to reach locations where cars or pedestrians cannot go, because of the natural ventilation provided to the sensing device for more accurate measurements (without emitting pollutants, like sensing projects in cars, taxis, buses).

In the case of Milan, a "smart city" project in relation to EXPO 2015 could include the installation of electric bikes, and potentially they that could be used to charge the sensor device (and phone battery).

Why public sharing bikes?

Public bike sharing is increasing worldwide (together with traditional bike and car-free mobility), and is suitable for participatory mobile sensing thanks to its public utilization, its mobile nature, its diffusion (high resolution coverage of city centers).

It has usually high attention by mass media, and its usage in air sensing projects, *never fully experimented before*, might deliver public participation and increase public awareness on a crucial topic still too often neglected (i.e. outdoor exposure).

Existing bike sensing projects?

Lots of bike sensing projects exist, though they are/were mainly focused on:

- topographical sensing (i.e. iBike Boston, using GPS and accelerometer)
- cyclist performance sensing (i.e. BikeNet, using accelerometers, camera, microphone, thermistor, photodiode)

Only few are/were focused on air exposure sensing and air quality sensing, here below summarized:

bike sensing	what	why	how	who	where	when	reference	Notes
	**Aero flex**	acquiring air quality data at a high spatial and temporal resolution	PM, UFP, BC, and gas sensors mounted on 1 bike	VITO, Flemish Institute for Technological Research + EveryAware EU Project	Antwerp Mol (Belgium)	march-april 2009 april 2010	www.vito.be/EN/HomepageAdmin/Home/Overheden/mijnomgeving/aeroflex_sensor_fiets/Pages/aeroflex_sensor_fiets.aspx	- expensive sensors - poor bike design - poor data visualization - high potential showed in hot-spot identification
	**CamMob Sens**	pollution monitoring initiative exploring real-time data collection	CO and NO sensors given to volunteers, pedestrians and bikers (?)	University of Cambridge, UK	Cambridge (UK)	spring/summer 2010	www.escience.cam.ac.uk/mobiledata/	- poor visualizations, - was effective, and an improved version of the sensors is being used for monitoring Heathrow airport
	**Cycle App**	Informing Cyclists on the Air Quality of Routes (web-app)	no bike sensing, (data based on a land use regression NOx map)	McGill University	Montreal Island (Canada)	data from a 2005/'2006 survey	http://traq-research.mcgill.ca/cycleapp/	- poor website design - poor data visualization - lack of sensing - lack of live data
	**UHI Rotterdam**	study on Urban Heat Island	temperature/humidity/radiation sensors and GPS mounted on a cargo bilke	Wageningen University	Rotterdam	august 2009	http://edepot.wur.nl/136841	- small campaign with little data - showed spatial variability of temperature /humidity
	**The Copenhagen Wheel**	transform a bike into a hybrid e-bike that also provides real-time environmental data	prototype of a wheel unveiled at COP15 (successively developed as "superpedestrian" project)	Senseable City Laboratory, MIT	Copenhagen	december 2009	http://senseable.mit.edu/copenhagenwheel/	- the prototype showed the potential for fine-grained environmental sensing - no air quality sensing included in "superpedestrian"

Table 6-4
List of bike sensing projects focused on air quality data collection. Source: author's elaboration.

In brief the main component of the project could be:

- dasboard (sens-e-bike) for electric bike sharing (sensor device, directly recharged through the bike, the display showing critical levels of pollution, the smartphone dock-in station), LED on spokes for real-time visualization
- striking visualizations of real-time pollution/temperature concentration (over the city over the time)
- attractive App -and webplatform- for collecting and displaying data, integrated with useful functions for citizens and tourists ("most comfortable/less polluted A-B route, "cool spots" suggestions, ..); streaming the data from device (via Bluetooth) to the platform (via mobile connection)
- Data Platform: for analyzing and visualizing data

In the collection of data, privacy management will be guaranteed, and the users will be asked for explicit consent, and properly informed on data collection and usage.

More in detail, the data platform should be useful for managing data stored in a server:

- Data stored in a server and managed by the platform:

- Raw data coming from the sensors ("Sens.dots - Connect the physical and virtual worlds," n.d.).
- Data from EPA and from reference devices.
- Weather data form other API ("Wunderground Weather Forecast & Reports ," n.d.)
- Geographical/planning GIS-based data (i.e. 3d buildings, trees, shaded areas, etc.)

Data analysis process will cover:

- The raw values measured by the sensors will be used to further compute more fine-grained PM/heat concentration estimates to give better spatial coverage. This estimation will be based on aggregation/kriging techniques and machine learning that infer the values between the 10/20 sensors values and the PM/heat measured by reference devices or EPA data.
- The sensor measurements will be adjusted by applying calibration factors, and measurements in the city can be re-calibrated based on live EPA data.
- The PM/heat concentrations will be displayed both on the web platform and the mobile phone App.

Expected results coming from this project are based on its strength and novelty, identifiable as:

- Data quality and quantity: First time having air quality data for the "real-time city" that are both fine grained and with appropriate coverage, (thanks to the low cost sensors now reliable and commercially available, and to public bike sensing)
- Big data and human/digital interface: First time dealing with the "Big data" component for air quality data, and with the human/digital interaction: "how digital technologies (sensors+mobilephones) can change the way people live (and work, relax, run, breathe) and their implications at the urban scale".
- Visualizations: Striking and catching well-planned visualizations will make the topic understandable, appealing, and will reach large public attention and high awareness as never done before by past or existing project (EU project Everyaware, VITO project, Zurich/Lausanne network, etc.)
- Interdisciplinarity: First time approaching the study integrating the built environment, the people, air quality and temperature together (interdisciplinary interest and collaboration between environmental planners, urban climatologist and meteorologist, epidemiologist, urban designer and planners, public community)

Expected results: increase knowledge and integration with existing planning

Data from the sensing network will provide urban climate and air quality information that can be included in existing planning tools.

Increased knowledge for urban studies

The smart mobile network will provide fine-grained real-time data useful for the platform, in order to identify and understand sensitive urban-climatic and environmental problem areas; it will show its potential and it could be easily replicable for other cities.

Data visualization could therefore identify "air-scapes", underlining sensitive urban-climatic and environmental problem areas ("Hot-spots" or "Breath-Taking" maps), potentially leading to build a "UHI map" (difference urban-rural), a "Heat stress map" (extreme heat), and a "Heat risk map" (overlapping temperature data to people exposure, GIS based, such as data about elderly residence), and in analogy, "Air quality map" and "health risk map".

Additional potential availability of mobile cellular data, could let building two differentiated maps (day/night), which represents different situations: extreme day heat at urban center coinciding with the time when most people (resident and commuters) are present in the city center areas, will probably correspond exactly to the previously identified urban hot-spots (while at night both temperature and people exposure decrease in central city areas).

A further potential analysis could be the integrated study of "extreme heat" vs "air pollution increase" map (i.e. ozone), comparing different temporal data (before and after heatwaves).

A specific innovative climate platform would for the first time to collect the interests of citizens, businesses, media, politicians, NGOs, as already proven by existing but partial projects (i.e. weathersignal.com).

Mapping and Planning

Existing urban planning tools for the city of Milan, such as the PGT "Piano di Governo del Territorio" ("Comune di Milano - Piano di Governo del Territorio," n.d.), the most important plan for the strategic and territorial government of the city, can benefit from the project, since its deal with factors affecting urban climate and air quality (see § 1.3.A and §6.1.A, §6.2.B). The mapping by sensing component of the project, explored in this research, can be the base knowledge for identifying local heat and pollutant concentration, and to review potential conflicting previsions. Local measures could be implemented, such as installation of green roofs in a specific climate sensitive area, or limitation of traffic in a selected polluted street, as seen in the examples of Stuttgart, Seoul and Kaohsiung.

Other tools can benefit from the availability of such fine-grained maps and data. For instance, considering the raise of climate change attention in mitigation and more recently in adaptation, existing and emerging tools can benefit from the project integrating the local and the global scale.

For instance, the Sustainability Energy Action Plan (SEAP), adopted by the city of Milan ("Comune di Milano - Piano di Azione per l'Energia Sostenibile – PAES," n.d.), mostly oriented on mitigation, includes actions at the local scale, with effect at both the local and the global scale. At the same time, the Energy and Environment Plan of Milan ("Comune di Milano - Il Piano energetico ambientale," n.d.) also address efficiency and limitation of consumption as priorities. The availability of fine-grained data would enhance the actions identification, such as limiting anthropogenic air emissions from private car mobility of urban buildings blocks energy consumptions where needed the most.

About adaptation, the "100 resilient cities initiative", adopted by the city of Milan ("Milan's Resilience Challenge | 100 Resilient Cities," n.d.) includes actions to tackle climate change effects, such as heatwaves. It is clear that a fine-grained local scale knowledge of UHI is essential to study the heat concentration and to propose local solutions.

Monitoring and Assessing

Because the sensing network will provide real-time data, it would be possible to integrate its measurements to governmental data, as mentioned in § 6.2.A.
In particular, the monitoring phase of urban planning, aimed at verifying the predictions of planning, verifying the implementation of the strategies, and verifying their effectiveness on the urban challenges, require local date currently not available for some indicators, such as air pollution.
Monitoring a plan implementation is one of the aims of the Strategic Environmental Assessment tool ("Strategic Environmental Assessment - SEA - Environment - European Commission," n.d.), and most of the planning processes in Europe, and in Milan, need to implement its features. Data from projects like the one here proposed can be used for assessing options for the planning implementation.

Finally the "Smart City" concept, adopted by the city of Milan, ("Smart City MIlano," n.d.), includes the idea of sensing as an essential "smart" component of "mobility", "environment", "people", and "smart governance", in the framework of "Smart Cities and Smart Communities and Social Innovation". The real-time sensing can make the city more "sentient and therefore "responsive" (see § 2.3.A and § 6.1B).

Finally, as mentioned in the previous section, the project can be included in the projects for the Universal Exhibition in 2015, EXPO 2015, around the theme "Feeding the Planet, Energy for Life" ("Expo Milano 2015 - Feeding the Planet, Energy for Life," n.d.), since it will be focusing on environmental sustainability and technology innovation.

Increased awareness

Public awareness could be enhanced thanks to the bike sharing usage and the opportunity of gamification (i.e. example of Air Probe Challenge, described in ch.

5). Personal awareness might lead to modified lifestyle condition, and diffusion of more responsible practices, such as using the car only when alternatives are not available, and practicing outdoor activities in specific temporal and spatial frame.

See **Annex 3** for more details about the proposal.

Conclusion

On the basis of these research findings, the potential of sensing emerged to be very promising, but the current technology challenges suggest more of a future elaboration rather than immediate implementation. However, the development of the sensing industry is rapid, and the last two years 2013-2014 saw a fast-growing improvement of low-cost sensors technology. It is therefore likely to evolve in the next few years, and thus within a short-term period a paradigm shift towards more and more air quality attention, measurements, mapping and awareness, will be ready to for implementation at a large scale for urban mapping once sensors improve in data quality.

Urban planning should be prepared to profit from the opportunities that are likely to affect cities health and environment, and this chapter aimed to contribute to the process of making urban planning ready and benefit from the fruitful opportunities offered by sensing, as it has the potential to change the future of urban climate and air quality in our cities. For example, participatory sensing scenarios are beneficial for both increasing data quality and enhancing awareness of environmental and health topics.

The panoptic ICT top-down concern, familiar to smart city criticism, should be tackled by enhancing bottom-up “smartness”: promoting crowdsourcing and people-centric sensing will enhance urban sensing in an integrated perspective, both increasing data quality and citizens participation and awareness.

The second section of this chapter provided more details about recommendations in both profiting from the opportunities and in dealing with the limitations of using sensing.

The last conclusive section presented a project proposal that includes the findings of this research, demonstrating the potential for the city of Milan in implementing a sensing project, integrated into a model, in the final aim of mapping urban climate and air quality in the city of Milan.

While the conclusions from this research show promising opportunities and envision a changing role for urban planning in improving health and well-being in cities, further research is needed in order to explore the realistic possibility of implementation of the “next generation sensing” in urban climate and air quality mapping.

References

ArcGIS. (n.d.). Retrieved January 03, 2015, from http://www.arcgis.com/features/

Bacci, P., & Maugeri, M. (1992). The urban heat island of Milan. *Il Nuovo Cimento C*, *15*(4), 417–424. doi:10.1007/BF02511742

Barrett, K., de Leeuw, F., Fiala, J., Larssen, S., Sundvor, I., Fjellsbø, L., … Černikovský, L. (2008). Health impacts and air pollution–an exploration of factors influencing estimates of air pollution impact upon the health of European citizens. *ETC/ACC Tech Pap*, *13*.

Batty, M. (1976). *Urban modelling*. (L. Martin & L. March, Eds.) (p. 381). Cambridge, UK: Cambridge University Press. Retrieved from http://www.casa.ucl.ac.uk/urbanmodelling/

Batty, M. (2013). *The New Science of Cities* (p. 520). The MIT press. Retrieved from http://mitpress.mit.edu/books/new-science-cities

Batty, Mi. (1997). The Computable City. *International Planning Studies*, *2*(2), 155–173. doi:10.1080/13563479708721676

Becker, M., Caminiti, S., Fiorella, D., Francis, L., Gravino, P., Haklay, M. (Muki), … Tria, F. (2013). Awareness and learning in participatory noise sensing. *PloS One*, *8*(12), e81638. doi:10.1371/journal.pone.0081638

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(17), 7301–6. doi:10.1073/pnas.0610172104

Borga, G. (2014). City Sensing. *Milano IT: Franco Angeli*.

Borghi, S., Corbetta, G., & Biase, L. De. (2000). A heat island model for large urban areas and its application to Milan. *Il Nuovo Cimento - Società Italiana Di Fisica*, *23*(5), 547–566. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=867864

Bruse, M. (2004). ENVI-met website. *Online: Http://www.envimet.com*.

Burke, J., Estrin, D., & Hansen, M. (2006). Participatory sensing. In *World Sensor Web Workshop, ACM Sensys 2006, October 31, 2006* (pp. 1–5). Boulder, Colorado, US. Retrieved from http://escholarship.org/uc/item/19h777qd.pdf

Calabrese, F., Kloeckl, K., & Ratti, C. (2008). Wikicity: Real-time location-sensitive tools for the city. *Handbook of Research on Urban Informatics: The Practice and Promise of the Real-Time City*, 390–413.

Calabrese, F., & Ratti, C. (2006). Real time rome. *Networks and Communication Studies*, *20*(3-4), 247–258.

Calvino, I. (1995). World Memory. In *Numbers in the Dark and Other Stories, translated by Tim Parks* (pp. 135–136). New York: Vintage.

Campbell, A. T., Eisenman, S. B., Lane, N. D., Miluzzo, E., & Peterson, R. A. (2006). People-centric urban sensing. In *Proceedings of the 2nd annual international workshop on Wireless internet* (p. 18). ACM.

Centro Meteorologico Lombardo. (n.d.). Retrieved January 03, 2015, from http://www.centrometeolombardo.com/

Chandler, T. (1965). *The climate of London* (p. 292). London, UK: Hutchinson & Co. Retrieved from http://books.google.com/books?hl=en&lr=&id=P2gFAAAAQAAJ&oi=fnd&pg=PA361&dq=The+Climate+Of+London&ots=4mzVvHXnTV&sig=nwHLJuY9SAwtd8eHkq7SovyIzXM

Chen, L., & Ng, E. (2011). Quantitative urban climate mapping based on a geographical database: A simulation approach using Hong Kong as a case study. *International Journal of Applied Earth Observation and Geoinformation*, *13*(4), 586–594. doi:http://dx.doi.org/10.1016/j.jag.2011.03.003

Climate Atlas Region Stuttgart 2008. (n.d.). Retrieved January 02, 2015, from http://www.staedtebauliche-klimafibel.de/sh2.php?f=abb-5-10.jpg

Comune di Milano - Il Piano energetico ambientale. (n.d.). Retrieved January 04, 2015, from http://comune.milano.it/portale/wps/portal/searchresultdetail?WCM_GLOBAL_CONTEXT=

/wps/wcm/connect/ContentLibrary/giornale/giornale/tutte+le+notizie/mobilit+trasporti+ambiente/ambiente_piano+energetico+ambientale

Comune di Milano - Piano di Azione per l'Energia Sostenibile – PAES. (n.d.). Retrieved January 04, 2015, from https://www.comune.milano.it/portale/wps/portal/CDM?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/contentlibrary/Ho bisogno di/Ho bisogno di/Piano di Azione per Energia Sostenibile&categId=com.ibm.workplace.wcm.api.WCM_Category/IT_CAT_Bisogni_09/69896100446e01acba81bbd36d110d8a/PUBLISHED&categ=IT_CAT_Bisogni_09&type=content

Comune di Milano - Piano di Governo del Territorio. (n.d.). Retrieved January 04, 2015, from http://www.comune.milano.it/portale/wps/portal/CDM?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/ContentLibrary/ho bisogno di/ho bisogno di/PGT_2012&categId=com.ibm.workplace.wcm.api.WCM_Category/IT_TAX_Bisogni_37/f789020044a9ba01b691bfa6efd47d08/PUBLISHED&categ=IT_TAX_Bisogni_37&type=content

Condon, P. M., Cavens, D., & Miller, N. (2009). *Urban planning tools for climate change mitigation*. Lincoln Institute of Land Policy Cambridge, MA.

Diappi, L. (2004). *Evolving Cities: Geocomputation In Territorial Planning*. Burlington: Ashgate.

Dodge, M., Doyle, S., Hudson-Smith, A., & Fleetwood, S. (1998). Towards the virtual city: VR & internet GIS for urban planning.

Droege, P. (2006). *The renewable city: a comprehensive guide to an urban revolution*. Wiley-Academy Chichester, UK.

Duany, A., Speck, J., & Lydon, M. (2009). *The Smart Growth Manual* (Vol. 5, p. 240). McGraw Hill Professional. Retrieved from http://books.google.com/books?id=ESjbAgAAQBAJ&pgis=1

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*(1), 31–44. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204600000347

Eum, J. H., Scherer, D., Fehrenbach, U., Köppel, J., & Woo, J. H. (2013). Integrating urban climate into urban master plans using spatially distributed information-The Seoul example. *Land Use Policy*, *34*, 223–232. doi:10.1016/j.landusepol.2013.03.016

European Cooperation in the field of Scientific and Technical Research. (2011). *European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability - EuNetAir* (pp. 1–66). Retrieved from http://w3.cost.eu/fileadmin/domain_files/ESSEM/Action_TD1105/mou/TD1105-e.pdf

Everyaware Project. (2014). *Everyaware Project - Final Report Period* (p. 56). Turin, IT. Retrieved from http://www.everyaware.eu/resources/deliverables/D7.3.pdf

Expo Milano 2015 - Feeding the Planet, Energy for Life. (n.d.). Retrieved January 02, 2015, from http://www.expo2015.org/en

Farr, D. (2012). *Sustainable Urbanism: Urban Design With Nature* (p. 305). Hoboken, New Jersey: John Wiley & Sons. Retrieved from http://books.google.com/books?hl=it&lr=&id=6he0qcS3ZaUC&pgis=1

Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749–758. doi:10.1016/j.rser.2013.05.057

Gerboles, M., & Buzica, D. (2009). *Evaluation of micro-sensors to monitor ozone in ambient air*. Ispra (VA), Italy. doi:10.2788/5978

Goldsmith, S., & Crawford, S. (2014). *The Responsive City: Engaging Communities Through Data-Smart Governance*. John Wiley & Sons.

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal*, *69*(4), 211–221.

Greenfield, A. (2006). *Everyware: The dawning age of ubiquitous computing*. New Riders.

Gross, N. (1999). The earth will don an electronic skin. *Business Week, August*, *30*.

Heat wave risk of European cities. (n.d.). Retrieved from http://www.arcgis.com/home/webmap/viewer.html?webmap=d4124af689f14cbd82b88b815ae81d76

Hebbert, M., & Webb, B. (2012). Towards a liveable urban climate: lessons from Stuttgart. *Liveable Cities: Urbanising World*, 120–137.

Heeks, R. (2008). ICT4D 2.0: The next phase of applying ICT for international development. *Computer*, *41*(6), 26–33. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4548169

Hollands, R. G. (2008). Will the real smart city please stand up? *City*, *12*(3), 303–320. doi:10.1080/13604810802479126

Howard, L. (1818). *The climate of London* (p. 221). Retrieved from http://books.google.com/books?hl=en&lr=&id=P2gFAAAAQAAJ&oi=fnd&pg=PA361&dq=The+cliamte+of+London&ots=4mzVvHWsXT&sig=Z0k_EPGU85wB0yQNNhWw6TlsHSc

Hsu, A., & Zomer, A. (2014, June). An Interactive Air-Pollution Map. *The Atlantic*. Retrieved from http://www.theatlantic.com/health/archive/2014/06/the-air-we-breathe/372411/

Iveson, K. (2013). Cities within the City: Do-It-Yourself Urbanism and the Right to the City. *International Journal of Urban and Regional Research*, *37*(3), 941–956. doi:10.1111/1468-2427.12053

Jacobs, J. (1961). *The Death and Life of Great American Cities-Vintage* (p. 459). New York: Vintage Books, Random House.

Jang, M., & Suh, S.-T. (2010). U-city: new trends of urban planning in Korea based on pervasive and ubiquitous geotechnology and geoinformation. In *Computational Science and Its Applications–ICCSA 2010* (pp. 262–270). Springer.

Kitchin, R. (2014). The Real-Time City? Big Data and Smart Urbanism. *GeoJournal*, *79*(1), 1–14. Retrieved from http://link.springer.com/article/10.1007/s10708-013-9516-8

Kratzer, A. (1956). *The climate of cities*. *Scientific American*. Bedford, Massachusetts: Air Force Cambridge Research Laboratories. Retrieved from http://adsabs.harvard.edu/abs/1967SciAm.217b..15L

Landsberg, H. E. (1973). The meteorologically utopian city. *Bulletin of the American Meteorological Society*, *54*(2), 86–89.

Lee, H., Han, H., Leem, T., Yigitcanlar, T., Ho Lee, S., Hoon Han, J., & Taik Leem, Y. (2008). Towards ubiquitous city: concept, planning, and experiences in the Republic of Korea. *Knowledge-Based Urban Development: Planning and Applications in the Information Era*, 148–170.

Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*, *52*(7), 697–713.

Littlefair, P., Santamouris, M., Alvarez, S., Dupagne, A., Hall, D., Teller, J., … Papanikolaou, N. (2000). *Environmental site layout planning: solar access, microclimate and passive cooling in urban areas*. *BRE Report BR* (p. 151). London, UK: CRC. Retrieved from http://orbi.ulg.ac.be/handle/2268/28963

Lonati, G., Giugliano, M., & Cernuschi, S. (2006). The role of traffic emissions from weekends' and weekdays' fine PM data in Milan. *Atmospheric Environment*, *40*(31), 5998–6011. doi:10.1016/j.atmosenv.2005.12.033

Manfredini, F., Pucci, P., & Tagliolato, P. (2012). Mobile phone network data. new sources for urban studies. *Geographic Information Analysis for Sustainable Development and Economic Planning: New Technologies.Hershey PA, USA: IGI Global*, 115–128.

Marcazzan, G. M., Vaccaro, S., Valli, G., & Vecchi, R. (2001). Characterisation of PM10 and PM2.5 particulate matter in the ambient air of Milan (Italy). *Atmospheric Environment*, *35*(27), 4639–4650. doi:10.1016/S1352-2310(01)00124-8

Mariani, L., & Pangallo, G. S. (2005). Approccio qualitativo all'analisi degli effetti urbani sul clima. *Rivista Italiana Di Agrometerologia*, *2*, 31–36.

MATLAB. (n.d.). Retrieved January 03, 2015, from http://www.mathworks.com/products/matlab/index.html?s_tid=gn_loc_drop

Michelozzi, P., De'Donato, F., Bisanti, L., Russo, A., Cadum, E., DeMaria, M., … Perucci, C. (2005). The impact of the summer 2003 heat waves on mortality in four Italian cities. *Eurosurveillance*, *10*(7). Retrieved from http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=556

Milan's Resilience Challenge | 100 Resilient Cities. (n.d.). Retrieved January 04, 2015, from http://www.100resilientcities.org/cities/entry/milan#/-_/

Ministry of Transport and Infrastructure of Baden-Württemberg. (2012). *Climate Booklet for Urban Development* (p. 275). Stuttgart, Germany. Retrieved from http://www.staedtebauliche-klimafibel.de/?p=0

Ng, E., Chen, L., Wang, Y., & Yuan, C. (2012). A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. *Building and Environment*, *47*, 256–271.

Offenhuber, D., & Ratti, C. (2014). *Decoding the City. Urbanism in the Age of Big Data*. (D. Offenhuber & C. Ratti, Eds.). Berlin, Boston. doi:10.1515/9783038213925

Oke, T. R. (1984). Towards a prescription for the greater use of climatic principles in settlement planning. *Energy and Buildings*, *7*(1), 1–10.

Oke, T. R. (2004). *Initial guidance to obtain representative meteorological observations at urban sites*. *geog.ubc.ca* (Vol. 81). World Meteorological Organization Geneva. Retrieved from http://www.geog.ubc.ca/~toke/IOM-81-UrbanMetObs.pdf

Oke, T. R. (2006). Towards better scientific communication in urban climate. *Theoretical and Applied Climatology*, *84*(1-3), 179–190.

Osservatorio Meteorologico di Milano Duomo. (2014). *Il Clima cambia le città* (p. 40). Milan, IT.

Pichierri, M., Bonafoni, S., & Biondi, R. (2012). Remote Sensing of Environment Satellite air temperature estimation for monitoring the canopy layer heat island of Milan. *Remote Sensing of Environment*, *127*, 130–138.

PM10 interpolated maps — European Environment Agency (EEA). (n.d.). Retrieved January 02, 2015, from http://www.eea.europa.eu/themes/air/interactive/pm10-interpolated-maps

PM2.5 interpolated maps — European Environment Agency (EEA). (n.d.). Retrieved January 02, 2015, from http://www.eea.europa.eu/themes/air/interactive/pm2-5-interpolated-map

Poli, T., Gattoni, L. Pietro, Paolini, R., Pansa, G., Favaron, M., & Pilati, S. (2009). The influence of the urban heat island over building energy demand: the case of Milan. In *The seventh International Conference on Urban Climate, 29 June - 3 July 2009, Yokohama, Japan* (pp. 1–4). Yokohama, Japan.

Ratti, C., Pulselli, R., & Williams, S. (2006). Mobile landscapes: using location data from cell phones for urban analysis. *Environment and Planning B: Planning and Design*, *33*(5), 727–748. Retrieved from http://www.envplan.com/ep/epb/fulltext/b33/b32047.pdf

Ratti, C., & Townsend, A. (2011). The Social Nexus. *Scientific American*, *305*(3), 42–48. doi:10.1038/scientificamerican0911-42

Ren, C., Lau, K. L., Yiu, K. P., & Ng, E. (2013). The application of urban climatic mapping to the urban planning of high-density cities: The case of Kaohsiung, Taiwan. *Cities*, *31*(0), 1–16. doi:http://dx.doi.org/10.1016/j.cities.2012.12.005

Ren, C., Ng, E. Y., & Katzschner, L. (2011). Urban climatic map studies: a review. *International Journal of Climatology*, *31*(15), 2213–2233. doi:10.1002/joc.2237

Rosenzweig, C., Solecki, W. D. W., Hammer, S. A. S., & Mehrotra, S. (2011). *Climate change and cities: first assessment report of the Urban Climate Change Research Network*. Cambridge University Press. Retrieved from http://books.google.com/books?hl=en&lr=&id=9GHW24KCuBYC&oi=fnd&pg=PR7&dq=Climate+Change+and+Cities.+First+Assessment+Report+of+the+Urban+Climate+Change+Research+Network&ots=_2rzZWs1QD&sig=T36sbMPIw0uDhlWBVb-7pulOsYo

Sassen, S. (2014). Saskia Sassen talk at MIT Senseable "City Engaging Data 2013" conference.

Sens.dots - Connect the physical and virtual worlds. (n.d.). Retrieved January 02, 2015, from http://www.sensdots.com/

Shepard, M. (2011). *Sentient city: Ubiquitous computing, architecture, and the future of urban space*. The MIT press.

Shwayri, S. T. (2013). A Model Korean Ubiquitous Eco-City? The Politics of Making Songdo. *Journal of Urban Technology*, *20*(1), 39–55. doi:10.1080/10630732.2012.735409

Smart City MIlano. (n.d.). Retrieved January 02, 2015, from http://www.milanosmartcity.org/joomla/

Snyder, E. G., Watkins, T. H., Solomon, P. a, Thoma, E. D., Williams, R. W., Hagler, G. S. W., … Preuss, P. W. (2013). The changing paradigm of air pollution monitoring. *Environmental Science & Technology*, *47*(20), 11369–77. doi:10.1021/es4022602

Stadtklima Stuttgart | Climate analysis maps. (n.d.). Retrieved January 02, 2015, from http://www.stadtklima-stuttgart.de/index.php?climate_climate_atlas_1992_9_maps

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, *31*(2), 200–217.

Stewart, I. D. (2013). Local Climates of the City. *Architectural Design*. doi:10.1002/ad.1625

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. doi:10.1175/BAMS-D-11-00019.1

Stone, B. (2005). Urban heat and air pollution: An emerging role for planners in the climate change debate. *Journal of the American Planning Association*, *71*(1), 13–25. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360508976402

Stone, B., & Rodgers, M. O. M. (2001). Urban form and thermal efficiency: How the design of cities influences the urban heat island effect. *Journal of the American Planning Association*, *67*(2), 186–198. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360108976228

Stone, B., Vargo, J., & Habeeb, D. (2012). Managing climate change in cities: Will climate action plans work? *Landscape and Urban Planning*, *107*(3), 263–271. doi:10.1016/j.landurbplan.2012.05.014

Strategic Environmental Assessment - SEA - Environment - European Commission. (n.d.). Retrieved January 04, 2015, from http://ec.europa.eu/environment/eia/sea-legalcontext.htm

Stroh, E., Harrie, L., & Gustafsson, S. (2007). A study of spatial resolution in pollution exposure modelling. *International Journal of Health Geographics*, *6*(1), 19. doi:1476-072X-6-19 [pii]

Subramanian, K. (2012). Does Your Organization Face Data Obesity Problem? Retrieved December 16, 2014, from http://www.cloudave.com/19193/does-your-organization-face-data-obesity-problem/

Szell, M. (2014). Connecting Paradigms. *Science*, *343*(6174), 970–971. doi:10.1126/science.1249599

Taha, H. (1997). Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, *25*(2), 99–103. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0031097861&partnerID=40&md5=7569bfa46642e949dafcd06c85a84018

The SOLWEIG-model. (n.d.). Retrieved December 29, 2014, from http://gvc.gu.se/english/research/climate/urban-climate/software/solweig

Treville, A., & Dosi, M. P. (2012). New Climate Analysis Regions moving towards a low carbon economy, 1–100.

United Nations. (1992). Rio Declaration on Environment and Development. Retrieved December 17, 2014, from http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

United Nations. (2014). *World Urbanization Prospects 2014* (2014th ed.). New York: United Nations.

United Nations Economic Commission for Europe. (1998). The Aarhus Convention. Retrieved December 17, 2014, from http://ec.europa.eu/environment/aarhus/

United States Environmental Protection Agency. (n.d.). Next Generation Air Measuring. Retrieved December 07, 2014, from http://www.epa.gov/airscience/next-generation-air-measuring.htm

United States Environmental Protection Agency. (2008). *Reducing Urban Heat Islands: Compendium of Strategies*. *Environmental Protection Agency, retrieved May* (Vol. 12, p. 39p). Washington, DC: United States Environmental Protection Agency. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Reducing+Urban+Heat+Islands+:+Compendium+of+Strategies#0

United States Environmental Protection Agency. (2013). *Roadmap for Next Generation Air Monitoring*.

United States Environmental Protection Agency. (2014). *Air Sensors Guidebook* (p. 73). Research Triangle Park, NC: US Environmental Protection Agency. Retrieved from ww.epa.gov.ord

United States Green Building Council. (2014). *Green Neighborhood Development: LEED reference guide for neighborhood development* (Vol. v. 4). US Green Building Council.

Wunderground Weather Forecast & Reports . (n.d.). Retrieved January 02, 2015, from http://www.wunderground.com/

Yamamoto, Y. (2006). Measures to mitigate urban heat islands. *Science and Technology Trends Quarterly Review*, *18*(1), 65–83. Retrieved from http://www.nistep.go.jp/achiev/ftx/eng/stfc/stt018e/qr18pdf/STTqr1806.pdf

Zhou, Y., & Shepherd, J. M. (2009). Atlanta’s urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards*, *52*(3), 639–668. doi:10.1007/s11069-009-9406-z

CONCLUSION

- SUMMARY OF CONTRIBUTION

Urban planning is facing the environmental questions posed by climate change and air pollution in urbanized and increasingly crowded areas in both the developed and developing world. “Urban climate” and “air quality” were introduced as urban and local problems with harmful effects on which urban planning has a big role. Because the phenomena involved have a strong local urban component, urban planning can define local measures in order to limits its responsibility. While current studies are exploring mitigation and particularly adaptation solutions to be applied to target locations, data and urban models are mostly available at the regional/city level, with little information available at the local/neighborhood level, and the “people's level”.

Mapping was therefore explored as a planning tool used for its rich potential in investigation and exploration, observation and interpretation, analysis and communication of small scale and large-scale urban environments, with the ability to transfer sectorial outcomes into planning language, and increasing the base knowledge for urban studies and for urban planning and policy decisions. The literature review of theoretical studies and practical examples of mapping urban climate and air quality, showed how mapping is conducted by modeling and sensing with different advantages and disadvantages. Annex 1 included an overview of the most relevant sensing networks for urban climate and air quality, in its aim to contribute to the ongoing research in this field.
According to the review, new available sensing technologies are pushing a paradigm shift: from traditional top-down climate/environmental modeling and scarce governmental monitoring to innovative diffused sensor networks and participatory sensing scenarios. The opportunities for spatial and environmental planning explored in this work are vast: mapping at a local scale and at a fine-grained resolution can enhance UHI and pollution concentration studies, and allow hotspots spatial and temporal variation studies. In addition, real-time information supports the creation of an urban smart information platform for interdisciplinary communication and collaboration, ultimately used by planners and decision makers, for planning more sentient, resilient, and responsive cities.

A specific contribution in exploring sensors technology and its applicability was made thanks to the fieldwork experiment and the case study analysis of the innovative local sensing project (Clairity at MIT) thanks to the collaboration

during this research). Firstly, in planning the mobile sensing campaign, an overview of the most relevant mobile sensing devices available for mapping urban climate and air quality was included. Annex 2 included an overview of low-cost portable sensors that can be used for ongoing and future research on air sensing and can be helpful for comparing devices features and performances.
Secondly, in designing and executing the fieldwork, numerous unexpected problems arose and were discussed, creating a reference case for further experimentations.

Overall, the potential of sensing emerged from this work seems to be very high, but more for future elaboration than immediate implementation, given the recent technology and the current challenges experienced. In fact, strong and unexpected findings were underlined in the data analysis and interpretation.
On the one hand, building a local sensing network, such as Clairity, is innovative and forward thinking but still struggles with issues connected to recent sensor technology. In addition, being a stationary network, data representativeness is challenging and designing the location of the sensing nodes requires further research. Communication and transparency challenges were found to be underrated but essential to avoid the misinterpretation currently experienced in many citizen science sensing projects, to avoid incorrect decision-making processes.
On the other hand, mobile sensing shares some technology issues, with the extra challenges of sensing in mobility (i.e. air flow, connectivity). However, it showed the best potential for an unprecedented resolution in mapping urban climate and air quality parameters within the urban environment. It allowed hot-spot mapping in both urban climate and air quality.
Therefore, mobile sensing emerged as a feasible option and the only way to gain a proper representativeness and increase resolution. However, it needs to be framed in a context where calibration and reference to official data is conducted, otherwise the qualitative approach can lead to unreliable results. Including the sensing data in a platform can be problematic too, but machine-learning techniques are helpful to increase data quality coming from different low-cost sensors.

While these findings emphasize the challenges of this recent technology, rapid developments are occurring, and it is likely that sensors will improve in data quality and be ready to be implemented at a large scale for urban mapping. In fact, as shown in the US-EPA initiative and annual conference on air sensing, the development of the sensing industry is rapid, and the last two years 2013-2014 saw a fast growing and improving low-cost sensor technology. It is therefore likely to assist in the next few years, thus in the short-term future, pushing a paradigm shift towards more and more air quality attention, measurements, mapping and awareness, and once sensors improve in data quality and they will be ready to be implemented at a large scale for urban mapping.
Urban planning, therefore, should be ready and profit from this opportunity, as it will change the future of urban climate and air quality in our cities. In addition,

participatory sensing scenarios are beneficial for both increasing data quality and enhancing awareness on environmental and health topics.

A final contribution was proposed in the last chapter of this work, where, on the basis of the research findings, some recommendations to urban planning aimed at contributing to the process of making urban planning ready and profit from the fruitful opportunities offered by sensing, as they are likely to affect cities health and environment.
The spread of personal sensing through wearables and the pervasive sensing might lead to the panoptic ICT top-down concern, familiar to smart city criticism. However, it should be tackled by enhancing bottom-up “smartness”: promoting crowdsourcing and people-centric sensing will enhance urban sensing in an integrated perspective, both increasing data quality and citizens participation and awareness.

The last conclusive contribution is a project proposal that includes the findings of this research, demonstrating the potential for the city of Milan in implementing a sensing project, integrated into a model, in the final aim of mapping urban climate and air quality in the city of Milan. It can be replicated in other cities, and its characteristics were included in Annex 3, which can be useful for further implementation.

In conclusion, while the findings from this research show promising opportunities and envision a changing role for urban planning in improving health and well-being in cities, further research is needed in order to explore the realistic possibility of implementation of the “next generation sensing” in urban climate and air quality mapping.

- IDEAS FOR FUTURE RESEARCH

As sensing technology advances, future research should investigate the possibility of implementation of the “next generation sensing” in urban climate and air quality mapping. In fact, as already mentioned, rapid developments are occurring, and it is likely that sensors will improve in data quality and be ready to be implemented at a large scale in the coming years. In addition, business interest is high, following the recent increase in citizens’ interest in pursuing healthy lifestyles, which requires knowledge about outdoor activities and pollution (where to go running, which streets are better to avoid while cycling, etc.). Besides personal sensing, and wearable sensing devices, most of the recent sensing projects address the social media sharing factor, and the willingness to contribute to participatory sensing, a collective mapping of urban environmental local problems, such as hotpots, for the community. All of these emerging components should be included in further research on air sensing for urban mapping.

A second idea relates to the research on the unexpected reaction of potential unpredicted reaction to increased awareness. Since air quality at the local scale is a result of many factors, such as city form and wind, some local areas, street, squares, or even green areas, might show persistent low-quality air, which suggests avoiding outdoor activities for citizens. Potentially, even running or cycling in a public park with certain air condition monitored by sensors, can be more harmful than other areas.
In fact, while the main expected results of air sensing in participatory scenarios, like what here explored with the European "Everyaware" project (see § 2.2), is a positive output coming from an increased awareness, leading to more sustainable citizens' behavior and ultimately to a decrease of the local emissions, such as car emissions, potential negative effect can (de)generate.

In addition, potential reaction of insurance companies and real estate market business should be further explored. While it has been proven that air pollution and heat concentration increase exposure (discomfort or health risk) or energy consumption (UHI), affecting property values, especially for residential market (see §1.2), fine-grained mapping is not currently available, and where available at early sensing stages (see §2.1 and 2.2), they are not conducted by governmental organizations.
However, as emerged from this work, it is likely that in the short-term future governmental organizations such as US-EPA (which is already working in this direction), might supplement air quality measurements for regulatory compliance, and therefore mapping air quality can reach a fine grained resolution differentiating neighborhoods and buildings in their air quality. Mapping might show bad quality differences from one neighborhood to another, from one street to another, according to local sources, urban morphology and weather parameters involved, comparable to noise mapping. Publicity and transparency of such mapping might raise business awareness, such as location of activities, insurance and property cost.

Together with these aspects, the economic impact of air pollution is also relevant in the current debate, and deserve further exploration.
In fact, at a local scale, detrimental effects of air pollution on property values are still under research, and currently, agreed assessments of the socio-economic impact of air are not available. Additionally, real estate market affects land use decisions in a way that the same group of people often suffer from both a low socio-economic status and high exposure to air pollution, making the results questionable (see §3.1.B). Therefore, studies at the local scale are needed to connect pollution concentration to health and real estate, and research for dynamics at the local/neighborhood scale.

ABBREVIATIONS

CASA	Center for Advanced Spatial Analysis
CC	Climate Change
CO	Carbon Oxide
CO2	Carbon Dioxide
DEM	Digital Elevation Model
DIY	Do-It-Yourself
EEA	European Environmental Agency
EPA	Environmental Protection Agency
EU	European Union
GPS	Global PositioningSystem
H/W	Height / Wide
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
LCA	Lyfe Cycle Assessment
MIT	Massachusetts Institute of Technology
NGOs	Non-governmental organizations
NO	Nitrogen Oxide
NO2	Nitrogen Dioxide
NOx	Nitrogen Oxides
PM	Particulate Matter
PM10	Particulate Matter 10
PM2.5	Particulate Matter 2.5
ppb	parts per million
ppm	parts per million
RH	Relative Humidity
SEA	Strategic Environmental Assessment
SCL	Senseable City Laboratory
SO2	Sulphur Dioxide
SVF	Sky View Factor
T	Temperature
UCL	University College of London
UHI	Urban Heat Island
US	United States
USD	United States Dollars
VOC	Volatile Organic Compounds
WHO	World Health Organization
WMO	World Meteorological Organization
µg/m3	micrograms per cubic meter

GLOSSARY

Accuracy, Precision, Bias
Precision and bias refer to the accuracy of a sensor measurement. Accuracy is the overall agreement of a sensor's measurement to the true value. Precision refers to how well the sensor reproduces the measurement of a pollutant under identical circumstances. Bias refers to measurement error; for example, a sensor may always measure a little higher or lower than the true concentration (United States Environmental Protection Agency, 2014, p. 20).

Calibration
Calibration is the process of checking and adjusting an instrument's measurements to ensure that it is reporting accurate data. Calibration compares the response of the instrument to a known reference value. Calibration is important because sensor performance can change over time. If at all possible, sensors should be calibrated for their response before, during, and after a set of data collections (United States Environmental Protection Agency, 2014, p. 21).

Carbon Monoxide (CO)
This gas prevents the normal transport of oxygen by the blood. This can lead to a significant reduction in the supply of oxygen to the heart, particularly in people suffering from heart disease ("Air Quality Now - Pollution Basics," n.d.).

Detection Limit, Sensitivity
Environmental pollutants can often be present in very low concentrations, particularly when measurements are being made far from the source of the pollution. A sensor will be most useful when it is able to measure a target pollutant over the full range of concentrations commonly found in the atmosphere (United States Environmental Protection Agency, 2014, p. 19).

Dry-Bulb Temperature
The air temperature is the average temperature of the air surrounding the occupant, with respect to location and time. According to ASHRAE 55 standard, the spatial average takes into account the ankle, waist and head levels, which vary for seated or standing occupants. The temporal average is based on three-minutes intervals with at least 18 equally spaced points in time. Air temperature is measured with a dry-bulb thermometer and for this reason it is also known as dry-bulb temperature ("Standard 55 | ashrae.org," n.d.)

Lead And Heavy Metals
Even small amounts of lead can be harmful, especially to infants and young children. In addition, lead taken in by the mother can interfere with the health of the unborn child. Exposure has also been linked to impaired mental function, visual-motor performance and neurological damage in children, and memory and attention span ("Air Quality Now - Pollution Basics," n.d.).

Mean Radiant Temperature

The radiant temperature is related to the amount of radiant heat transferred from a surface, and it depends on the material's ability to absorb or emit heat, or its emissivity. The mean radiant temperature, depends on the temperatures and emissivities of the surrounding surfaces as well as the view factor, or the amount of the surface that is "seen" by the object. So the mean radiant temperature experienced by a person in a room with the sunlight streaming in varies based on how much of her body is in the sun ("ISO 7726:1998(en) Ergonomics of the thermal environment," n.d.).

Nitrogen Dioxide (NO2)

Nitrogen dioxide can irritate the lungs and lower resistance to respiratory infections such as influenza. Continued or frequent exposure to concentrations that are typically much higher than those normally found in the ambient air may cause increased incidence of acute respiratory illness in children ("Air Quality Now - Pollution Basics," n.d.).

Ozone (O3)

Ozone irritates the airways of the lungs, increasing the symptoms of those suffering from asthma and lung diseases ("Air Quality Now - Pollution Basics," n.d.).

Particles (PM10, PM2.5) And Soot

Fine particles can be carried deep into the lungs where they can cause inflammation and a worsening of the condition of people with heart and lung diseases. In addition, they may carry surface-absorbed carcinogenic compounds into the lungs ("Air Quality Now - Pollution Basics," n.d.).

Response Time

A sensor may be quick or slow to measure a pollutant in the air. A sensor that responds quickly may be useful for mobile monitoring and for observing very rapid changes in pollutant concentrations. A sensor that responds slowly may be more suited to stationary monitoring of pollutants that vary in concentration gradually. The specific data collection goals and intentions will determine which type of sensor is best. It is desirable for a sensor to respond in less than 1 minute if it is to be used in any mode other than stationary monitoring (United States Environmental Protection Agency, 2014, p. 21).

Sulphur Dioxide (SO2)

Even moderate concentrations may result in a decrease in lung function in asthmatics. Tightness in the chest and coughing occur at high levels, and lung function of asthmatics may be impaired to the extent that medical help is required. Sulphur dioxide pollution is considered more harmful when particulate and other pollution concentrations are high ("Air Quality Now - Pollution Basics," n.d.).

Toxic Organic Micropollutants

TOMPs (Toxic Organic MicroPollutants) are produced by the incomplete combustion of fuels (or waste). They comprise a complex range of chemicals some of which, although they are emitted in very small quantities, are highly toxic or carcinogenic. Compounds in this category include: PAHs (Poly Aromatic Hydrocarbons), PCBs (Poly Chlorinated Biphenyls), dioxins, etc. TOMPS can causing a wide range of effects, from cancer to reduced immunity to nervous system disorders and interfere with child development. There is no "threshold" dose - the tiniest amount can cause damage (“Air Quality Now - Pollution Basics,” n.d.).

Volatile Organic Compounds (VOCs) such as Benzene

VOCs are organic chemicals that have a high vapor pressure at ordinary room temperature. Possible chronic health effects include cancer, central nervous system disorders, liver and kidney damage, reproductive disorders, and birth defects (“Air Quality Now - Pollution Basics,” n.d.).

Cited references

Air Quality Now - Pollution Basics. (n.d.). Retrieved February 18, 2015, from http://www.airqualitynow.eu/pollution_health_effects.php

ISO 7726:1998(en) Ergonomics of the thermal environment. (n.d.). Retrieved February 18, 2015, from https://www.iso.org/obp/ui/#iso:std:iso:7726:ed-2:v1:en

Standard 55 | ashrae.org. (n.d.). Retrieved February 18, 2015, from https://www.ashrae.org/resources--publications/bookstore/standard-55

United States Environmental Protection Agency. (2014). Air Sensors Guidebook (p. 73). Research Triangle Park, NC: US Environmental Protection Agency. Retrieved from ww.epa.gov.ord

REFERENCES

Aiden, E., & Michel, J.-B. (2013, December). The Predictive Power of Big Data. *Newsweek*. Retrieved from http://www.newsweek.com/predictive-power-big-data-225125

Air Quality Egg. (n.d.). Retrieved December 29, 2014, from http://airqualityegg.com/

Air Quality Index (AQI) - A Guide to Air Quality and Your Health. (n.d.). Retrieved January 02, 2015, from http://www.airnow.gov/index.cfm?action=aqibasics.aqi

Air Quality Now - Pollution Basics. (n.d.). Retrieved February 18, 2015, from http://www.airqualitynow.eu/pollution_health_effects.php

Air Quality Standards - Environment - European Commission. (n.d.). Retrieved December 28, 2014, from http://ec.europa.eu/environment/air/quality/standards.htm

Air Sensors 2014. (n.d.). Retrieved December 29, 2014, from https://sites.google.com/site/airsensors2014/home

Air-quality | EveryAware. (n.d.). Retrieved December 29, 2014, from http://www.everyaware.eu/activities/case-studies/air-quality/

AirBeam: Share & Improve Your Air by HabitatMap. (n.d.). Retrieved December 29, 2014, from https://www.kickstarter.com/projects/741031201/airbeam-share-and-improve-your-air

AirCasting. (n.d.). Retrieved December 29, 2014, from http://aircasting.org/

AirProbe International Challenge. (n.d.). Retrieved December 08, 2014, from http://www.everyaware.eu/APIC/

Akbari, H., & Rose, L. S. (2001). Characterizing the fabric of the urban environment: A case study of Salt Lake City, Utah. *Lawrence Berkeley National Laboratory*. Retrieved from http://escholarship.org/uc/item/0wk718sm

Alberti, M. (2008). *Advances in urban ecology: integrating humans and ecological processes in urban ecosystems*. Boston, MA: Springer New York. doi:10.1007/978-0-387-75510-6

Anderson, R. J., & Crocker, T. D. (1971). Air Pollution and Residential Property Values. *Urban Studies*, *8*(3), 171–180. doi:10.1080/00420987120080391

Anselin, L., & Lozano-Gracia, N. (2008). Errors in variables and spatial effects in hedonic house price models of ambient air quality. *Empirical Economics*, *34*(1), 5–34.

ANSYS Fluent. (n.d.). Retrieved December 29, 2014, from http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Fluent

Approved 19" Rack Environmental Dust Monitor, Model EDM 180 - GRIMM Aerosol Technik - Master in Real-Time Aerosol and Dust Monitoring. (n.d.). Retrieved December 06, 2014, from http://www.grimm-aerosol.com/en/environmental-dust-monitors/103-approved-19-rack-environmental-dust-monitor-model-edm-180.html#ad-image-0

ArcGIS. (n.d.). Retrieved January 03, 2015, from http://www.arcgis.com/features/

Arling, J., O'Connor, K., & Mercieca, M. (2010). *Air Quality Sensor Network for Philadelphia*. Philadelphia. Retrieved from http://wireless.ece.drexel.edu/air_quality/

Arnfield, A. J. (2003). Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. *International Journal of Climatology*, *23*(1), 1–26. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0037267157&partnerID=40&md5=c8b373dd14c04f053a08bdb60f7273ce

Arya, S. P. (1999). Air pollution meteorology and dispersion.

Bacci, P., & Maugeri, M. (1992). The urban heat island of Milan. *Il Nuovo Cimento C*, *15*(4), 417–424. doi:10.1007/BF02511742

Baccini, M., Biggeri, A., Accetta, G., Kosatsky, T., Katsouyanni, K., Analitis, A., … Michelozzi, P. (2008). Heat effects on mortality in 15 European cities. *Epidemiology (Cambridge, Mass.)*, *19*(5), 711–719. doi:10.1097/EDE.0b013e318176bfcd [doi]

Barbesta, M., & Schaffer, D. (2009). Concrete that Cleans Itself and the Air. *Concrete International*, *31*(2), 49–51.

Barrett, K., de Leeuw, F., Fiala, J., Larssen, S., Sundvor, I., Fjellsbø, L., … Černikovský, L. (2008). Health impacts and air pollution–an exploration of factors influencing estimates of air pollution impact upon the health of European citizens. *ETC/ACC Tech Pap*, *13*.

Basara, J. B., Illston, B. G., Fiebrich, C. A., Browder, P. D., Morgan, C. R., McCombs, A., … Crawford, K. C. (2011). The Oklahoma city micronet. *Meteorological Applications*, *18*(3), 252–261. doi:10.1002/met.189

Batty, M. (1976). *Urban modelling*. (L. Martin & L. March, Eds.) (p. 381). Cambridge, UK: Cambridge University Press. Retrieved from http://www.casa.ucl.ac.uk/urbanmodelling/

Batty, M. (1997). The Computable City. *International Planning Studies*, *2*(2), 155–173. doi:10.1080/13563479708721676

Batty, M. (2013). *The New Science of Cities* (p. 520). The MIT press. Retrieved from http://mitpress.mit.edu/books/new-science-cities

BBC News - Power of Big Data. (n.d.). Retrieved December 03, 2014, from http://www.bbc.com/news/business-29147254

BeACON - The BErkeley Atmospheric CO2 Observation Network. (n.d.). Retrieved December 29, 2014, from http://beacon.berkeley.edu/

Becker, M., Caminiti, S., Fiorella, D., Francis, L., Gravino, P., Haklay, M. (Muki), … Tria, F. (2013). Awareness and learning in participatory noise sensing. *PloS One*, *8*(12), e81638. doi:10.1371/journal.pone.0081638

Bellucci, F., Bogner, J. E., & Sturchio, N. C. (2012). Greenhouse gas emissions at the urban scale. *Elements*, *8*(6), 445–449.

Bettencourt, L. M. A., Lobo, J., Helbing, D., Kühnert, C., & West, G. B. (2007). Growth, innovation, scaling, and the pace of life in cities. *Proceedings of the National Academy of Sciences of the United States of America*, *104*(17), 7301–6. doi:10.1073/pnas.0610172104

Blečić, I., Cecchini, A., Falk, M., Marras, S., Pyles, D. R., Spano, D., & Trunfio, G. A. (2014). Urban metabolism and climate change: A planning support system. *International Journal of Applied Earth Observation and Geoinformation*, *26*, 447–457.

Borga, G. (2014). City Sensing. *Milano IT: Franco Angeli*.

Borghi, S., Corbetta, G., & Biase, L. De. (2000). A heat island model for large urban areas and its application to Milan. *Il Nuovo Cimento - Società Italiana Di Fisica*, *23*(5), 547–566. Retrieved from http://cat.inist.fr/?aModele=afficheN&cpsidt=867864

Brandsma, T., & Wolters, D. (2012). Measurement and statistical modeling of the urban heat island of the city of Utrecht (the Netherlands). *Journal of Applied Meteorology and Climatology*, *51*(6), 1046–1060. doi:10.1175/JAMC-D-11-0206.1

Briggs, D. J. D., Collins, S., Elliott, P., Fischer, P., Kingham, S., Lebret, E., … Van Der Veen, A. (1997). Mapping urban air pollution using GIS: a regression-based approach. *International Journal of Geographical Information Science*, *11*(7), 699–718. doi:10.1080/136588197242158

Britter, R., & Hanna, S. (2003a). Flow Dispersion in Urban Areas. *Annual Review of Fluid Mechanics*. doi:10.1146/annurev.fluid.35.101101.161147

Britter, R., & Hanna, S. R. (2003b). Flow and dispersion in urban areas. *Annual Review of Fluid Mechanics*, *35*(1), 469–496. doi:10.1146/annurev.fluid.35.101101.161147

Brook, R. D., Rajagopalan, S., Pope III, C. A., Brook, J. R., Bhatnagar, A., Diez-Roux, A. V, … American Heart Association Council on Epidemiology and Prevention and Council on Nutrition,Physical Activity and Metabolism, C. on the K. in C. D. (2010). Particulate matter air pollution and cardiovascular disease: An update to the scientific statement from the American Heart Association. *Circulation*, *121*(21), 2331–2378. doi:10.1161/CIR.0b013e3181dbece1 [doi]

Bruse, M. (2004). ENVI-met website. *Online: Http://www.envimet.com*.

Budde, M., Busse, M., & Beigl, M. (2012). Investigating the use of commodity dust sensors for the embedded measurement of particulate matter. *Networked Sensing Systems (INSS), 2012 Ninth International Conference on Networked Sensing*, 1–4. doi:10.1109/INSS.2012.6240545

Budde, M., El Masri, R., Riedel, T., & Beigl, M. (2013). Enabling Low-Cost Particulate Matter Measurement for Participatory Sensing Scenarios. In *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia (MUM 2013)*. doi:10.1145/2541831.2541859

Bueno, B., Hidalgo, J., Pigeon, G., Norford, L., & Masson, V. (2013). Calculation of Air Temperatures above the Urban Canopy Layer from Measurements at a Rural Operational Weather Station. *Journal of Applied Meteorology and Climatology*, *52*(2), 472–483. doi:10.1175/JAMC-D-12-083.1

Bueno, B., Norford, L., Pigeon, G., & Britter, R. (2011). Combining a Detailed Building Energy Model with a Physically-Based Urban Canopy Model. *Boundary-Layer Meteorology*, *140*, 471–489. doi:10.1007/s10546-011-9620-6

Bueno, B., Norford, L., Pigeon, G., & Britter, R. (2012). A resistance-capacitance network model for the analysis of the interactions between the energy performance of buildings and the urban climate. *Building and Environment*, *54*, 116–125. doi:10.1016/j.buildenv.2012.01.023

Burke, J., Estrin, D., & Hansen, M. (2006). Participatory sensing. In *World Sensor Web Workshop, ACM Sensys 2006, October 31, 2006* (pp. 1–5). Boulder, Colorado, US. Retrieved from http://escholarship.org/uc/item/19h777qd.pdf

Burton, E., Jenks, M., & Williams, K. (2003). *The compact city: a sustainable urban form?*. Routledge.

Busato, F., Lazzarin, R., & Noro, M. (2014). Three years of study of the Urban Heat Island in Padua: Experimental results. *Sustainable Cities and Society*, *10*, 251–258. doi:10.1016/j.scs.2013.05.001

Buttstädt, M., Sachsen, T., Ketzler, G., Merbitz, H., & Schneider, C. (2011). A new approach for highly resolved air temperature measurements in urban areas. *Atmospheric Measurement Techniques Discussions*, *4*(1), 1001–1019. doi:10.5194/amtd-4-1001-2011

Calabrese, F., Colonna, M., Lovisolo, P., Parata, D., & Ratti, C. (2011). Real-time urban monitoring using cell phones: A case study in Rome. *Intelligent Transportation Systems, IEEE Transactions on*, *12*(1), 141–151.

Calabrese, F., Kloeckl, K., & Ratti, C. (2008). Wikicity: Real-time location-sensitive tools for the city. *Handbook of Research on Urban Informatics: The Practice and Promise of the Real-Time City*, 390–413.

Calabrese, F., & Ratti, C. (2006). Real time rome. *Networks and Communication Studies*, *20*(3-4), 247–258.

Calthorpe, P. (2011). *Urbanism in the age of climate change*. Washington, DC: Island Press.

Calvino, I. (1995). World Memory. In *Numbers in the Dark and Other Stories, translated by Tim Parks* (pp. 135–136). New York: Vintage.

CamMobSens. (n.d.). Retrieved December 29, 2014, from http://www.escience.cam.ac.uk/mobiledata/

Campbell, A. T., Eisenman, S. B., Lane, N. D., Miluzzo, E., & Peterson, R. A. (2006). People-centric urban sensing. In *Proceedings of the 2nd annual international workshop on Wireless internet* (p. 18). ACM.

Carneiro, C., Morello, E., Ratti, C., & Golay, F. (2009). Solar Radiation over the Urban Texture: LIDAR Data and Image Processing Techniques for Environmental Analysis at City Scale. In J. Lee & S. Zlatanova (Eds.), *3D Geo-Information Sciences* (Vol. 2009, pp. 319–435). Springer.

CENS: Center for Embedded Networked Sensing. (n.d.). Retrieved December 29, 2014, from https://research.cens.ucla.edu/

Centre for Advanced Spatial Analysis. (n.d.). Retrieved December 30, 2014, from http://www.bartlett.ucl.ac.uk/casa

Centro de Operações Prefeitura do Rio de Janeiro | Acompanhe em tempo real tudo o que está acontecendo na cidade do Rio. (n.d.). Retrieved December 30, 2014, from http://www.centrodeoperacoes.rio.gov.br/

Centro Meteorologico Lombardo. (n.d.). Retrieved January 03, 2015, from http://www.centrometeolombardo.com/

Chandler, T. (1965). *The climate of London* (p. 292). London, UK: Hutchinson & Co. Retrieved from http://books.google.com/books?hl=en&lr=&id=P2gFAAAAQAAJ&oi=fnd&pg=PA361&dq=The+Climate+Of+London&ots=4mzVvHXnTV&sig=nwHLJuY9SAwtd8eHkq7SovyIzXM

Chay, K. Y., & Greenstone, M. (2005). Does Air Quality Matter? Evidence from the Housing Market. *Journal of Political Economy*, *113*(2), 376–424. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=bth&AN=16477827&site=ehost-live

Che-Ani, A. I., Shahmohamadi, P., Sairi, A., Mohd-Nor, M. F. I., Zain, M. F. M., & Surat, M. (2009). Mitigating the urban heat island effect: some points without altering existing city planning. *European Journal of Scientific Research*, *35*(2), 204–216.

Chen, F., Bornstein, R., Grimmond, C. S. B., Li, J., Liang, X., Martilli, A., … Wang, Y. (2012). Research priorities in observing and modeling urban weather and climate. *Bulletin of the American Meteorological Society*, *93*(11), 1725–1728. doi:10.1175/BAMS-D-11-00217.1

Chen, L., & Ng, E. (2009). Sky View Factor Analysis of Street Canyons And Its Implication For Urban Heat Island Intensity. *plea2009.arc.ulaval.ca*, *2*, 22–24. Retrieved from http://www.plea2009.arc.ulaval.ca/Papers/1.CHALLENGE/1.2 City/ORAL/1-2-07-PLEA2009Quebec.pdf

Chen, L., & Ng, E. (2011). Quantitative urban climate mapping based on a geographical database: A simulation approach using Hong Kong as a case study. *International Journal of Applied Earth Observation and Geoinformation*, *13*(4), 586–594. doi:http://dx.doi.org/10.1016/j.jag.2011.03.003

Ching, J., Burian, S., Chen, F., Cionco, R., Hultgren, T., McPherson, T., … Hanna, A. (2009). National Urban Database and Access Portal Tool, NUDAPT. *Bulletin of the American Meteorological Society*, *90*(8), 1157–1168. Retrieved from http://opensky.library.ucar.edu/collections/OSGC-000-000-000-427

CITI-SENSE. (n.d.). Retrieved December 29, 2014, from http://www.citi-sense.eu/

Clairity. (2014). *An Air Quality Sensor Network for MIT ' s Campus* (p. 74). Retrieved from http://clairity.mit.edu/site/documents/report.pdf

Clairity: MIT's Air Quality Network. (n.d.). Retrieved December 29, 2014, from http://clairity.mit.edu/site/html/

Climate Atlas Region Stuttgart 2008. (n.d.). Retrieved January 02, 2015, from http://www.staedtebauliche-klimafibel.de/sh2.php?f=abb-5-10.jpg

Climate Change, Clean Air and Sustainable Energy Action Plan. (2007). Retrieved December 29, 2014, from http://www1.toronto.ca/City Of Toronto/Environment and Energy/Programs for Residents/Files/pdf/C/clean_air_action_plan.pdf

Climate Neighbor. (n.d.). Retrieved December 29, 2014, from http://crit.com/portfolio/climate-neighbor/

Climate-ADAPT. (n.d.). Retrieved December 29, 2014, from http://climate-adapt.eea.europa.eu/

Clougherty, J. E., Kheirbek, I., Eisl, H. M., Ross, Z., Pezeshki, G., Gorczynski, J. E., … Matte, T. (2013). Intra-urban spatial variability in wintertime street-level concentrations of multiple combustion-related air pollutants: the New York City Community Air Survey (NYCCAS). *Journal Of Exposure Science & Environmental Epidemiology*, *23*(3), 232–240. doi:10.1038/jes.2012.125

Common Sense — Mobile sensing for community action. (n.d.). Retrieved December 29, 2014, from http://www.communitysensing.org/

Comune di Milano - Il Piano energetico ambientale. (n.d.). Retrieved January 04, 2015, from http://comune.milano.it/portale/wps/portal/searchresultdetail?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/ContentLibrary/giornale/giornale/tutte+le+notizie/mobilit+trasporti+ambiente/ambiente_piano+energetico+ambientale

Comune di Milano - Piano di Azione per l'Energia Sostenibile – PAES. (n.d.). Retrieved January 04, 2015, from https://www.comune.milano.it/portale/wps/portal/CDM?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/contentlibrary/Ho bisogno di/Ho bisogno di/Piano di Azione per Energia Sostenibile&categId=com.ibm.workplace.wcm.api.WCM_Category/IT_CAT_Bisogni_09/69896100446e01acba81bbd36d110d8a/PUBLISHED&categ=IT_CAT_Bisogni_09&type=content

Comune di Milano - Piano di Governo del Territorio. (n.d.). Retrieved January 04, 2015, from http://www.comune.milano.it/portale/wps/portal/CDM?WCM_GLOBAL_CONTEXT=/wps/wcm/connect/ContentLibrary/ho bisogno di/ho bisogno di/PGT_2012&categId=com.ibm.workplace.wcm.api.WCM_Category/IT_TAX_Bisogni_37/f789020044a9ba01b691bfa6efd47d08/PUBLISHED&categ=IT_TAX_Bisogni_37&type=content

Condon, P. M., Cavens, D., & Miller, N. (2009). *Urban planning tools for climate change mitigation*. Lincoln Institute of Land Policy Cambridge, MA.

Congress for the New Urbanism. (2013). *Charter of the new urbanism*. (E. Talen, Ed.) (Vol. Second edi). McGraw-Hill Professional.

Copenhagen wheel project. (n.d.). Retrieved December 29, 2014, from http://senseable.mit.edu/copenhagenwheel/

Criterion Planners – Planning Support Tools. (n.d.). Retrieved December 29, 2014, from http://crit.com/our-portfolio/planning-support-software/

Crouse, D., Goldberg, M. S., & Ross, N. A. (2009). A prediction-based approach to modelling temporal and spatial variability of traffic-related air pollution in Montreal, Canada. *Atmospheric Environment*, *43*(32), 5075–5084.

CUHK. (2009). *Urban Climatic Map and Standards for Wind Environment - Feasibility Study FINAL REPORT* (p. 518). Hong Kong.

Cui, L., & Shi, J. (2012). Urbanization and its environmental effects in Shanghai, China. *Urban Climate*, *2*(0), 1–15. doi:http://dx.doi.org/10.1016/j.uclim.2012.10.008

CycleApp | Air Quality of Cycling Routes in Montreal. (n.d.). Retrieved December 30, 2014, from http://traq-research.mcgill.ca/cycleapp/montreal/

Dacunto, P. J., Cheng, K. C., Acevedo-Bolton, V., Klepeis, N. E., Repace, J. L., Ott, W. R., & Hildemann, L. M. (2013). Identifying and quantifying secondhand smoke in multiunit homes with tobacco smoke odor complaints. *Atmospheric Environment*, *71*, 399–407. doi:10.1016/j.atmosenv.2013.02.018

Daughton, C. G. (2012a). Real-time estimation of small-area populations with human biomarkers in sewage. *The Science of the Total Environment*, *414*, 6–21. doi:10.1016/j.scitotenv.2011.11.015

Daughton, C. G. (2012b). Using biomarkers in sewage to monitor community-wide human health: isoprostanes as conceptual prototype. *The Science of the Total Environment*, *424*, 16–38. doi:10.1016/j.scitotenv.2012.02.038

Deguen, S., & Zmirou-Navier, D. (2010). Social inequalities resulting from health risks related to ambient air quality--A European review. *European Journal of Public Health*, *20*(1), 27–35. doi:10.1093/eurpub/ckp220 [doi]

Di Sabatino, S., Leo, L. S., Cataldo, R., Ratti, C., & Britter, R. (2010). Construction of digital elevation models for a southern European city and a comparative morphological analysis with respect to Northern European and North American cities. *Journal of Applied Meteorology and Climatology*, *49*(7), 1377–1396. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-77957727742&partnerID=40&md5=ed542b6e542f0ed060350be7138351dc

Diappi, L. (2004). *Evolving Cities: Geocomputation In Territorial Planning*. Burlington: Ashgate.

Dodge, M., Doyle, S., Hudson-Smith, A., & Fleetwood, S. (1998). Towards the virtual city: VR & internet GIS for urban planning.

Droege, P. (2006). *The renewable city: a comprehensive guide to an urban revolution*. Wiley-Academy Chichester, UK.

Droege, P. (2009). *100% renewable: energy autonomy in action*. (P. Droege, Ed.) (p. 326). London, UK: Earthscan. Retrieved from http://books.google.com/books?hl=en&lr=&id=2ahMx9eh7m0C&oi=fnd&pg=PP2&dq=100%+Renawable.+Energy+autonomy+in+Action&ots=Xp4wo6bJQq&sig=6YpIvGHOPFCBOMo7QpKycbRkXcA

Droege, P. (2010). *Climate Design: Design and Planning for the Age of Climate Change*. ORO editions.

Droege, P. (2011). *Urban energy transition: from fossil fuels to renewable power*. Elsevier. Retrieved from http://books.google.com/books?hl=en&lr=&id=0bEecvixZRMC&oi=fnd&pg=PP2&dq=Urban+Energy+Transition.+From+Dossil+Fuels+to+Renawable+Power&ots=vOEggENude&sig=5unS6vSSqvkJr9wvsSkt0baUfvU

Duany, A., Speck, J., & Lydon, M. (2009). *The Smart Growth Manual* (Vol. 5, p. 240). McGraw Hill Professional. Retrieved from http://books.google.com/books?id=ESjbAgAAQBAJ&pgis=1

Dunne, J. P., Stouffer, R. J., & John, J. G. (2013). Reductions in labour capacity from heat stress under climate warming. *Nature Climate Change*, *3*(6), 563–566.

DUSTTRAK II Aerosol Monitor 8532;Area Aerosol Monitors. (n.d.). Retrieved December 06, 2014, from http://www.tsi.com/dusttrak-ii-aerosol-monitor-8532/

Dylos DC1100 Professional Air Quality Monitor. (n.d.). Retrieved December 04, 2014, from http://www.dylosproducts.com/ornodcproair.html

EcoDistricts | Revitalizing cities from the neighborhood up. (n.d.). Retrieved December 29, 2014, from http://ecodistricts.org/

Edmonds, J., & Johnson, E. (1973). Matching, Euler tours and the Chinese postman. *Mathematical Programming*. Retrieved from http://link.springer.com/article/10.1007/BF01580113

Elen, B., Peters, J., van Poppel, M., Bleux, N., Theunis, J., Reggente, M., & Standaert, A. (2013). The Aeroflex: A bicycle for mobile air quality measurements. *Sensors (Switzerland)*, *13*, 221–240. doi:10.3390/s130100221

Eliasson, I. (2000). The use of climate knowledge in urban planning. *Landscape and Urban Planning*, *48*(1), 31–44. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204600000347

Elm Air Quality Sensor Network | PerkinElmer. (n.d.). Retrieved January 02, 2015, from http://elm.perkinelmer.com/map/

Emmanuel, M. R. (2005). *An Urban Approach to Climate-sensitive Design: Strategies for the Tropics*. Retrieved from http://books.google.com/books?hl=it&lr=&id=D7OJ23XA-18C&pgis=1

Eum, J. H., Scherer, D., Fehrenbach, U., Köppel, J., & Woo, J. H. (2013). Integrating urban climate into urban master plans using spatially distributed information-The Seoul example. *Land Use Policy*, *34*, 223–232. doi:10.1016/j.landusepol.2013.03.016

European Cooperation in the field of Scientific and Technical Research. (2011). *European Network on New Sensing Technologies for Air-Pollution Control and Environmental Sustainability -*

EuNetAir (pp. 1–66). Retrieved from http://w3.cost.eu/fileadmin/domain_files/ESSEM/Action_TD1105/mou/TD1105-e.pdf

European Cooperation in the field of Scientific and Technical Research. (2013). *Sewage biomarker analysis for community health assessment* (pp. 1–25). Retrieved from http://w3.cost.eu/fileadmin/domain_files/ESSEM/Action_ES1307/mou/ES1307-e.pdf

European Environment Agency. (2006). *Urban sprawl in Europe - The ignored challenge*. *EAA Report* (Vol. 10, p. 58). Copenhagen, DK. Retrieved from http://www.eea.europa.eu/publications/eea_report_2006_10/eea_report_10_2006.pdf

European Environment Agency. (2012). *Urban adaptation to climate change in Europe: Challenges and opportunities for cities together with supportive national and European policies* (Vol. 2/2012). Copenhagen: EEA.

European Environment Agency. (2014). *Air quality in Europe - 2014 Report* (p. 82). Copenhagen, DK: European Environment Agency. Retrieved from http://www.eea.europa.eu/publications/air-quality-in-europe-2014

Evans, S. (2009). *3D cities and numerical weather prediction models: An overview of the methods used in the LUCID project* (No. 148) (Vol. 44, pp. 0–18). London, UK: Centre for Advanced Spatial Analysis.

Everyaware Project. (2014). *Everyaware Project - Final Report Period* (p. 56). Turin, IT. Retrieved from http://www.everyaware.eu/resources/deliverables/D7.3.pdf

Expo Milano 2015 - Feeding the Planet, Energy for Life. (n.d.). Retrieved January 02, 2015, from http://www.expo2015.org/en

Fanger, P. O. (1970). *Thermal comfort: analysis and applications in environmental engineering* (p. 244). McGraw-Hill. Retrieved from http://books.google.com/books?ei=ZuUOSsztFouqNpXHvbIJ&id=mUFSAAAAMAAJ&pgis=1

Farr, D. (2012). *Sustainable Urbanism: Urban Design With Nature* (p. 305). Hoboken, New Jersey: John Wiley & Sons. Retrieved from http://books.google.com/books?hl=it&lr=&id=6he0qcS3ZaUC&pgis=1

Fenger, J. (1999). Urban air quality. *Atmospheric Environment*, *33*(29), 4877–4900. doi:http://dx.doi.org.libproxy.mit.edu/10.1016/S1352-2310(99)00290-3

Fernando, H. J. S., Zajic, D., Di Sabatino, S., Dimitrova, R., Hedquist, B., & Dallman, A. (2010). Flow, turbulence, and pollutant dispersion in urban atmospheres. *Physics of Fluids*, *22*(5), 51301. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=51059623&site=eds-live

Foley, J. a, Defries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., … Snyder, P. K. (2005). Global consequences of land use. *Science (New York, N.Y.)*, *309*(5734), 570–574. doi:309/5734/570 [pii]

Gago, E. J., Roldan, J., Pacheco-Torres, R., & Ordóñez, J. (2013). The city and urban heat islands: A review of strategies to mitigate adverse effects. *Renewable and Sustainable Energy Reviews*, *25*, 749–758. doi:10.1016/j.rser.2013.05.057

Gal, T., & Sumeghi, Z. (2007). Mapping the roughness parameters in a large urban area for urban climate applications. *Acta Climatologica ET Chorologica*, *40-41*, 27–36. Retrieved from http://www2.sci.u-szeged.hu/eghajlattan/akta07/027-036.pdf

Gennaio, M.-P., Hersperger, A. M., & Bürgi, M. (2009). Containing urban sprawl—Evaluating effectiveness of urban growth boundaries set by the Swiss Land Use Plan. *Land Use Policy*, *26*(2), 224–232.

Gerboles, M., & Buzica, D. (2009). *Evaluation of micro-sensors to monitor ozone in ambient air*. Ispra (VA), Italy. doi:10.2788/5978

Givoni, B. (1998). *Climate considerations in building and urban design*. *Building* (pp. 241–300). Retrieved from http://books.google.com/books?id=MGkArZ_berAC&pgis=1

Gleye, P. H. (2014). City Planning versus Urban Planning: Resolving a Profession's Bifurcated Heritage. *Journal of Planning Literature*, 1–15. doi:10.1177/0885412214554088

Goldsmith, S., & Crawford, S. (2014). *The Responsive City: Engaging Communities Through Data-Smart Governance*. John Wiley & Sons.

Goodchild, M. F. (2007). Citizens as sensors: the world of volunteered geography. *GeoJournal*, *69*(4), 211–221.

Greenfield, A. (2006). *Everyware: The dawning age of ubiquitous computing*. New Riders.

Grimmond, C., & Oke, T. (2002). Turbulent Heat Fluxes in Urban Areas : Observations and a Local-Scale Urban Meteorological Parameterization Scheme (LUMPS). *Journal of Applied Meteorology*, *41*(7), 792–810.

Grimmond, C. S. B. (2007). Urbanization and global environmental change: local effects of urban warming. *Geographical Journal*, *173*(1), 83–88. doi:10.1111/j.1475-4959.2007.232_3.x

Grimmond, C. S. B., Blackett, M., Best, M. J., Baik, J. J., Belcher, S. E., Beringer, J., … Coutts, A. (2011). Initial results from Phase 2 of the international urban energy balance model comparison. *International Journal of Climatology*, *31*(2), 244–272.

Grimmond, C. S. B., Blackett, M., Best, M. J., Barlow, J., Baik, J. J., Belcher, S. E., … Zhang, N. (2010). The international urban energy balance models comparison project: First results from phase 1. *Journal of Applied Meteorology and Climatology*, *49*(6), 1268–1292. Retrieved from http://journals.ametsoc.org/doi/abs/10.1175/2010JAMC2354.1

Gross, N. (1999). The earth will don an electronic skin. *Business Week, August*, *30*.

Harman, I. N. (2003). *The energy balance of urban areas*. *The energy balance of urban areas*. The University of Reading.

Hasenfratz, D., Saukh, O., Walser, C., Hueglin, C., Fierz, M., & Thiele, L. (2014). Pushing the spatio-temporal resolution limit of urban air pollution maps. In *Pervasive Computing and Communications (PerCom), 2014 IEEE International Conference on* (pp. 69–77). IEEE.

Hatzopoulou, M., Weichenthal, S., Barreau, G., Goldberg, M., Farrell, W., Crouse, D., & Ross, N. (2013). A web-based route planning tool to reduce cyclists' exposures to traffic pollution: A case study in Montreal, Canada. *Environmental Research*, *123*, 58–61.

Heat wave risk of European cities. (n.d.). Retrieved from http://www.arcgis.com/home/webmap/viewer.html?webmap=d4124af689f14cbd82b88b815ae81d76

Hebbert, M., & Webb, B. (2012). Towards a liveable urban climate: lessons from Stuttgart. *Liveable Cities: Urbanising World*, 120–137.

Hedley, A. J., McGhee, S. M., Barron, B., Chau, P., Chau, J., Thach, T. Q., … Wong, C.-M. (2008). Air pollution: costs and paths to a solution in Hong Kong--understanding the connections among visibility, air pollution, and health costs in pursuit of accountability, environmental justice, and health protection. *Journal of Toxicology and Environmental Health. Part A*, *71*(9-10), 544–54. doi:10.1080/15287390801997476

Heeks, R. (2008). ICT4D 2.0: The next phase of applying ICT for international development. *Computer*, *41*(6), 26–33. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=4548169

Herberger, S., & Ulmer, H. (2012). New IAQ sensor for demand controlled ventilation: REHVA. *HVAC Journal*, *04*(August), 37–40. Retrieved from http://www.rehva.eu/publications-and-resources/hvac-journal/2012/042012/new-iaq-sensor-for-demand-controlled-ventilation/?L=0%2527%2520and%2520char%2528124%2529%2520user%2520char%252

Hernández-Muñoz, J., & Vercher, J. (2011). Smart cities at the forefront of the future internet. Retrieved from http://link.springer.com/chapter/10.1007/978-3-642-20898-0_32

Heusinkveld, B. G., Steeneveld, G. J., van Hove, L. W. a., Jacobs, C. M. J., Holtslag, a. a. M., & Hove, L. W. A. (2014). Spatial variability of the Rotterdam urban heat island as influenced by urban land use. *Journal of Geophysical Research: Atmospheres*, *119*(2), 677–692. doi:10.1002/2012JD019399

Heusinkveld, B. G., Van Hove, L. W. A., Jacobs, C. M. J., Steeneveld, G. J., Elbers, J. A., Moors, E. J., & Holtslag, A. A. M. (2010). Use of a mobile platform for assessing urban heat stress in Rotterdam. In *Proceedings of the 7th Conference on Biometeorology, Freiburg, Germany* (pp. 433–438).

Hirano, Y., & Fujita, T. (2012). Evaluation of the impact of the urban heat island on residential and commercial energy consumption in Tokyo. *Energy*, *37*(1), 371–383.

Hofman, J., Lefebvre, W., & Janssen, S. (2014). Increasing the spatial resolution of air quality assessments in urban areas: A comparison of biomagnetic monitoring and urban scale modelling. *Atmospheric …*, *92*, 130–140. Retrieved from http://www.sciencedirect.com/science/article/pii/S1352231014002854

Hollands, R. G. (2008). Will the real smart city please stand up? *City*, *12*(3), 303–320. doi:10.1080/13604810802479126

House-Peters, L. A., & Chang, H. (2011). Modeling the impact of land use and climate change on neighborhood-scale evaporation and nighttime cooling: A surface energy balance approach. *Landscape and Urban Planning*, *103*, 139–155. doi:10.1016/j.landurbplan.2011.07.005

Howard, L. (1818). *The climate of London* (p. 221). Retrieved from http://books.google.com/books?hl=en&lr=&id=P2gFAAAAQAAJ&oi=fnd&pg=PA361&dq=The+cliamte+of+London&ots=4mzVvHWsXT&sig=Z0k_EPGU85wB0yQNNhWw6TlsHSc

Hsu, A., & Zomer, A. (2014, June). An Interactive Air-Pollution Map. *The Atlantic*. Retrieved from http://www.theatlantic.com/health/archive/2014/06/the-air-we-breathe/372411/

Hudson-Smith, A., Milton, R., Dearden, J., & Batty, M. (2007). *Virtual cities: digital mirrors into a recursive world*. Centre for Advanced Spatial Analysis (UCL).

I-PLACE3S. (n.d.). Retrieved December 29, 2014, from http://www.sacog.org/services/scenario-planning/

Ichinose, T., Shimodozono, K., & Hanaki, K. (1999). Impact of anthropogenic heat on urban climate in Tokyo. *Atmospheric Environment*, *33*(24-25), 3897–3909. doi:10.1016/S1352-2310(99)00132-6

ICLEI. (n.d.). Retrieved December 29, 2014, from http://www.iclei.org/

Ihara, T., Kikegawa, Y., Asahi, K., Genchi, Y., & Kondo, H. (2008). Changes in year-round air temperature and annual energy consumption in office building areas by urban heat-island countermeasures and energy-saving measures. *Applied Energy*, *85*(1), 12–25. doi:10.1016/j.apenergy.2007.06.012

Indoor Portable Particle Counter GT-321 | Met One Instruments. (n.d.). Retrieved December 06, 2014, from http://www.metone.com/particulate-gt321.php

International Panel on Climate Change. (2014). *Fifth Assessment Report - Synthesis Report* (p. 43). Retrieved from http://www.ipcc.ch/report/ar5/syr/

ISO 7726:1998(en) Ergonomics of the thermal environment. (n.d.). Retrieved February 18, 2015, from https://www.iso.org/obp/ui/#iso:std:iso:7726:ed-2:v1:en

iSPEX: measure aerosols with your smartphone. (n.d.). Retrieved December 31, 2014, from http://ispex.nl/en/gallery/

Ito, M., Katagiri, Y., Ishikawa, M., & Tokuda, H. (2007). Airy notes: An experiment of microclimate monitoring in shinjuku gyoen garden. In *Networked Sensing Systems, 2007. INSS'07. Fourth International Conference on* (pp. 260–266). IEEE.

Iveson, K. (2013). Cities within the City: Do-It-Yourself Urbanism and the Right to the City. *International Journal of Urban and Regional Research*, *37*(3), 941–956. doi:10.1111/1468-2427.12053

Jacobs, J. (1961). *The Death and Life of Great American Cities-Vintage* (p. 459). New York: Vintage Books, Random House.

Jalkanen, L. (2012). WMO/IGAC impacts of megacities on air pollution and climate. *Urban Climate*, *1*(0), 67–68. doi:http://dx.doi.org/10.1016/j.uclim.2012.10.004

Jang, M., & Suh, S.-T. (2010). U-city: new trends of urban planning in Korea based on pervasive and ubiquitous geotechnology and geoinformation. In *Computational Science and Its Applications–ICCSA 2010* (pp. 262–270). Springer.

Jankovic, V. (2013). A historical review of urban climatology and the atmospheres of the industrialized world. *WIREs: Climate Change*, *4*(6), 539. Retrieved from http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=90674342&site=eds-live

Järvi, L., Grimmond, C. S. B., & Christen, A. (2011). The Surface Urban Energy and Water Balance Scheme (SUEWS): Evaluation in Los Angeles and Vancouver. *Journal of Hydrology*, *411*(3–4), 219–237. doi:http://dx.doi.org/10.1016/j.jhydrol.2011.10.001

Jerrett, M., Arain, A., Kanaroglou, P., Beckerman, B., Potoglou, D., Sahsuvaroglu, T., … Giovis, C. (2004). A review and evaluation of intraurban air pollution exposure models. *Journal of Exposure Science and Environmental Epidemiology*, *15*(2), 185–204.

Jerrett, M., Burnett, R. T., Ma, R., Pope, C. A., Krewski, D., Newbold, K. B., … Thun, M. J. (2005). Spatial Analysis of Air Pollution and Mortality in Los Angeles. *Epidemiology*, *16*(6), 727–736. doi:10.1097/01.ede.0000181630.15826.7d

Kalnay, E., & Cai, M. (2003). Impact of urbanization and land-use change on climate. *Nature*, *423*(May). doi:10.1038/nature01649.1.

Kasanko, M., Barredo, J. I., Lavalle, C., McCormick, N., Demicheli, L., Sagris, V., & Brezger, A. (2006). Are European cities becoming dispersed?: A comparative analysis of 15 European urban areas. *Landscape and Urban Planning*, *77*(1), 111–130.

Katzschner, L., & Thorsson, S. (2009). Microclimatic Investigations as Tool for Urban Design. In *INTERNATIONAL CONFERENCE ON URBAN CLIMATE* (Vol. 7).

Kickstarter TZOA Air-Tracker. (n.d.). Retrieved December 30, 2014, from https://www.kickstarter.com/projects/tzoa/meet-tzoa-the-worlds-first-enviro-tracker

Kikegawa, Y., Genchi, Y., Kondo, H., & Hanaki, K. (2006). Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning. *Applied Energy*, *83*(6), 649–668.

Kitchin, R. (2014). The Real-Time City? Big Data and Smart Urbanism. *GeoJournal*, *79*(1), 1–14. Retrieved from http://link.springer.com/article/10.1007/s10708-013-9516-8

Kolokotroni, M., Ren, X., Davies, M., & Mavrogianni, A. (2012). London's urban heat island: Impact on current and future energy consumption in office buildings. *Energy and Buildings*, *47*(0), 302–311. doi:10.1016/j.enbuild.2011.12.019

Kratzer, A. (1956). *The climate of cities*. *Scientific American*. Bedford, Massachusetts: Air Force Cambridge Research Laboratories. Retrieved from http://adsabs.harvard.edu/abs/1967SciAm.217b..15L

Krewski, D., Jerrett, M., Burnett, R. T., Ma, R., Hughes, E., Shi, Y., … Calle, E. E. (2009). *Extended follow-up and spatial analysis of the American Cancer Society study linking particulate air pollution and mortality*. Health Effects Institute Boston, MA.

Kumar, P., Fennell, P., & Britter, R. (2008). Effect of wind direction and speed on the dispersion of nucleation and accumulation mode particles in an urban street canyon. *Science of the Total Environment*, *402*(1), 82–94. Retrieved from http://www.sciencedirect.com/science/article/pii/S0048969708004622

Kumar, P., Ketzel, M., Vardoulakis, S., Pirjola, L., & Britter, R. (2011). Dynamics and dispersion modelling of nanoparticles from road traffic in the urban atmospheric environment—a review. *Journal of Aerosol Science*, *42*(9), 580–603. Retrieved from http://www.sciencedirect.com/science/article/pii/S0021850211000887

Landsberg, H. (1981). *The urban climate* (p. 275). New York: Academic Press. Retrieved from http://books.google.com/books?hl=en&lr=&id=zkKHiEXZGBIC&oi=fnd&pg=PP2&dq=The+Urban+Climate&ots=-jZeXArFLb&sig=RGGCnEokQ_OcWVImDDISGwqMC04

Landsberg, H. E. (1973). The meteorologically utopian city. *Bulletin of the American Meteorological Society*, *54*(2), 86–89.

Lee, H., Han, H., Leem, T., Yigitcanlar, T., Ho Lee, S., Hoon Han, J., & Taik Leem, Y. (2008). Towards ubiquitous city: concept, planning, and experiences in the Republic of Korea. *Knowledge-Based Urban Development: Planning and Applications in the Information Era*, 148–170.

Lee, T. W., Lee, J. Y., & Wang, Z.-H. (2012). Scaling of the urban heat island intensity using time-dependent energy balance. *Urban Climate*, *2*, 16–24.

Lindberg, F. (2007). Modelling the urban climate using a local governmental geo-database. *Meteorological Applications*, *14*(3), 263–273.

Lindberg, F., Holmer, B., & Thorsson, S. (2008). SOLWEIG 1.0–Modelling spatial variations of 3D radiant fluxes and mean radiant temperature in complex urban settings. *International Journal of Biometeorology*, *52*(7), 697–713.

Littlefair, P., Santamouris, M., Alvarez, S., Dupagne, A., Hall, D., Teller, J., … Papanikolaou, N. (2000). *Environmental site layout planning: solar access, microclimate and passive cooling in urban areas*. *BRE Report BR* (p. 151). London, UK: CRC. Retrieved from http://orbi.ulg.ac.be/handle/2268/28963

Local Warming. (n.d.). Retrieved December 07, 2014, from http://senseable.mit.edu/localwarming2014/

Lonati, G., Giugliano, M., & Cernuschi, S. (2006). The role of traffic emissions from weekends' and weekdays' fine PM data in Milan. *Atmospheric Environment*, *40*(31), 5998–6011. doi:10.1016/j.atmosenv.2005.12.033

London Climate Plan. (n.d.). Retrieved December 29, 2014, from http://www.london.gov.uk/thelondonplan/climate/

Makido, Y., Dhakal, S., & Yamagata, Y. (2012). Relationship between urban form and CO 2 emissions: Evidence from fifty Japanese cities. *Urban Climate*, *2*, 55–67.

Manfredini, F., Pucci, P., & Tagliolato, P. (2012). Mobile phone network data. new sources for urban studies. *Geographic Information Analysis for Sustainable Development and Economic Planning: New Technologies.Hershey PA, USA: IGI Global*, 115–128.

Marcazzan, G. M., Vaccaro, S., Valli, G., & Vecchi, R. (2001). Characterisation of PM10 and PM2.5 particulate matter in the ambient air of Milan (Italy). *Atmospheric Environment*, *35*(27), 4639–4650. doi:10.1016/S1352-2310(01)00124-8

Mariani, L., & Pangallo, G. S. (2005). Approccio qualitativo all'analisi degli effetti urbani sul clima. *Rivista Italiana Di Agrometerologia*, *2*, 31–36.

Martino, M., Britter, R., Outram, C., Zacharias, C., Biderman, A., & Ratti, C. (2010). Senseable City. *Digital Urban Modelling and Simulation*.

Martins, H. (2012). Urban compaction or dispersion? An air quality modelling study. *Atmospheric Environment*, *54*(0), 60–72. doi:http://dx.doi.org.libproxy.mit.edu/10.1016/j.atmosenv.2012.02.075

MassDEP:: Air & Climate :: Air Quality & Monitoring :: MassAir. (n.d.). Retrieved December 06, 2014, from http://public.dep.state.ma.us/MassAir/Pages/MapCurrent.aspx?pm=88502&ht=1&hi=102

Masson, V., Grimmond, C. S. B., & Oke, T. R. (2002). Evaluation of the Town Energy Balance (TEB) scheme with direct measurements from dry districts in two cities. *Journal of Applied Meteorology*, *41*(10), 1011–1026.

MATLAB. (n.d.). Retrieved January 03, 2015, from http://www.mathworks.com/products/matlab/index.html?s_tid=gn_loc_drop

Matte, T., Ross, Z., & Kheirbek, I. (2013). Monitoring intraurban spatial patterns of multiple combustion air pollutants in New York City: Design and implementation. *Journal of Exposure …*, (October 2012), 223–231. doi:10.1038/jes.2O12.126

Matzarakis, A., Rutz, F., & Mayer, H. (2007). Modelling radiation fluxes in simple and complex environments—application of the RayMan model. *International Journal of Biometeorology*, *51*(4), 323–334.

Mead, M. I., Stewart, G. B., Landshoff, P., Calleja, M., Hayes, M., Baldovi, J. J., … Hodgson, T. F. (2013). The use of electrochemical sensors for monitoring urban air quality in low-cost, high-density networks. *Atmospheric Environment*, *70*(5), 186–203.

Melhuish, E., & Pedder, M. (1998). Observing an urban heat island by bicycle. *Weather*, *53*(4), 121–128.

Mensink, C., De Ridder, K., Deutsch, F., Lefebre, F., & Van de Vel, K. (2008). Examples of scale interactions in local, urban, and regional air quality modelling. *Atmospheric Research*, *89*(4), 351–357. doi:10.1016/j.atmosres.2008.03.020

Michelozzi, P., De'Donato, F., Bisanti, L., Russo, A., Cadum, E., DeMaria, M., … Perucci, C. (2005). The impact of the summer 2003 heat waves on mortality in four Italian cities. *Eurosurveillance*, *10*(7). Retrieved from http://www.eurosurveillance.org/ViewArticle.aspx?ArticleId=556

Middel, A., Häb, K., Brazel, A. J. A., Martin, C. A., & Guhathakurta, S. (2014). Impact of urban form and design on mid-afternoon microclimate in Phoenix Local Climate Zones. *Landscape and Urban Planning*, *122*, 16–28. Retrieved from http://www.sciencedirect.com/science/article/pii/S0169204613002120

Milan's Resilience Challenge | 100 Resilient Cities. (n.d.). Retrieved January 04, 2015, from http://www.100resilientcities.org/cities/entry/milan#/-_/

Mills, G. (2006). Progress toward sustainable settlements: A role for urban climatology. *Theoretical and Applied Climatology*, *84*, 69–76. doi:10.1007/s00704-005-0145-0

Millward, H. (2006). Urban containment strategies: A case-study appraisal of plans and policies in Japanese, British, and Canadian cities. *Land Use Policy*, *23*(4), 473–485.

Ministry of Transport and Infrastructure of Baden-Württemberg. (2012). *Climate Booklet for Urban Development* (p. 275). Stuttgart, Germany. Retrieved from http://www.staedtebauliche-klimafibel.de/?p=0

MIT SENSEable City Lab. (n.d.). Retrieved December 30, 2014, from http://senseable.mit.edu/

Mitchell, R. B., & Rapkin, C. (1954). *Urban Traffic--A Function of Land Use*. Columbia University Press.

Morello, E., & Ratti, C. (2007). Raster Cities: image processing techniques for environmental urban analysis. In K. Thwaites, S. Porta, O. Romice, & M. Greaves (Eds.), *Urban Sustainability through Environmental Design: approaches to time, people and place responsive urban spaces* (pp. 119–122). London, UK: Spon Press.

Morello, E., & Ratti, C. (2009a). A digital image of the city: 3D isovists in Lynch's urban analysis. *Environment and Planning B: Planning and Design*, *36*(5), 837–853. doi:10.1068/b34144t

Morello, E., & Ratti, C. (2009b). Sunscapes: "Solar envelopes" and the analysis of urban DEMs. *Computers, Environment and Urban Systems*, *33*(1), 26–34. doi:10.1016/j.compenvurbsys.2008.09.005

Morpurgo, A., Pedersini, F., & Reina, A. (2012). A low-cost instrument for environmental particulate analysis based on optical scattering. *… Conference (I2MTC), 2012 …*. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=6229220

Muller, C., & Chapman, L. (2013). Sensors and the city: a review of urban meteorological networks. *International Journal of Climatology*, *33*(7), 1585–1600. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/joc.3678/full

Mun, M., Reddy, S., Shilton, K., Yau, N., Burke, J., Estrin, D., … Boda, P. (2009). PEIR, the personal environmental impact report, as a platform for participatory sensing systems research. In *Proceedings of the 7th international conference on Mobile systems, applications, and services* (pp. 55–68). ACM.

Murty, R. N., Mainland, G., Rose, I., Chowdhury, A. R., Gosain, A., Bers, J., & Welsh, M. (2008). Citysense: An urban-scale wireless sensor network and testbed. In *Technologies for Homeland Security, 2008 IEEE Conference on* (pp. 583–588). IEEE.

Nadeau, D. F., Brutsaert, W., Parlange, M. B., Bou-Zeid, E., Barrenetxea, G., Couach, O., … Vetterli, M. (2009). Estimation of urban sensible heat flux using a dense wireless network of observations. *Environmental Fluid Mechanics*, *9*(6), 635–653.

Narumi, D., Kondo, A., & Shimoda, Y. (2009). Effects of anthropogenic heat release upon the urban climate in a Japanese megacity. *Environmental Research*, *109*(4), 421–431.

National Ambient Air Quality Standards (NAAQS) | Air and Radiation | US EPA. (n.d.). Retrieved December 28, 2014, from http://www.epa.gov/air/criteria.html

Ng, E., Chen, L., Wang, Y., & Yuan, C. (2012). A study on the cooling effects of greening in a high-density city: an experience from Hong Kong. *Building and Environment*, *47*, 256–271.

Northcross, A. L., Edwards, R. J., Johnson, M. A., Wang, Z.-M., Zhu, K., Allen, T., & Smith, K. R. (2013). A low-cost particle counter as a realtime fine-particle mass monitor. *Environmental Science: Processes and Impacts*, *15*, 433. doi:10.1039/c2em30568b

Nowak, D. J., Crane, D. E., & Stevens, J. C. (2006). Air pollution removal by urban trees and shrubs in the United States. *Urban Forestry & Urban Greening*, *4*(3), 115–123.

Nuissl, H., Haase, D., Lanzendorf, M., & Wittmer, H. (2009). Environmental impact assessment of urban land use transitions—A context-sensitive approach. *Land Use Policy*, *26*(2), 414–424. doi:http://dx.doi.org/10.1016/j.landusepol.2008.05.006

Nunez, M., & Oke, T. R. (1977). Energy Balance of an Urban Canyon.

NYC Community Air Survey. (n.d.). Retrieved December 29, 2014, from http://www.nyc.gov/html/doh/html/environmental/community-air-survey.shtml

Offenhuber, D., & Ratti, C. (2014). *Decoding the City. Urbanism in the Age of Big Data*. (D. Offenhuber & C. Ratti, Eds.). Berlin, Boston. doi:10.1515/9783038213925

Oke, T. R. (1976). The distinction between canopy and boundary-layer urban heat islands. *Atmosphere*, *14*(4), 268–277. doi:10.1080/00046973.1976.9648422

Oke, T. R. (1981). Canyon geometry and the nocturnal urban heat island: Comparison of scale model and field observations. *Journal of Climatology*, *1*(3), 237–254. doi:10.1002/joc.3370010304

Oke, T. R. (1984). Towards a prescription for the greater use of climatic principles in settlement planning. *Energy and Buildings*, *7*(1), 1–10.

Oke, T. R. (1987). *Boundary layer climates* (Second., Vol. Routledge, p. 435). London and New York: Routledge. Retrieved from http://books.google.com/books?hl=en&lr=&id=K_2dW7crfVIC&oi=fnd&pg=PP1&dq=Boundary+Layer+Climates&ots=112YqtIAbW&sig=OpORoBqDxjfdojOonDHY-OjpGzk

Oke, T. R. (1997). Urban climates and global change. In A. Perry & R. Thomson (Eds.), *Applied climatology: principles and practice* (pp. 273–287). London, UK: Routledge.

Oke, T. R. (2004). *Initial guidance to obtain representative meteorological observations at urban sites*. *geog.ubc.ca* (Vol. 81). World Meteorological Organization Geneva. Retrieved from http://www.geog.ubc.ca/~toke/IOM-81-UrbanMetObs.pdf

Oke, T. R. (2006). Towards better scientific communication in urban climate. *Theoretical and Applied Climatology*, *84*(1-3), 179–190.

One Country Two Lungs. (n.d.). Retrieved December 03, 2014, from http://senseable.mit.edu/twolungs/

OpenSense. (n.d.). Retrieved December 29, 2014, from http://www.opensense.ethz.ch/trac/

OpenSense Live Data Browser. (n.d.). Retrieved December 29, 2014, from http://data.opensense.ethz.ch/position.html

Osservatorio Meteorologico di Milano Duomo. (2014). *Il Clima cambia le città* (p. 40). Milan, IT.

Overeem, A., & Robinson, J. R. (2013). Crowdsourcing urban air temperatures from smartphone battery temperatures. *Geophysical …*. Retrieved from http://onlinelibrary.wiley.com/doi/10.1002/grl.50786/full

Participatory Sensing Application. (n.d.). Retrieved December 30, 2014, from http://www.smartsantander.eu/index.php/blog/item/181-participatory-sensing-application

Paulsen, H., & Riegger, U. (2006). SensorGIS-Geodaten in Echtzeit. *GIS-Business*, *8*(2006), 17–19.

Personal Weather Station: KMACAMBR9 by Wunderground.com. (n.d.). Retrieved January 01, 2015, from http://www.wunderground.com/personal-weather-station/dashboard?ID=KMACAMBR9

Peters, J., Theunis, J., Van Poppel, M., & Berghmans, P. (2013). Monitoring PM10 and ultrafine particles in urban environments using mobile measurements. *Aerosol and Air Quality Research*, *13*, 509–522. doi:10.4209/aaqr.2012.06.0152

Pichierri, M., Bonafoni, S., & Biondi, R. (2012). Remote Sensing of Environment Satellite air temperature estimation for monitoring the canopy layer heat island of Milan. *Remote Sensing of Environment*, *127*, 130–138.

Pielke, R. A. (2005). Land use and climate change. *Science (New York, N.Y.)*, *310*(5754), 1625–1626. doi:310/5754/1625 [pii]

Pigeonblog. (n.d.). Retrieved December 08, 2014, from http://realtimecities.wikispaces.com/Pigeonblog

Pileri, P., & Maggi, M. (2010). Sustainable planning? First results in land uptakes in rural, natural and protected areas: the Lombardia case study (Italy). *Journal of Land Use Science*, *5*(2), 105–122.

Pincetl, S., Bunje, P., & Holmes, T. (2012). An expanded urban metabolism method: Toward a systems approach for assessing urban energy processes and causes. *Landscape and Urban Planning*, *107*(3), 193–202. doi:10.1016/j.landurbplan.2012.06.006

PlaNYC. (n.d.). Retrieved December 29, 2014, from http://www.nyc.gov/html/planyc/html/home/home.shtml

PM10 interpolated maps — European Environment Agency (EEA). (n.d.). Retrieved January 02, 2015, from http://www.eea.europa.eu/themes/air/interactive/pm10-interpolated-maps

PM2.5 interpolated maps — European Environment Agency (EEA). (n.d.). Retrieved January 02, 2015, from http://www.eea.europa.eu/themes/air/interactive/pm2-5-interpolated-map

Poli, T., Gattoni, L. Pietro, Paolini, R., Pansa, G., Favaron, M., & Pilati, S. (2009). The influence of the urban heat island over building energy demand: the case of Milan. In *The seventh International Conference on Urban Climate, 29 June - 3 July 2009, Yokohama, Japan* (pp. 1–4). Yokohama, Japan.

Pope III, C. A., & Dockery, D. W. (2006). Health effects of fine particulate air pollution: lines that connect. *Journal of the Air & Waste Management Association*, *56*(6), 709–742. doi:10.1080/10473289.2006.10464485

Porta, S., Latora, V., Wang, F., Rueda, S., Strano, E., Scellato, S., … Latora, L. (2012). Street Centrality and the Location of Economic Activities in Barcelona. *Urban Studies*. doi:10.1177/0042098011422570

ProjectZero. (n.d.). Retrieved December 29, 2014, from http://www.projectzero.dk/

Ratti, C., Baker, N., & Steemers, K. (2005). Energy consumption and urban texture. *Energy and Buildings*, *37*(7), 762–776. doi:10.1016/j.enbuild.2004.10.010

Ratti, C., & Claudel, M. (2015). *The Future of the City*. (J. Calamia & K. Boller, Eds.) (p. 237). Yale University Press.

Ratti, C., Di Sabatino, S., & Britter, R. (2006). Urban texture analysis with image processing techniques: Winds and dispersion. *Theoretical and Applied Climatology*, *84*(1-3), 77–90. doi:10.1007/s00704-005-0146-z

Ratti, C., Pulselli, R., & Williams, S. (2006). Mobile landscapes: using location data from cell phones for urban analysis. *Environment and Planning B: Planning and Design*, *33*(5), 727–748. Retrieved from http://www.envplan.com/ep/epb/fulltext/b33/b32047.pdf

Ratti, C., & Richens, P. (2004). Raster analysis of urban form. *Environment and Planning B: Planning and Design*, *31*(2), 297–309. doi:10.1068/b2665

Ratti, C., Robinson, D., Baker, N., & Steemers, K. (2000). LT Urban: the energy modelling of urban form. In *Proceedings of PLEA*.

Ratti, C., & Townsend, A. (2011). The Social Nexus. *Scientific American*, *305*(3), 42–48. doi:10.1038/scientificamerican0911-42

Raven, J. (2011). Cooling the Public Realm: Climate-Resilient Urban Design. In *Resilient Cities* (pp. 451–463). Springer.

Real Time Rome. (n.d.). Retrieved December 30, 2014, from http://senseable.mit.edu/realtimerome/

Reid, M. J., Harman, C., Grung, M., & Thomas, K. V. (2011). The current status of community drug testing via the analysis of drugs and drug metabolites in sewage. *Norsk Epidemiologi*, *21*(1), 15–23. doi:10.1016/j.drugalcdep.2011.06.007; Reid, M.J., Langford, K.H., Morland, J., Thomas, K.V., Analysis and interpretation of specific ethanol metabolites, ethyl sulfate, and ethyl glucuronide in sewage effluent for the quantitative measurement of regional alcohol consumption (2011) Alcohol Clin Exp Res, 35, pp. 1593-1599; Thomas, K.V., Reid, M.J., What else can the analysis of sewage for urinary biomarkers reveal about communities? (2011) Environ Sci Technol, , doi: 10.1021/es202522d; van Nuijs, A.L.

Relationship between Aerosol Light Scattering and Fine Mass. (n.d.). Retrieved December 06, 2014, from http://capita.wustl.edu/CAPITA/CapitaReports/BScatFMRelation/BSCATFM.HTML#content

Ren, C., Lau, K. L., Yiu, K. P., & Ng, E. (2013). The application of urban climatic mapping to the urban planning of high-density cities: The case of Kaohsiung, Taiwan. *Cities*, *31*(0), 1–16. doi:http://dx.doi.org/10.1016/j.cities.2012.12.005

Ren, C., Ng, E. Y., & Katzschner, L. (2011). Urban climatic map studies: a review. *International Journal of Climatology*, *31*(15), 2213–2233. doi:10.1002/joc.2237

Resch, B., Britter, R., & Outram, C. (2011). Standardised geo-sensor webs for integrated urban air quality monitoring. *Environmental Monitoring*, 513–528. Retrieved from http://senseable.mit.edu/papers/pdf/2011_Resch_UAQM_EM.pdf

Resch, B., Britter, R., & Ratti, C. (2012). Live Urbanism–Towards SENSEable Cities and Beyond. In *Sustainable Environmental Design in Architecture* (pp. 175–184). Springer. Retrieved from http://link.springer.com/chapter/10.1007/978-1-4419-0745-5_10

Resch, B., Mittleboeck, M., Lipson, S., Welsh, M., Bers, J., Britter, R., … Blaschke, T. (2011). Integrated urban sensing: a geo-sensor network for public health monitoring and beyond.

Ridker, R. G., & Henning, J. A. (1967). The determinants of residential property values with special reference to air pollution. *The Review of Economics and Statistics*, 246–257. Retrieved from http://www.jstor.org/stable/1928231

Robinson, D., Haldi, F., Kämpf, J., Leroux, P., Perez, D., Rasheed, A., & Wilke, U. (2009). CitySim: Comprehensive micro-simulation of resource flows for sustainable urban planning. In *Proc. Building Simulation*.

Robinson, J., Kocman, D., Smolnikar, M., Mohorcic, M., & Horvat, M. (2014). Empowerment in practice-insights from CITI-SENSE project in Ljubljana. In *EGU General Assembly Conference Abstracts* (Vol. 16, p. 5458).

Rosenzweig, C., Solecki, W. D. W., Hammer, S. A. S., & Mehrotra, S. (2011). *Climate change and cities: first assessment report of the Urban Climate Change Research Network*. Cambridge University Press. Retrieved from http://books.google.com/books?hl=en&lr=&id=9GHW24KCuBYC&oi=fnd&pg=PR7&dq=Climate+Change+and+Cities.+First+Assessment+Report+of+the+Urban+Climate+Change+Research+Network&ots=_2rzZWs1QD&sig=T36sbMPIw0uDhlWBVb-7pulOsYo

Ross, S. L., & Oke, T. R. (1988). Tests of three urban energy balance models. *Boundary-Layer Meteorology*, *44*(1-2), 73–96. doi:10.1007/BF00117293

Ruvolo, J. (2013). Bridging The Divided City. *Cityscapes*, *3*, 58–68. Retrieved from http://www.cityscapesdigital.net/2013/05/30/bridging-the-divided-city/

Safecast. (n.d.). Retrieved December 30, 2014, from http://blog.safecast.org/

Sanchez, L., Galache, J. A., Gutiérrez, V., Hernández, J. M., Bernat, J., Gluhak, A., & García, T. (2011). SmartSantander: The meeting point between Future Internet research and experimentation and the smart cities. In *Future Network & Mobile Summit (FutureNetw), 2011* (pp. 1–8). IEEE.

Sandifer, J., & Mountain, K. (2014). Remote Sensing and Identifying the Urban Heat Island from Space: An Overview. *Heat Islands*, 9.

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., & Assimakopoulos, D. N. (2001). On the impact of urban climate on the energy consumption of buildings. *Solar Energy*, *70*(3), 201–216.

Santi, P., Resta, G., Szell, M., Sobolevsky, S., Strogatz, S., & Ratti, C. (2013). Quantifying the benefits of vehicle pooling with shareability networks. Retrieved from http://arxiv.org/abs/1310.2963

Sassen, S. (2014). Saskia Sassen talk at MIT Senseable "City Engaging Data 2013" conference.

Schindler, M., & Caruso, G. (2014). Urban compactness and the trade-off between air pollution emission and exposure: Lessons from a spatially explicit theoretical model. *Computers, Environment and Urban Systems*, *45*, 13–23. doi:10.1016/j.compenvurbsys.2014.01.004

Seinfeld, J. H., & Pandis, S. N. (2012). *Atmospheric chemistry and physics: from air pollution to climate change*. John Wiley & Sons.

Semple, S., Apsley, A., & MacCalman, L. (2013). An inexpensive particle monitor for smoker behaviour modification in homes. *Tobacco Control*, *22*(5), 295–8. doi:10.1136/tobaccocontrol-2011-050401

Sens.dots - Connect the physical and virtual worlds. (n.d.). Retrieved January 02, 2015, from http://www.sensdots.com/

Sensaris - Wireless sensors. (n.d.). Retrieved December 29, 2014, from http://www.sensaris.com/

Sensing City. (n.d.). Retrieved December 29, 2014, from http://www.sensingcity.org/

Sensor City. (n.d.). Retrieved December 29, 2014, from http://www.sensorcity.nl/

Sensorcon | American Made Single Gas Meters and Environmental Sensors. (n.d.). Retrieved December 29, 2014, from http://sensorcon.com/

Seto, K. C., & Christensen, P. (2013). Remote sensing science to inform urban climate change mitigation strategies. *Urban Climate*, *3*, 1–6.

Shahmohamadi, P., Che-Ani, A. I., Maulud, K. N. A., Tawil, N. M., & Abdullah, N. A. G. (2011). The Impact of Anthropogenic Heat on Formation of Urban Heat Island and Energy Consumption Balance. *Urban Studies Research*, *2011*.

Shepard, M. (2011). *Sentient city: Ubiquitous computing, architecture, and the future of urban space*. The MIT press.

Sherwood, S. C., & Huber, M. (2010). An adaptability limit to climate change due to heat stress. *Proceedings of the National Academy of Sciences of the United States of America*, *107*(21), 9552–9555. doi:10.1073/pnas.0913352107 [doi]

Shwayri, S. T. (2013). A Model Korean Ubiquitous Eco-City? The Politics of Making Songdo. *Journal of Urban Technology*, *20*(1), 39–55. doi:10.1080/10630732.2012.735409

Sillman, S., & Samson, P. J. P. (1995). Impact of temperature on oxidant photochemistry in urban, polluted rural and remote environments. *Journal of Geophysical Research: Atmospheres (1984–2012)*, *100*(D6), 11497–11508. Retrieved from http://onlinelibrary.wiley.com/doi/10.1029/94JD02146/full

Simon, H. A., & Chase, W. G. (1973). Skill in chess: Experiments with chess-playing tasks and computer simulation of skilled performance throw light on some human perceptual and memory processes, *61*(4), 394–403. Retrieved from http://link.springer.com/chapter/10.1007/978-1-4757-1968-0_18

Smart Citizen : Citizen Science Platform for participatory processes of the people in the cities. (n.d.). Retrieved January 02, 2015, from https://www.smartcitizen.me/

Smart City MIlano. (n.d.). Retrieved January 02, 2015, from http://www.milanosmartcity.org/joomla/

SmartSantander Maps. (n.d.). Retrieved December 29, 2014, from http://maps.smartsantander.eu/

Smith, V. K., & Huang, J. C. (1995). Can Markets Value Air-Quality - a Metaanalysis of Hedonic Property Value Models. *Journal of Political Economy*, *103*(1), 209–227. doi:10.1086/261981

Snik, F., Rietjens, J. H. H., Apituley, A., Volten, H., Mijling, B., Di Noia, A., … Keller, C. U. (2014). Mapping atmospheric aerosols with a citizen science network of smartphone spectropolarimeters. *Geophysical Research Letters*, *41*(20), n/a–n/a. doi:10.1002/2014GL061462

Snyder, E. G., Watkins, T. H., Solomon, P. a, Thoma, E. D., Williams, R. W., Hagler, G. S. W., … Preuss, P. W. (2013). The changing paradigm of air pollution monitoring. *Environmental Science & Technology*, *47*(20), 11369–77. doi:10.1021/es4022602

Solene - Software for simulating of sunshine, lighting and thermal radiation | Cerma. (n.d.). Retrieved December 29, 2014, from http://www.cerma.archi.fr/?q=en/solene-software-simulating-sunshine-lighting-and-thermal-radiation-0

Stadtklima Stuttgart | Climate analysis maps. (n.d.). Retrieved January 02, 2015, from http://www.stadtklima-stuttgart.de/index.php?climate_climate_atlas_1992_9_maps

Standard 55 | ashrae.org. (n.d.). Retrieved February 18, 2015, from https://www.ashrae.org/resources--publications/bookstore/standard-55

Steemers, K. (2003). Energy and the city: Density, buildings and transport. *Energy and Buildings*, *35*(1), 3–14. doi:10.1016/S0378-7788(02)00075-0

Stewart, I. D. (2011). A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology*, *31*(2), 200–217.

Stewart, I. D. (2013). Local Climates of the City. *Architectural Design*. doi:10.1002/ad.1625

Stewart, I. D., & Oke, T. R. (2012). Local Climate Zones for Urban Temperature Studies. *Bulletin of the American Meteorological Society*, *93*(12), 1879–1900. doi:10.1175/BAMS-D-11-00019.1

Steyn, D., & Mathur, R. (2014). *Air Pollution Modeling and its Application XXIII*. (R. Mathur, Ed.)*Springer eBooks; Springer Proceedings in Complexity,* (p. 640). Cham: Springer International Publishing : Retrieved from http://ctwfind0.wesleyan.edu/wesleyan/Record/wu.2990211

Stone, B. (2005). Urban heat and air pollution: An emerging role for planners in the climate change debate. *Journal of the American Planning Association*, *71*(1), 13–25. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360508976402

Stone, B. (2009). Land Use as Climate Change Mitigation. *Environmental Science & Technology*, *43*(24), 9052–9056. doi:10.1021/es902150g

Stone, B., Hess, J. J., & Frumkin, H. (2010). Urban form and extreme heat events: are sprawling cities more vulnerable to climate change than compact cities? *Environmental Health Perspectives*, *118*(10), 1425–1428. doi:10.1289/ehp.0901879 [doi]

Stone, B., & Rodgers, M. O. M. (2001). Urban form and thermal efficiency: How the design of cities influences the urban heat island effect. *Journal of the American Planning Association*, *67*(2), 186–198. Retrieved from http://www.tandfonline.com/doi/abs/10.1080/01944360108976228

Stone, B., Vargo, J., & Habeeb, D. (2012). Managing climate change in cities: Will climate action plans work? *Landscape and Urban Planning*, *107*(3), 263–271. doi:10.1016/j.landurbplan.2012.05.014

Strategic Environmental Assessment - SEA - Environment - European Commission. (n.d.). Retrieved January 04, 2015, from http://ec.europa.eu/environment/eia/sea-legalcontext.htm

Street, M., Reinhart, C., Norford, L., & Ochsendorf, J. (2013). Urban heat island in Boston–an evaluation of urban air-temperature models for predicting building energy use. Retrieved from http://www.ibpsa.org/proceedings/BS2013/p_1492.pdf

Stroh, E., Harrie, L., & Gustafsson, S. (2007). A study of spatial resolution in pollution exposure modelling. *International Journal of Health Geographics*, *6*(1), 19. doi:1476-072X-6-19 [pii]

Subramanian, K. (2012). Does Your Organization Face Data Obesity Problem? Retrieved December 16, 2014, from http://www.cloudave.com/19193/does-your-organization-face-data-obesity-problem/

Sullivan, J., & Collins, J. M. (2009). The use of low-cost data logging temperature sensors in the evaluation of an urban heat island in Tampa, Florida. In *Papers of the Applied Geography Conferences* (Vol. 32, p. 252).

Sun, X., Du, J., & Zhou, J. (2013). Application of participatory sensing in meteorological information service system. *Applied Mechanics and Materials*, *385-386*, 1887–1890. doi:10.4028/www.scientific.net/AMM.385-386.1887.

Svensson, M. K. (2004). Sky view factor analysis – implications for urban air temperature differences. *Meteorological Applications*, *11*, 201–211. doi:10.1017/S1350482704001288

Szell, M. (2014). Connecting Paradigms. *Science*, *343*(6174), 970–971. doi:10.1126/science.1249599

Szell, M., Grauwin, S., & Ratti, C. (2014). Contraction of online response to major events. *PloS One*, *9*(2), e89052. doi:10.1371/journal.pone.0089052

Taha, H. (1997). Urban climates and heat islands: Albedo, evapotranspiration, and anthropogenic heat. *Energy and Buildings*, *25*(2), 99–103. Retrieved from http://www.scopus.com/inward/record.url?eid=2-s2.0-0031097861&partnerID=40&md5=7569bfa46642e949dafcd06c85a84018

Taleb, D., & Abu-Hijleh, B. (2013). Urban heat islands: Potential effect of organic and structured urban configurations on temperature variations in Dubai, UAE. *Renewable Energy*, *50*, 747–762.

The Shinyei experiment: Real-time Air Quality readings from Beijing. (n.d.). Retrieved from http://aqicn.org/sensor/shinyei/

The SOLWEIG-model. (n.d.). Retrieved December 29, 2014, from http://gvc.gu.se/english/research/climate/urban-climate/software/solweig

Thepvilojanapong, N., Ono, T., & Tobe, Y. (2010). A deployment of fine-grained sensor network and empirical analysis of urban temperature. *Sensors*, *10*(3), 2217–2241.

Timmermans, R. M. A., Denier van der Gon, H. A. C., Kuenen, J. J. P., Segers, A. J., Honoré, C., Perrussel, O., … Schaap, M. (2013). Quantification of the urban air pollution increment and its dependency on the use of down-scaled and bottom-up city emission inventories. *Urban Climate*, *6*(0), 44–62. doi:http://dx.doi.org/10.1016/j.uclim.2013.10.004

Tittarelli, A., Borgini, A., Bertoldi, M., Desaeger, E., Ruprecht, A., Stefanoni, R., … Crosignani, P. (2008). Estimation of particle mass concentration in ambient air using a particle counter. *Atmospheric Environment*, *42*(36), 8543–8548. doi:10.1016/j.atmosenv.2008.07.056

Toppi, T., Zangheri, P., & Paolini, R. (2009). Simplified method for modification of weather data file for energy simulations within urban areas. *Proc. of the 8th Workshop CIB W108 …*. Retrieved from http://www.irbnet.de/daten/iconda/CIB16454.pdf

Toronto Public Health - Heat Vulnerability. (n.d.). Retrieved December 29, 2014, from http://map.toronto.ca/maps/map.jsp?app=TPH_HVMAP

Treville, A. (2011a). LCA methodology as a support tool for decision makers in policy and planning for sustainable development. Case study for a Developing Country. *ELCAS2011: Proceedings of the 2nd International Exergy, Life Cycle Assessment and Sustainability Workshop \& Symposium, 19 - 21 June 2011, Nisyros Island, Greece*, 691–698. Retrieved from http://www.elcasnet.com/elcas2011/index.htm

Treville, A. (2011b). Proposal of an impact prediction tool for the environmental assessment of projects and spatial planning, based on LCA. *ELCAS2011: Proceedings of the 2nd International Exergy, Life Cycle Assessment and Sustainability Workshop \& Symposium, 19 - 21 June 2011, Nisyros Island, Greece*, 708–715. Retrieved from http://www.elcasnet.com/elcas2011/index.htm

Treville, A. (2012). Effectiveness of Strategic Environmental Assessment of urban and regional planning in Northern Italy: limitation of risks and impact of land consumption. *PLANUM*, *25*, 1–7.

Treville, A. (2013). Heatwaves and UHI: Modeling the inter-relationships between climate effects and the built environment for designing resilient cities. In F. Musco & E. Zanchini (Eds.), *Proceedings of climate changes cities conference on climate adaptation in urban areas, Venice, 23-24 May 2013* (pp. 111–114). Venice: Corila.

Treville, A., & Dosi, M. P. (2012). New Climate Analysis Regions moving towards a low carbon economy, 1–100.

Treville, A., Li, T., Nyhan, M., Britter, R., & Ratti, C. (2014). Urban Hot-Spots : A Smart Real-Time Sensor Network for Urban Climate Stress & Air Quality Mapping pollution and Urban Heat Islands. In *Air Sensors 2014 - A New Frontier. Monitoring Technology for Today's World* (p. 2014). Research Triangle Park, NC: United States Environmental Protection Agency. Retrieved from https://sites.google.com/site/airsensors2014/26_AirSensor-EPA_poster_small.pdf?attredirects=0&d=1

Treville, A., & Minucci, G. (2012). Low Carbon Planning as an opportunity to build a more resilient city (and regions). *3rd Global Forum on Urban Resilience and Adaptation*, 1. Retrieved from http://resilient-cities.iclei.org/fileadmin/sites/resilient-cities/files/Images_and_logos/Resilience_Resource_Point/RC2012__Congress_report.pdf

Treville, A., Vandini, L., & Cegna, R. (2014). The Visual Language Technique in Urban Studies Research: Investigation, Interpretation and Communication of City Complexity . In L. Cocchiarella (Ed.), *The Visual Language of Technique*. Springer.

Tsujita, W., Yoshino, A., Ishida, H., & Moriizumi, T. (2005). Gas sensor network for air-pollution monitoring. *Sensors and Actuators B: Chemical*, *110*(2), 304–311. doi:10.1016/j.snb.2005.02.008

Turner, B. L., Meyer, W. B., & Skole, D. L. (1994). Global land-use/land-cover change: towards an integrated study. *AMBIO-STOCKHOLM-*, *23*, 91.

Unger, J. (2009). Connection between urban heat island and sky view factor approximated by a software tool on a 3D urban database. *International Journal of Environment and Pollution*. doi:10.1504/IJEP.2009.021817

Unger, J., Savić, S., & Gál, T. (2011). Modelling of the annual mean urban heat island pattern for planning of representative urban climate station network. *Advances in Meteorology*, *2011*.

United Nations. (1992). Rio Declaration on Environment and Development. Retrieved December 17, 2014, from http://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

United Nations. (2014). *World Urbanization Prospects 2014* (2014th ed.). New York: United Nations.

United Nations Economic Commission for Europe. (1998). The Aarhus Convention. Retrieved December 17, 2014, from http://ec.europa.eu/environment/aarhus/

United States Environmental Protection Agency. (n.d.). Next Generation Air Measuring. Retrieved December 07, 2014, from http://www.epa.gov/airscience/next-generation-air-measuring.htm

United States Environmental Protection Agency. (2008). *Reducing Urban Heat Islands: Compendium of Strategies*. *Environmental Protection Agency, retrieved May* (Vol. 12, p. 39p). Washington, DC: United States Environmental Protection Agency. Retrieved from http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Reducing+Urban+Heat+Islands+:+Compendium+of+Strategies#0

United States Environmental Protection Agency. (2013). *Roadmap for Next Generation Air Monitoring*.

United States Environmental Protection Agency. (2014). *Air Sensors Guidebook* (p. 73). Research Triangle Park, NC: US Environmental Protection Agency. Retrieved from ww.epa.gov.ord

United States Green Building Council. (2014). *Green Neighborhood Development: LEED reference guide for neighborhood development* (Vol. v. 4). US Green Building Council.

Van den Dobbelsteen, A., Broersma, S., & Stremke, S. (2011). Energy potential mapping for energy-producing neighborhoods. *International Journal of Sustainable Building Technology and Urban Development*, *2*(2), 170–176.

Voogt, J. (2004). Urban heat islands: hotter cities. *America Institute of Biological Sciences*.

Voogt, J. (2007). How researchers measure urban heat islands. In *United States Environmental Protection Agency (EPA), State and Local Climate and Energy Program, Heat Island Effect, Urban Heat Island Webcasts and Conference Calls*.

Voogt, J., & Oke, T. R. (2003). Thermal remote sensing of urban climates. *Remote Sensing of Environment*, *86*(3), 370–384.

Wang, Z.-H., Bou-Zeid, E., & Smith, J. A. (2010). Application of a sensor network to study the energy budget in urban canopies. In *Proceedings of 15th symposium on meteorological observation and instrumentation, Atlanta*.

Wichmann, H. E., Spix, C., Tuch, T., Wölke, G., Peters, A., Heinrich, J., … Heyder, J. (2000). Daily mortality and fine and ultrafine particles in Erfurt, Germany part I: role of particle number and particle mass. *Research Report (Health Effects Institute)*, (98), 5–86; discussion 87–94. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11918089

Wolf, T., & McGregor, G. (2013). The development of a heat wave vulnerability index for London, United Kingdom. *Weather and Climate Extremes*, *1*, 59–68.

World Health Organization. (2006). *Air Quality Guidelines. Global Update 2005* (p. 485global). Copenhagen, DK: World Health Organization. Retrieved from http://www.who.int/phe/health_topics/outdoorair/outdoorair_aqg/en/

World Meteorological Organization. (2008). *Guide to Meteorological Instruments and Methods of Observation*. Geneva, Switzerland: Genf, Schweiz: Secretariat of the WMO. Retrieved from http://www.wmo.int/pages/prog/gcos/documents/gruanmanuals/CIMO/CIMO_Guide-7th_Edition-2008.pdf

Wunderground Weather Forecast & Reports . (n.d.). Retrieved January 02, 2015, from http://www.wunderground.com/

Yamamoto, Y. (2006). Measures to mitigate urban heat islands. *Science and Technology Trends Quarterly Review*, *18*(1), 65–83. Retrieved from http://www.nistep.go.jp/achiev/ftx/eng/stfc/stt018e/qr18pdf/STTqr1806.pdf

Yao, R., Luo, Q., & Li, B. (2011). A simplified mathematical model for urban microclimate simulation. *Building and Environment*, *46*(1), 253–265. doi:10.1016/j.buildenv.2010.07.019

Yoshimura, Y., Sobolevsky, S., Ratti, C., Girardin, F., Carrascal, J. P., Blat, J., & Sinatra, R. (2014). An analysis of visitors' behavior in The Louvre Museum: a study using Bluetooth data. *Environment and Planning B: Planning and Design*, *41*(6), 1113–1131. doi:10.1068/b130047p

Young, D. T., Chapman, L., Muller, C. L., Cai, X.-M., & Grimmond, C. S. B. (2014). A Low-Cost Wireless Temperature Sensor: Evaluation for Use in Environmental Monitoring Applications. *Journal of Atmospheric and Oceanic Technology*, *31*(4), 938–944. doi:10.1175/JTECH-D-13-00217.1

Zheng, S., Cao, J., Kahn, M. E., & Sun, C. (2013). Real Estate Valuation and Cross-Boundary Air Pollution Externalities: Evidence from Chinese Cities. *The Journal of Real Estate Finance and Economics*, *48*(3), 398–414. doi:10.1007/s11146-013-9405-4

Zhong, C., Schläpfer, M., Arisona, S., & Ratti, C. (2014). *Revealing the Changing Spatial Structure of Cities from Human Activity Patterns*. *mit.edu* (p. 26). Retrieved from http://web.mit.edu/schlmark/www/Zhong_Preprint.pdf

Zhou, Y., & Shepherd, J. M. (2009). Atlanta's urban heat island under extreme heat conditions and potential mitigation strategies. *Natural Hazards*, *52*(3), 639–668. doi:10.1007/s11069-009-9406-z

ANNEXES

- **ANNEX 1: SENSING NETWORKS**
- **ANNEX 2: MOBILE SENSING**
- **ANNEX 3: PROJECT PROPOSAL**

- ANNEX 1: SENSING NETWORKS

ANNEX 1 - SENSOR NETWORKS

Networks of environmental and climate sensors are essential to monitor air process, and to assess both long-term and short-term atmospheric change. Depending on the application, networks of different sizes are required to study the range of atmospheric processes, at various spatial and temporal scales:

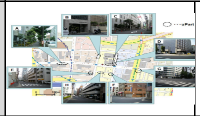
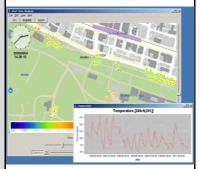
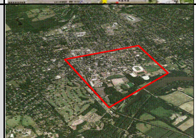
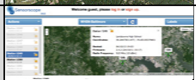
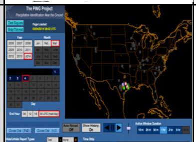
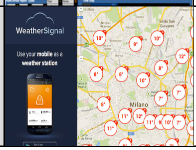
Spatial scale areal extent	Description	Atmospheric processes and applications	Networks examples
Global > 10^8 m	Global network of networks, internationally facilitated	global climate change, satellite calibration/validation	NOAA Global Historical Climate Network (GHCN); Global Climate Observing System (GCOS)
Macroscale/Synoptic 10^5–10^7 m	Networks of national monitoring stations located around countries, usually in rural areas.	Used for examining regional and national synoptic events, national weather forecasting, modeling	US Automated Weather Observing System (AWOS), US Climate Reference Network (USCRN), AMeDAS, Japan, and the UK Met Office MIDAS network have stations in rural and urban areas that provide hourly surface weather data for weather forecasting, aviation. These data are also provided to global data networks
Regional/Mesoscale 10^4–10^6 m	Monitor regional meso-scale events. Urban, peri-urban and rural areas covered.	Thunderstorms, downbursts, squall lines, temperature variations over urban and rural areas, sea circulations	Coarse array networks – currently several Mesonets ('meso-scale networks') e.g. in the US, China, Finland
City-scale 10^4–10^5 m	Monitoring weather and climate at the scale of the whole city.	Air pollution urban heat island studies, urban climate studies,	Fine-array networks such as EPA and other monitoring stations (i.e. the Oklahoma City Micronet, installed to examine urban climate variability)
Local scale/ Neighborhood 10^2–10^4 m	Effects of minor landscape, neighborhoods with similar types of urban development. Monitoring equipment is sited to be representative of neighborhood (i.e. a set height, representative surface cover, little obstructions, to avoid micro-climate effects)	Air pollution Urban heat island, variations with land use, surface cover, tornadoes	Few local-scale networks exists, since most individual climate stations within city-scale networks or meso-scale networks are often representative of the neighborhood in which it is located (unless they are specifically examining microclimates). **See also below**
Micro-scale 10-10^2 m	Microclimate phenomena. Influenced by urban areas the dimensions of component elements: buildings, trees, roads, streets, courtyards, and gardens. Equipment located to be representative of the micro-climate	Air pollution, human comfort and exposure, urban canyon studies, IHU studies, turbulence and dispersion studies, impact of buildings, agricultural meteorology	**See below**
Building/Street/ 'People' scale <10 m	Indoor/outsoor sensors	Indoor/outdoor air quality control, indoor microclimate (cooling/heating)	Domestic wireless sensor networks (home automation to control lighting, thermostat), underground parking lot air quality control, personal and participatory sensing, etc.

For the purpose of this study, the street/"people's" level, is further investigated.
The following table contains examples of networked sensors for meteorological and environmental studies at the micro-scale.
On the left of the table, a quick letter describes the sensor network in terms of:

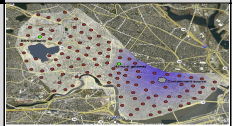
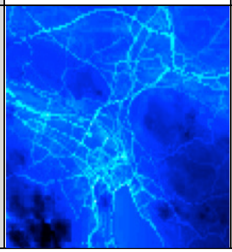
The Sensor Network is		if it is
Smart:	**S**	integrated with other data for different purposes (academic research, governmental decision support, users information) in a smart platform
Mobile:	**M**	wireless and mobile (not fixed and subjected to vandalism, permission, siting), fine-grained-scale, potentially covering all city area at a local/micro level
Environmental:	**E**	measure (at least) air pollution
Climate:	**C**	measure (at least) temperature, humidity
Real-Time:	**R**	data (at least) hourly
Urban/City local-scale:	**U**	areal extent (at least) at local/neighborhood scale (10^2-10^3m)
Participatory:	**P**	participatory sensing, crowd-sourced, citizens involved in data gathering
..	**(..)**	offline or potential future implementation

CONTENT

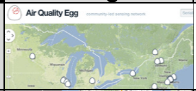
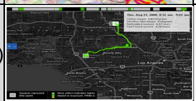
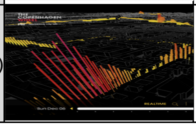
1. Sensor Networks specifically for temperature (weather/climate) data

							Image	Name	Who	Where	What	How	Sensor (See Annex2)	When	Main aim	+ Notes	- Notes
S	-	-	C	R	-	-	OPAL/LAQN, London; OKNET/**Mesonet**/Micronet, Oklahoma City; EcoNET, North Carolina; Testbed, Helsinki; Berlin Network; TWIN, Taipei, CoWIn, Hong Kong; Quantuum, St Louise.									not at local/micro scale	
-	-	-	C	(r)	U	-		**UScan**	Tokyo Denki University	Tokyo	temperature, vibration, illumination	200 sensors, (250x450m) 100.000 mq	uParts (TC1047A for temperature)	2 months (july-aug 2007)	fine-scale temperature variations	correlation between T and sunshine	field campaign, maintenance cost (permit, vandalism, weather exposure)
X	-	-	X	(x)	U	-		**AiryNotes**	Graduate School of Media and Governance, Keio University	Tokyo (Shinjuku Garden)	temperature	165 sensors, 580.000 mq	uParts TC1047A for temperature)	april 2006	info about temperature in the park, showing UHI and latent heat	Visitors of the park understood the role of the park in lowering the T. of the surrounding urban areas	small field campaign, some technical problems (i.e. crows broke some sensors)
-	-	-	C	(r)	U	-		**LUCE**	Ecole Polytechnique Federale de Lausanne	Lausanne	temperature and humidity, air and surface, etc.	92 (750x500m)	(Sensirion SHT75 for temperature and humidity)	oct-2006-apr 2007	estimate H	first full experiment on microclimate	field campaign (maintenance cost)
-	-	-	C	R	U	-		**SNOP**	Princeton University (Elie Bou-Zeid)	Princeton	temperature, radiation, etc.	7 (300x300)	Eddy-Covariance (EC) station Sensorscope, (decagon VP3, and sensirion sht75 for T.)	active	microclimate	unique microclimate permanent sensor network	limited to urban canyon analysis inside the campus
-	-	-	C	R	U	-		**WHSN**	Princeton University	Baltimore	temperature, radiation, etc.	7 (400x400)	decagon VP-3	active	microclimate	urban canyon study	results are site-specific
S	M	-	C	R	(u)	P		**mPING**	University of Oklahoma	US	qualitative weather data	mobile phone App	qualitative users sensing	active	improving forecasting	The national weather service is using it to improve its forecasting	qualitative
-	M	-	C	R	(u)	P		**Weather Signal**	OpenSignal	worldwide	temperature, humidity	mobile phone App	Mobile phone sensor (mainly Samsung Galaxy 4S, sensor Sensirion SHTC1)	active	crowd sourced weather maps	like Wundergound.com, they gather data for forecasting	lack of data calibration, lack of indoor/outdoor differentiation,

2. Sensor Networks for environmental data

	Image	Name	Who	Where	What	How	Sensor (See Annex2)	When	Main aim	+ Notes	- Notes
(s) - (e) (c) (r) (u) -		**Citysense**	Harvard University	Cambridge, USA	temperature, wind, humidity, CO_2, noise	25 sensors (100 proposed) 18.000.000mq	Vaisala WXT510 Weather Sensor (humidity/temperature with sensor Humicap180)	2006-2010? offline	weather, air and water pollution, biochemical agents	first real network at a micro scale covering a whole city	network offline (technology constrains, lack of management)
S M E C R U (p)		**Smart Santander**	EU project (companies and institutions including Telefonica I+D and the University of Cantabria	Santander, Spain	temperature, CO, noise, light and car presence	2000, at streetlights, facades 150 in public vehicles	Libelium Waspmote (MCP9700 for temperature)	ongoing / being developed	smart city	Ambitious EU project: "a unique in the world city-scale experimental research for a smart city"; includes mobile App	not completely developed and fully implemented
S M - - R U -		**Sensor City**	Province of Drenthe and the municipality of Assen	Assen, NL	sound and mobility	200 sound sensors and several tens of mobile sensors	On Board Unit (a smart box) and a tablet in cars	january 2013-ongoing	To identify "sound zones". To anticipate instead of react to the current traffic situation	Focus on the networking, development and application of knowledge and sensors technology	(The project do not include air quality sensors and measurements)
S M E (c) (r) U P		**Sensing City**	Sensing City (social enterprise) and Arup, and MIT Little Devices	Christchurch, New Zeeland	water quality (future development includes air pollution and mobility)	Sensor kits have been distributed to students who measured water quality	Little Water Sensor kits created by MIT	Sept. 2013 - ongoing	Public participation in environmental topics	Successful involvement of citizens	Only water measurement at the moment. In May 2014, the air quality project is expected to be implemented.
- M E C R U -		**Open Sense**	ETH Zurich (EPF Lausanne)	Zurich and Lousanne	temperature, humidity, CO, CO_2, NO_2, O_3, UFPs)	Lausanne: 3 stationary stations, 2 mobile on buses, 1 mobile on electric car; Zurich: 1 stationary station, 10 mobile on trams 1 mobile on bus	OpenSense stations (stationary and mobile)	since 2011 (mobile stations since 2013)	Accurate location-dependent and real-time information on air pollution	Coverage, maintenance, flexibility, data dissemination	Mobility of the sensors is crucial and challenging at the same time

3. Other Air Quality sensing Projects/Networks:

							Image	Name	Developer	website	Notes
-	-	E	C	R	(u)	P		**Air Quality Egg**	A kickstarter project of designers and technologists working on urban social and environmental problems	http://airqualityegg.com/citi-sense	(about 200 Base Eggs are active)
-	M	E	C	R	U	P		**Air Casting**	HabitatMap (NGO in NY) and others (including Google Earth Outreach Developer Grant)	http://aircasting.org/	DYI project, it includes health exposure data (and an air casting luminescent vest)
S	M	E	C	R	(u)	P		**Common Sense**	UC Berkley	http://www.communitysensing.org/ air quality egg	The project, not implemented yet, will also put air quality sensing system on street sweepers in San Francisco - deploy our handheld device with a community action group in West Oakland
S	M	E	C	R	(u)	(p)		**CamMobSens**	University of Cambridge, UK	http://www.escience.cam.ac.uk/mobiledata/	CamMobSens conducted a large scale deployment, lasting three months, in the greater Cambridge area in the Spring/Summer of 2010. Work has now started on a NERC funded project to deploy an improved version of these devices, incorporating a novel particulates/aerosol sensor, at ~60 locations around Heathrow airport.
-	M	E	C	(r)	(u)	P		**Citi-Sense**	EU Project	http://www.citi-sense.eu/	Using different sensors devices (i.e CanarIT), the project is creating pilot implementation prototypes for monitoring outdoor air quality, especially in public spaces, and indoor air pollution in schools, through citizens observations.
S	M	E	C	R	U	P		**EveryAware**	EU Project	http://www.everyaware.eu/ http://cs.everyaware.eu/event/airprobe/map2	Included an AIrProbe web game. An international challange was held in London, Turin, Antwerp and Kassel.
S	M	E	-	R	(u)	(p)		**Urban Sensing**	CENS/UCLA	https://research.cens.ucla.edu	A series of research project under the topics of "embeddable sensors" (SES) and participatory sensing (PART-URB), i.e. the PIER, personal environmental impact report project.
S	W	E	C	R	(u)	(p)		**Common Scents (The Copenhagen Wheel)**	Senseable City Laboratory, MIT	http://senseable.mit.edu/copenhagenwheel/	During the unveiling of the project and its prototype, data from sensors was collected on Dec 2nd, 2009. They showed the potential for a mobile sensing for fine-grained environmental information

4. Other Sensing Projects/Networks or research campaigns:

- SmartCitizen (FabLab Barcelona)
- Elm (PerkinElmer)
- BikeNet (Columbia University)
- BikeCity (Harvard University)
- CarTel (MIT)
- ZebraNet (Princeton University)
- GeoCENS Project (University of Calgary)
- Citizen-Sensor (New Parson School)
- EcoBus (Pancevo, Serbia)
- P-Sense (University of South Florida)
- The Green Watch, CityPulse (Futur en Seine, France)
- N-Smarts (UC Berkeley)
- PM-Air (Preemptive Media, NY)
- e-Science (UCL London)
- MobileDust (KIT Intitute)
- GasMobile (ETH Zurich)
- Message (Imperial College, University of Cambridge and University of NewCastle)
- Geotech (AQMesh, Envirologger)
- Botworld (ENVI-met project)
- Da_sense (TU Darmstadt)
- Aeroflex (VITO—Flemish Institute for Technological Research)
- Dust Sensing Project (University of Melbourne)
- Air Visibility Monitoring (University of Southern California)
- Sensor Probes (Carneige Mellon University)
- HazeWatch (University of New South Wales)
- SAPALDIA Biobank (University of Zurich)
- MetroSense, CenceMe (Darthmouth College)
- New York community air pollution monitoring project (EPA)
- Urban Atmospheres Initiative (UC Berkeley, Intel)
- Citizen Noise Pollution Monitoring (Sony, University of Brussel)
- SensorMap, SenseWeb (Microsoft)
- various UHI campaigns (Rotterdam, Atlanta, Tokyo, London, Padua)

References

- Akyildiz IF, Sankarasubramaniam W, Su Y, Cayirci E. 2002. Wireless sensor networks: a survey. *Computer Networks* **38**(4): 393–422. Basara JB, Illston BG, Fiebrich CA, Browder PD, Morgan CR,
- Chang B, Wang H-Y, Peng T-Y, Hsu Y-S. 2010. Development and evaluation of a city-wide wireless weather sensor network. *Educational Technology & Society* **13**(3): 270–280.
- Chen F, Bornstein R, Grimmond CSB, Li J, Laing X, Martilli A, Miao S, Voogt J, Wang Y. 2012. Research priorities in observing and modelling urban weather and climate. *Bulletin of the American Meteorological Society* **93**(11): 1725–1728.
- Dargie W, Poellabauer C. 2010. *Fundamentals of Wireless Sensor Networks: Theory and Practice*. John Wiley and Sons: Chichester, UK.
- Davies L, Bell JNB, Bone J, Head M, Hill L, Howard C, Hobbs SJ, Jones DT, Power SA, Rose N, Ryder C, Seed L, Stevens G, Toumi R, Voulvoulis N, White PCL. 2011. Open air laboratories (OPAL): a community-driven research programme. *Environmental Pollution* **159**(8–9): 2203–2210.
- Estrin D, Michener W, Bonito G. 2003. *Environmental Cyber Infrastructure Needs for Distributed Sensor Networks: A Report from a National Science Foundation Sponsored Workshop*. Scripps: La Jolla, CA, USA.
- Grimmond CSB. 2006. Progress in measuring and observing the urban atmosphere. *Theoretical and Applied Climatology* **84**(1–3): 3–22. Grimmond CSB, Roth M, Oke TR, Au YC, Best M, BettsR CG, Cleugh
- H, Dabbert W, Emmanuel R, Freitas E, Fortuniak K, Hanna S, Klein P, Kalkstein LS, Lui CH, Nickson A, Pearlmutter D, Sailor D, Voogt J. 2010. Climate and more sustainable cities: climate information for improved planning and management of cities (producers/capabilities perspective). *Procedia Environmental Sciences* **1**: 247–274.
- Gutierrez JA, Naeve M, Callaway E, Bourgeois M, Mitter V, Heile B. 2001. IEEE 802.15.4: a developing standard for low-cost wireless personal area networks. *IEEE Network* **15**(5): 12–19.
- Hart JK, Martinez K. 2006. Environmental sensor networks: a revolution in the earth system science? *Earth-Science Reviews* **78**(3–4): 177 – 191.
- Hicks BB, Callahan WJ, Pendergrass WR III, Dobosy RJ, Novakovskaia E. 2012. Urban turbulence in space and time. *American Meteorological Society* **51**: 205–218.
- Howard L. 1818. *Climate of London Deduced from Meteorological Observations*, Vol. **1**. W. Phillips: London.
- Hung TK, Wo OC. 2012. Development of a community weather information network (Co-WIN) in Hong Kong. *Weather* **67**(2): 48–50.
- IPCC (Intergovernmental Panel on Climate Change). 2001. *Climate Change 2001: The Scientific Basis*. Cambridge University Press: Cambridge, UK.
- Mikami T, Ando H, Morishima W, Izumi T, Shioda T. 2003. A new urban heat island monitoring system in Tokyo. In *Proceedings of the Fifth International Conference on Urban Climate*, Lodz, September 2003.
- Murty RN, Mainland G, Rose I, Chowdhury AR, Gosain A, Bers J, Welsh M. 2008. CitySense: an urban-scale wireless sensor network and testbed, In *Proceedings of the 2008 IEEE International Conference on Technologies for Homeland Security*, Waltham, MA.
- Nadeau DF, Brutsaert W, Parlange MB, Bou-Zeid E, Barrenetxea G, Couach O, Boldi M-O, Selker JS, Vetterli M. 2009. Estimation of urban sensible heat flux using dense wireless network of observations. *Environmental Fluid Mechanics* **9**: 635–653.
- Oke TR. 2004. Siting and Exposure of meteorological instruments at urban sites, *27th NATO/CCMS International Technical Meeting on Air Pollution Modelling and its Application* , Banff, October 25 – 29, 2004.
- Oke TR. 2006. Towards better scientific communication in urban climate. *Theoretical and Applied Climatology* **84**(1–3): 179–190. Ono T, Kanai K, Ishizuka H, Thepvilojanapong N, Iwai M, Tobe
- Y. 2008. Analysis of fine-grained urban temperature collected with a sensor network. *IEEE SENSORS 2008 Conference*, Lecce, Italy, 26th–29th October 2008.
- Polak J, Hoose N. 2009. *Mobile Environmental Sensing System Across Grid Environments*, Retrieved September 15, 2011. Available at http://bioinf.ncl.ac.uk/message/files/MESSAGE_Flyer_Feb2009.pdf
- Rundel PW, Graham EA, Allen MF, Fisher JC, Harmon TC. 2009. Environmental sensor networks in ecological research. *New Phytologist* **182**: 589–607.
- Ryder CL, Toumi R. 2011. An urban solar flux island: measurements from London. *Atmospheric Environment* **45**: 3414–3423.
- Schroeder JL, Burgett WS, Haynie KB, Sonmez I, Skwira GD, Doggett AL, Lipe JW. 2005. The West Texas Mesonet: a technical overview. *Journal of Atmospheric and Oceanic Technology* **22**(2):
- Stewart ID. 2011. A systematic review and scientific critique of methodology in modern urban heat island literature. *International Journal of Climatology* **31**: 200–217.
- Stewart ID, Oke T. 2009. A new classification system for urban climate sites. *Bulletin of the American Meteorological Society* **90**: 922–923.

- Stewart ID, Oke TR. 2012. 'Local Climate Zones' for urban temperature studies. *Bulletin of the American Meteorological Society* **93**:
- Takahashi K, Mikami T, Takahashi H. 2009. Influence of the urban heat island phenomenon in Tokyo in land and sea breezes, *The Seventh International Conference on Urban Climate*, 29 June–3 July 2009, Yokohama, Japan.
- Thepvilojanapong N, Ono T, Tobe Y. 2010. A deployment of fine- grained sensor network and empirical analysis of urban temperature. *Sensors* **10**(3): 2217–2241.
- Tomlinson CJ, Chapman L, Thornes E, Baker CJ. 2012. Derivation of Birmingham's summer urban heat island from MODIS satellite images. *International Journal of Climatology* **32**(2): 214–224.
- Welsh M, Bers J. 2010. CitySense: an urban-scale sensor network. In *Ecological Urbanism*, Mostafavi M, Doherty G (eds). Harvard Grad- uate School of Design. Lars Mu ̈ller Publishers: Zurich, Switzerland, 164 – 165.
- WMO. 2006. *Initial Guidance to Obtain Representative Meteorological Observations at Urban Sites*, Instruments and Observing Methods Report No. 81, WMO/TD-No.1250.
- WMO. 2008. *Guide to Meteorological Instruments and Methods of Observation*, 7th edn. Instruments and Observing Methods Report No. 8.
- Ergo project. http://www.urban-atmospheres.net/Experiments/Ergo
- Urban Atmosphere Project. http://www.urban-atmospheres.net/
- Cambridge Mobile Urban Sensing. http://www.escience.cam.ac.uk/mobiledata/
- OpenSense Project. http://www.nano-tera.ch/projects/401.php
- D. Abadi. Data Management in the Cloud: Limitations and Opportunities. In IEEE Data Engineering Bulletin , 2009.
- P. Agouris et al. . Knowledge Aquisition and Data Storage in Mobile GeoSensor Networks. In Geosensor Networks , 2006.
- E. Brewer et al. . N-Smarts: Networked suite of mobile atmospheric real-time sensors. http: //www.cs.berkeley.edu/~honicky/nsmarts/
- B. Costa et al. . Air Project. http://www.pm-air.net/
- C. Dellarocas. Reputation mechanism design in online trading environments with pure moral hazard. Info. Sys. Research , 16(2), 2005.
- S. Gandhi et al. . Catching Elephants with Mice: Sparse Sampling for Monitoring Sensor Networks. In Sensys . ACM, 2007.
- R. Honicky et al. . Increasing the precision of mobile sensing systems through supersampling. In UrbanSense , 2008.
- Y. Jung et al. . Air Pollution Monitoring System Based On Geosensor Network. In IGARRS , 2008.
- A. Krause et al. . Towards community sensing. In IPSN , 2008.
- L. Luo et al. . Sharing and exploring sensor streams over geocentric interfaces. In GIS , 2008.
- S. Nittel. A Survey of Geosensor Networks: Advances in Dynamic Environmental Monitoring. In Sensors , 2009.
- P. Padhy et al. . A utility-based adaptive sensing and multi-hop communication protocol for wireless sensor networks. ACM Transactions On Sensor Networks , 6(3), 2010.
- P. Volgyesi et al. . Air Quality Monitoring with SensorMap. In IPSN , 2008.
- A. Walkowski. Model Based Optimization of Mobile Geosensor Networks . In Lecture Notes in GeoInformation and Cartography. The European Information Society, 2008.
- W. Willett et al. . Common Sense Community: Scaffolding mobile sensing and analysis for novice users. In Pervasive Computing , 2010.
- J. Yang et al. . Integration of wireless sensor networks in environmental monitoring cyber infrastructure. In WiNet , 2010
- https://maps.google.com/maps/ms?ie=UTF8&t=m&vpsrc=0&oe=UTF8&msa=0&msid=202250953567525689488.0004ad9bd3d09a00295a5&dg=feature

- ANNEX 2: MOBILE SENSING

ANNEX 2 - ENVIRONMENTAL AND CLIMATE SENSORS

CONTENT

1. Unit sensors commercially available: temperature and humidity

Image	company	name	TEMPERATURE accuracy ± °C	TEMPERATURE response time s	HUMIDITY accuracy ±%RH	HUMIDITY response time s	size (mm)	cost $
	Sensirion	SHT21	0.3	5-30	2	8	3 x 3 x 1.1	?
		STS21 (different I²C address than the SHT2x and is pin compatible)	0.3	5-30	2	8	3 x 3x 1.1	3

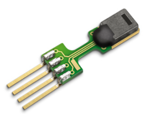
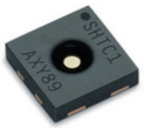
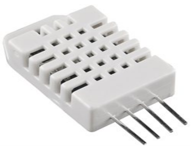
Image	company	name	TEMPERATURE accuracy ± °C	TEMPERATURE response time s	HUMIDITY accuracy ±%RH	HUMIDITY response time s	size (mm)	cost $
		SHT75	0.3	5-30	2	8	5 x 20 x 2	70
		SHTC1 (inside Galaxy 4S phone)	0.3	5-30	3	8	2 x 2 x 0.75	...
		SHT11	0.4	5-30	3	8	7.5 x 4.9x 2.5	21
	Aosong(Guangzhou) Electronics	DHT22	0.2	2	2-5	2	27 x 59 x 13.5	10
	Honeywell	HIH-4030			3.5	5	19.05 x 7.62	18

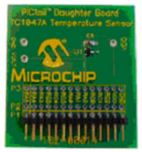
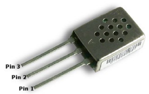
Image	company	name	TEMPERATURE accuracy ± °C	TEMPERATURE response time s	HUMIDITY accuracy ±%RH	HUMIDITY response time s	size (mm)	cost $
	Analog Devices	TMP36	2-3	?			5 x 6 x 1.7	2
	Microchip	TC1047ADM-PICTL - TC1047A	-	-	4	<15	2 x 2.10 x 1	10
		808H5V5	0.5	?	-	-	?	?
		MCP9700A	2	1.65	-	-	?	?
		WXT520	0.3	?	3	?	238 x 115 x 115	2000

Image	company	name	TEMPERATURE accuracy ± °C	TEMPERATURE response time s	HUMIDITY accuracy ±%RH	HUMIDITY response time s	size (mm)	cost $
	Decagon	VP-3	0.25		2	?	54 x 20 x 20	?
	Premenugo	DMA672.1	0.1	4	1.5	10s	150 x 20 x 20	20?
	Vaisala	HUMICAP Probe HMP155	0.1	<20	+ - 1	20	267 x 24 x 24	700 ?
		HUMICAP® 180 HM70	0.2	?	1	17 s	...	1800

2. Unit sensors commercially available: air quality

Image	company	name	what they measure	detection, sensitivity, resistance	response time (sec)	size (mm)	cost $
	Aphasense	NO2-A1	NO2	Sensitivity nA/ppm in 10ppm NO2 -400 to -750	Response time t 90 (s) from zero to 400ppm NO2 < 30	20 x 20 x 16.6	269
		CO-AF CO-AX	CO	Sensitivity nA/ppm in 400ppm CO 55 to 100	Response time t 90 (s) from zero to 10ppm CO < 50	20 x 20 x 16.6	119 (AF)
		CO-BF	CO	Sensitivity nA/ppm in 400ppm CO 80 to 130	Response time t 90 (s) from zero to 10ppm NO2 < 25	32 x 32 x6.5	109 (DF)
	Figaro	TGS 2201	NO, NO2	detection: 0.1-10 ppm sensitivity: 2.5	?	13 x 14 x 14	?
		TGS 2202	CO, H2, HC	detection: 10-1000 ppm sensitivity: 0.35	?		
		TGS 2442	CO	detection: 30-1000 sensitivity: 0.13-0.31	?	13 x 9 x 9	23

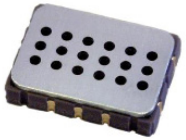
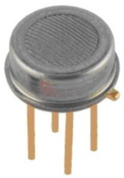
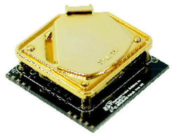
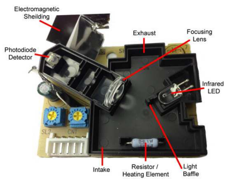
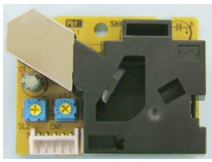
Image	company	name	what they measure	detection, sensitivity, resistance	response time (sec)	size (mm)	cost $
	e2v, UK	MiCS4514	CO	resistance: 100-15000 kΩ CO detection: 1-10000ppm	sensitivity: 1.2-50	5 x 7 x 1.55	9
		MiCS45..	NOx	resistance: 0.8-20 kΩ NO2 detection: 0.05-2ppm	sensitivity: >2		
		MiCS-5525	CO	detection 10-100ppm resistance: 100-1500 sensitivity: 5-50	?	25 x 11 x 11	10
		MiCS-5526	CO, VOC (C2H6OH, H2, NH3, CH4)	detection 10-1000ppm resistance: 100-1500 sensitivity: 1.2-5	?	5 x 7 x 1.55	13
		MiCS- 5521	CO (and HC, VOC)	CO detection: 1-1000 ppm resistance: 10-1000 sensitivity: 3 (1.8-6.6)	?	9 x 9 x 14	?
		MiCS-OZ-47	O3	20-200 ppb accuracy: +-20ppb	response time: 6 minutes	33 x 23 x 2	130
		MiCS2610	O3	detection 10-1000ppb resistance: 11 (3-60) sensitivity: 2 (.5-4)	?	9 x 9 x 14	8

Image	company	name	what they measure	detection, sensitivity, resistance	response time (sec)	size (mm)	cost $
	citytech	Sensoric O3 3E 1	O3	Measuring 0–1 ppm Sensitivity 1000 - 2000 nA/ppm (negative signal)	Response Time t50 < 15 s calculated from 3 min. exposure time t90 < 60 s	?	?
	Elt, Inc.	ELT S100	CO2	detection: 0-5000 ppm accuracy: + - 30, 5 - 5%	30 s (sampling 3s)	33 x 33 x 9	?
	SHARP optical	GP2Y1010AUOF	PM	0.5 (sensitivity)	?	46.0 × 30.0 × 17.6	12
	Shinyei	PPD42NJ	PM	Detectable particle size approx. 1 µm (min)	time for stabilization (1 min after power turned on)	59 x 45 x 22	150
		PPD42 NS	PM	Detectable particle size approx. 1 µm (min)	time for stabilization (1 min after power turned on)	59 x 45 x 22	200
	Dylos	DC1100, DC1700	PM	(>0.5 & >2.5 microns)	?	180 x 101 x 76 Weight: 2.5 lb	200, to 425

3. "Assembled" multi-sensor and DIY sensor devices, used for personal sensing and participatory sensing (with public web platform)

Image	name	platform/ network	developer	what they measure	Unit sensor (see above for reference)	Size , mm (weight, g)	Cost $	notes
	**EcoPM**	SensDot	Sensaris	PM	Shinyei PPD42 NS	97 x 75 x 46 (133 g)	..	-
	**EcoPM v.2**			PM 2.5 and PM 10	PPD42NJ	121 x 66 x 40	275	new model out in February 2014
				VOC	?			
				humidity	?			
				Temp.	?			
	**EcoSense**			CO, NOx,	MICS4514	80 x 50 x 20 (66 g)	..	Some studies showed low correlations for both CO and NOx measurements (font: EveryAware project, Song)
				Temp. humidity	Sensirion SHT11			
				noise	-			
	**ECO2sense**			CO2	ELT S100	80 x 50 x 35 (92g)	..	-
	**ECO3sense**			Ozone (O3)	e2V MICS 2610	80 x 50 x 20 (66g)	..	-
				Temp. Humidity	Sensirion SHT11			
				Luminosity	-			
	**M-pod**	MAQS	University of Colorado	Temp., Humidity	Sensirion, SHT21	120 x 60 x 40 ? ?	300	A recent study (Oct 2013) showed its good performance while underling the importance of multiple calibrations and warm-weather calibration.
				CO	MICS-5525			
				CO2	ELT, S100			
				CO, VOC	MICS-5526			
				CO, VOC, NO2	MICS-4514			

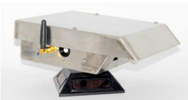
Image	name	platform/ network	developer	what they measure	Unit sensor (see above for reference)	Size , mm (weight, g)	Cost $	notes
	**SEEnsor node (Citi Sense)**	CitiSense	University of California, San Diego	NO2	Alphasense NO2-A1	110 x 67 x 40	1000	Used in many research projects at UCSD, including a measurement campaign in a PhD thesis (see reference), showing some calibration concern.
				CO	Alphasense CO-AX			
				O3	Sensoric O3 3E 1			
				Temp. humidity	??			
				pressure	?			
	**AirBase**	MyAirBase	CanarIT, startup company	O3, NO2, VOC, TSP, noise, Temp humidity,.	(not specified)	-	?	-
	**AirProbe**	EveryAware	EU project (.....)	CO	Alphasense CO-BF MiCS-5521, MiCS-5525	-	500	Built and used in a current European project, after an analysis of existing devices.
				NO2	MiCS-2710			
				VOC	AS-MLV (VOC)			
				O3	MiCS-2610			
				Temp. humidity	Sensirion SHT21			
				CO, H2, HC, NOx	Figaro 2201			
	**AirMonitor**	AirCasting (Habitat Map)	NGO based in New York	CO	Figaro TGS 2442	82 x 78 x 56	180 (case escluded)	A DIY device. Featured in the recent US EPA MyAir, My Health competition
				NO2	MiCS-2710			
				Humidity	HIH-4030			
				Temp.	TMP36			
	**Base Egg**	AirQuality Egg	community driven, kiskstarter , ..	NO2	MiCS-2710	80 x 53 x 53	185	Successful experience in forming a community to supports its project financing and development. The project is assuming it will once be able to interpret the data generated by the large amount of uncalibrated, and unvalidated measurement equipment they are rolling out at the moment.
				CO	MICS-5525			
				O3	MiCS-2610			
				VOC	MiCS- 5521			
				Temp., humidity	DHT22			
				PM	Shinyei PPD42NS or the Sharp GP2Y1010.			

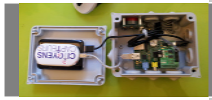
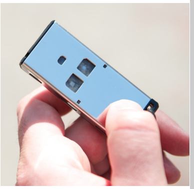
Image	name	platform/ network	developer	what they measure	Unit sensor (see above for reference)	Size , mm (weight, g)	Cost $	notes
	**Envboard**	TECO	KIT University	O3	MICS-2614	140 x 70 x 30	n.a.	It was used in The device has micro fans for air flow, and solar panels.
				CO, NOx	MICS-4514			
				PM	GP2Y1010			
				Temp., humidity	SHT21			
				VOC	iAQ-Engine			
				others	noise, pressure, acceletometer, gyroscope, thermistor, etc.			
	**Smart Citizen Kit**	Smart Citizen	Fab Lab Barcelona	NO2	MiCS-2710	67 x 56 x 30	155	The device will have solar panel (winner world smart city awards innovative initiative)
				CO	MICS-5525			
				Temp., humidity	DHT22			
				others	sound, light			
	**Gasser**	Gasser	LaboCytroen, France	NO2	Alphasense NO2-B4	150 x 100 x 50	255	-
	**Sensordrones**	Sensordrone Control	Sensorscon (company from Buffato, NY)	CO (electrochemical)	range: 0-2000 ppm resolution: 1 ppm accuracy: +- 10% response time: 10-20s	67 x 28 x 12 (28 g)	200	Low cost keychain size measurement device able to measure reducing gases, oxidizing gases and other mixtures of gases (CO,H2 S, Alcohol, Hydrogen, and others) among a number of other components. It was successful in selling a lot of devices through kickstarter.com to a quite large community. The project includes the development of a large amount of custom smartphone applications for the sensordrone, making it an easy to use and multifunctional device
				H2, CO, VOC (metal oxide)	range: 0-1000ppm response time: 30-60s			
				O3, NO2, Cl2 (metal oxide)	range: 0-5 ppm response time: 30-60s			
				Temp., (silicon bandgap)	+- 0.5 response time: 20-60s			
				humidity (capacitive)	+- 2% response time: 10-180s			

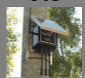
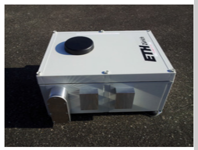
Image	name	platform/ network	developer	what they measure	Unit sensor (see above for reference)	Size , mm (weight, g)	Cost $	notes
	**Citizen Sensor**	Citizen Sensor	Joe Saavedra, Parsons The New School for Design NYC	CO, methane, Temp., humidity and others (noise, light)	not specified	n.a.	n.a.	It started as a
	Intel Berkeley Badge	Common Sense	Intel and UC Berkeley	Temp., humidity	SHT1	-	-	The project is developing a vehicular platform that is optimized for the particular challenges of municipal vehicles such as street sweepers.
				CO and NO2	MICS-4514			
				O3	MICS-2610			
				NO2 and O3	sensoric NO2 and O3			
				CO	microCEL CO			
	**Smart Cities board**	Smart Santander (and others) Waspmote 	Libelium	Temp.	MCP9700A	74 x 51 x 13 (20 g)	-	Currently used in Santander City, Spain, under the SmartSantander European Project
				humidity	808H5V5			
				PM	GP2Y1010AUOF			
				luminosity, noise	-			
	**Gas Sensor board**			CO, CO2, NO2, O3, CH4, H2S, NH3, C4H10, H2, VOC	-	74 x 51 x 13 mm (20 g)	-	Currently used in Santander City, Spain, under the SmartSantander European Project
	**Open Sense station**	Open Sense	ETH Zurich	O3	e2V MiCS-OZ-47	- (4500g)	*15000	The device is used under the current OpenSense project in Zurich and Lousanne, mounted in public transportation (trams and buses), integrated in a heterogeneous sensor network.
				CO	Alphasense CO-AF			
				NO2	Alphasense NO2 A1			
				UFPs	DICSmini Matter Aerosol*			
				Temp., humidity	Sensirion SHT7			
	**AirBot (Speck)**	Speck Gateway	Carnegie Mellon University	-	?	?	100	-

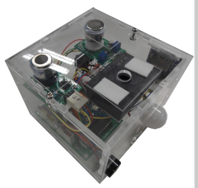
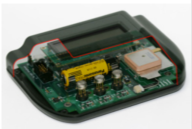
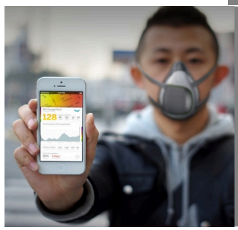
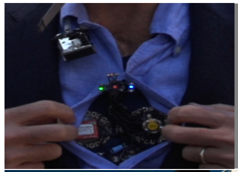
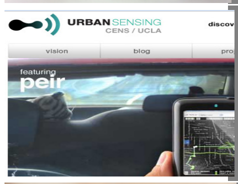
Image	name	platform/ network	developer	what they measure	Unit sensor (see above for reference)	Size , mm (weight, g)	Cost $	notes
	**PACMAN**	n.a.	National Institute of Water & Atmospheric ResearchAuckland, New Zealand	PM CO CO2 Temp. other (motion, distance)	GP2Y1010AU0F MQ-7 MG11 CO2 LM335A	100 X 100 X 80 (270 G)	n.a	-
	**MAQUMON (Mobile Air Quality Monitoring Network)**	Sensor Map portal	ISIS at Vanderbilt University	(O3 ,CO/VOC, NO2, Temp. and humidity)	?	?	?	Car-mounted sensor nodes measuring different pollutants in the air. The data points are tagged with location and time utilizing an on-board GPS.
	**Cube Sensors**	(under development, spring 2014)	CubeSensors (Slovenian private company)	Temp., humidity pressure, VOC, sound, light,	-	50 x 50 x 50	300	Indoor air quality personal sensing. (private company). Similar to AirQualityEggs project.
	**NODE+ CLIMA Climate & Weather Sensor**	**myNODE**	**Variable**	Temp., Humidity (and other modules available)	Temperature (accuracy: 1°C) Humidity (accuracy: 3.5 %RH)	90 x 25 x 25 (38 g)	199	Indoor air quality personal sensing. (Kickstarter project)
	**Netatmo Weather Station**	Neatamo webapp	Netatmo (French private company)	CO2, Temp., Humidity, sound	Temperature (accuracy: 0,3°C) Humidity (accuracy: 3%RH)	105 x 45 x 45	188	Indoor air quality personal sensing. (private company)

Image	name	platform/ network	developer	what they measure	Unit sensor (see above for reference)	Size , mm (weight, g)	Cost $	notes
	**Clarity.io**	Clarity.io	students from UC-Berkeley,	PM2.5, VOC, NOx temperature, humidity	?	?	50-75$	keychain-sized gadget lets you constantly track your personal exposure
	**TZOA**	TZOA	Canadian based kickstarter project	PM2.5, PM10, UV temperature, humidity	?	?	150$	high emphasis on design, as a sort of piece of “jewelry” in order to attract citizens usage
	**CairClip**	CairMap	Cairpol (French private company)	O2/NO2, H2S/CH3SH, NH3, COV	O3/NO2 (from 0 to 250 ppb) H2S/CH3SH (from 0 to 1000 ppb or 0 to 10/20 ppm) NH3 (from 0 to 36 ppm), COV (from 0 to 250 ppb)	62 x 32 x 32 (55 g)	-	Indoor air quality personal sensing. (private company)
	**DustDuino**	-	Public Lab	PM	Shinyei PPD42NS	100 x 100 x 100	DIY 100$	Based on Arduino.
	**WEPO**		Weareable Pollution Monitor	CO, PM	?	?	499$	Developed in New Delhi, India.
	ASM	-	Aginova Inc	temperature	XPROBE-TEMP-0006	65 x 70 x 20 (84 g)	150$	Tested in: (Young et al., 2014, p. 940)
	Hobo Pro V2 logger	-	Onset	temperature	U23–004	102 x 38 x 38 (118 g)	145$	Tested in: (Young et al., 2014, p. 940)
	iButton	-	Thermocron	temperature	DS1921G	6 x 17 x 17 (3.3 g)	23$	Tested in: (Young et al., 2014, p. 940)

4. Other examples of devices with air quality sensors

Image	name	developer	what they measure	notes
	**Samsung Galaxy 4S**	OpenData, Weather Signal*	temperature, humidity (Sensirion SHTC1)	*the smartphone has the Sensirion SHTC1 sensors, many Apps let stream the temperature/humidity data, the main project is Weather Signal by OpenData
	**Weather Station for Smartphone**	SHAKA (Estonian Start-up)	temperature (accuracy: +- 1°C, response time: 60 s), humidity (accuracy: +- 3%RH, response time: 8 s)	Simply plugs into the smartphone's standard 3,5mm headphone jack. A free app streams the data to a webpage. No need to charge or change a battery. (61 x 31 x 16 mm, 9.7 g) 99 $, deliver in march 2014
	**Fenix Hiking GPS Watch**	Garmin	temperature (accuracy: +-1), GPS, altimeter, barometer, 3 axis electronic compass	a mobile App let stream the data via Bluetooth (routes, waypoints, geocaches, ambient temperature data, etc.). 400$.
	**Tempe Wireless Temperature Sensor**	Garmin	temperature (accuracy: +- 1°C)	Get ambient temperature and transmit the data wirelessly to a compatible device. 27$
	**Aiwaves pollution Masks**	Frog Design, team from Shanghai	(concept do not specify air quality measures)	The mask is one of eight winning wearable technology concepts spawned by an internal competition at Frog Design The aim is building an air quality map of the city via crowd-sourced data monitoring.

	**Conscious Clothing**	winners of the US EPA MyAir competition, 3013	dust, temperature, in/out breathing	LilyPad arduino with sensors, and a Led interface, stream data to the smartphone. It monitors also the breath, in order to analyze health exposure
	**(EU project)**	EU- Joint Research Centre	temperature, CO2, NO, NO2, SO2	Micro-sensors for ambient air monitoring (measuring ship emissions) using an “unmanned flying platform” (UAV)
	**Pigeon blog**	Beatriz da Costa (Prof. UC Irvine)	temperature, CO, NO2	PigeonBlog was an attempt to combine DIY electronics development with a grassroots scientific data gathering initiative, while simultaneously investigating the potentials of interspecies co-production in the pursuit of resistant action. (2006-08)
	**Black Cloud**	Niemeyer and a team at UC Berkeley	air quality (not specified)	It was an environmental game fusing public participation, air quality sensors and web technology (2008-2010)
	**Safecast Air**	Safecast (Japan)	(nuclear) radiation	After Fukushima, they were installed in cars by volunteer team, with academic and scientific support. Open data with CC license
	**PEIR, the Personal Environmental Impact Report** **(and Cyclesense Biketastic)**	Center for Embedded Networked Sensing UCLA	indirect air quality measurements (gps)	Indirect measurements: a custom App uploads GPS and cell tower locations traces to a private repository, where they are processed by a set of scientific models. The processing pipeline includes an activity classifier. It then uses weather services, location of schools and hospitals, classes or food establishments.
	**iSPEX**	Leiden Observatory, TU Delft, and private partners	indirect aerosols measurements through smartphone pictures of the sky (with iSpex add-on)	In 2013 there were two national iSPEX measurement (Spectropolarimeter for Planetary EXploration) days (8 July , 5 September); about 10.000 iSPEX units have been distributed for the iPhone 4, 4s and 5.

References

- Aberer, K., Sathe, S., Chakraborty, D., Martinoli, A., Barrenetxea, G., Faltings, B. and Thiele, L.: OpenSense: Open community driven sensing of environment, Proceedings of the ACM SIGSPATIAL International Workshop on GeoStreaming, 39–42 (2010)
- Bales, E., Nikzad, N., Quick, N., Ziftci, C., Patrick, K. and Griswold, W., Citisense: Mobile air quality sensing for individuals and communities Design and deployment of the Citisense mobile air-quality system, Pervasive Computing Technologies for Healthcare (PervasiveHealth), 2012 6th International Conference on, 155–158 (2012)
- Budde, M., Berning, M., Busse, M., Miyaki, T. and Beigl, M., The TECO Envboard: A mobile sensor platform for accurate urban sensing – and more, 9th International Conference on Networked Sensing Systems (INSS 2012), IEEE (2012)
- Budde, M., Berning, M., Busse, M., Miyaki, T. and Beigl, M., Handheld Partic- ulate Matter Measurements with COTS Sensors 10th International Conference on Pervasive Computing (Pervasive 2012)
- Budde, M., Busse, M., and Beigl, M., Investigating the Use of Commodity Dust Sensors for the Embedded Measurement of Particulate Matter, 9th International Conference on Networked Sensing Systems (INSS 2012), IEEE (2012)
- Budde, M., Barbera, P., El Masri, R., Riedel, T. and Beigl, M., Retrofitting Smart- phones to be Used as Particulate Matter Dosimeters, 17th International Symposium on Wearable Computers (ISWC'13), 139–140
- Budde, M., El Masri, R., Riedel, T. and Beigl, M., Enabling Low-Cost Particu- late Matter Measurement for Participatory Sensing Scenarios, 12th International Conference on Mobile and Ubiquitous Multimedia (MUM'13), to appear (2013)
- Burke, J.A., Estrin, D., Hansen, M., Parker, A., Ramanathan, N., Reddy, S. and Srivastava, M.B.: Participatory sensing, Center for Embedded Network Sensing, University of California (2006)
- De Cristofaro, E. and Soriente, C.: Participatory privacy: Enabling privacy in participatory sensing, IEEE Network 27, 32–36 (2013)
- Demirbas, M., Rudra, C., Rudra, A. and Bayir, M.A.: imap: Indirect measurement of air pollution with cellphones, Pervasive Computing and Communications, 2009. PerCom 2009. IEEE International Conference on, 1–6 (2009)
- Dua, A., Bulusu, N. and Feng, W. and Hu, W.: Towards trustworthy participatory sensing, Proceedings of the 4th USENIX conference on Hot topics in security (2009)
- Elen, B., Theunis, J., Ingarra, S., Molino, A., Van den Bossche, J., Reggente, M. and Loreto, V., The EveryAware SensorBox: a tool for community-based air quality monitoring (2012)
- Fondazione ISI, Turin, Italy.: EveryAware: Enhance Environmental Awareness through Social Information Technologies, Report on: sensor selection, calibrationand testing; EveryAware platform; smartphone applications (2012)
- Hasenfratz, D., Saukh, O., Sturzenegger, S. and Thiele, L.: Participatory air pollution monitoring using smartphones, Proc. 1st Intl Workshop on Mobile Sensing:From Smartphones and Wearables to Big Data (2012)
- Hayes M., Calleja M. and Jones R.: CamMobSens: Cambridge Mobile Urban Sensing http://www.escience.cam.ac.uk/mobiledata/ (2010)
- Honicky, R., Brewer, E.A., Paulos, E. and White, R.: N-smarts: networked suite of mobile atmospheric real-time sensors, Proceedings of the second ACM SIGCOMM workshop on Networked systems for developing regions, 25–40 (2008)
- Hooker, B., Gaver, W., Steed, A. and Bowers, J.: The pollution e-sign, Workshop on Ubiquitous Sustainability. Ubicomp (2007)
- Jiang, Y., Li, K., Tian, L., Piedrahita, R., Yun, X., Mansata, O., Lv, Q., Dick, R.P., Hannigan, M. and Shang, L., MAQS: a personalized mobile sensing system for indoor air quality monitoring, Proceedings of the 13th international conference on Ubiquitous computing, 271–280, 2011
- Jones R., and Calleja M.: On the Road with Mobile Sensors, http://www. thenakedscientists.com/HTML/content/interviews/interview/1107/
- Kuznetsov, S. and Paulos, E.: Participatory sensing in public spaces: activating urban surfaces with sensor probes, Proceedings of the 8th ACM Conference on Designing Interactive Systems, 21–30 (2010)
- Kuznetsov,S.,Davis,G.,Cheung,J.andPaulos,E.:Cecin'estpasunepipebombe: authoring urban landscapes with air quality sensors, Proceedings of the 2011 annual conference on Human factors in computing systems, 2375–2384 (2011)
- Lane, N.D., Miluzzo, E., Lu, H., Peebles, D., Choudhury, T. and Campbell, A.T., A survey of mobile phone sensing, Communications Magazine 48, IEEE, 140–150 (2010)
- Mendez,D.,Perez,A.J.andLabrador,M.A.andMarron,J.J.:P-sense:aparticipa- tory sensing system for air pollution monitoring and control, Pervasive Computing and Communications Workshops (PERCOM Workshops), 2011 IEEE International Conference on, 344–347 (2011)

- Young, D. T., Chapman, L., Muller, C. L., Cai, X.-M., & Grimmond, C. S. B. (2014). A Low-Cost Wireless Temperature Sensor: Evaluation for Use in Environmental Monitoring Applications. Journal of Atmospheric and Oceanic Technology, 31(4), 938–944. doi:10.1175/JTECH-D-13-00217.1
- Mun, M., Reddy, S., Shilton, K., Yau, N., Burke, J., Estrin, D., Hansen, M., Howard, E., West, R. and Boda, P.: PEIR, the personal environmental impact re- port, as a platform for participatory sensing systems research, Proceedings of the 7th international conference on Mobile systems, applications, and services, 55–68 (2009)
- Nikzad, N., Verma, N., Ziftci, C., Bales, E., Quick, N., Zappi, P., Patrick, K., Dasgupta, S., Krueger, I., Rosing, T.S. and others, CitiSense: improving geospatial environmental assessment of air quality using a wireless personal exposure monitor- ing system, Proceedings of the conference on Wireless Health (2012)
- Nikzad, N., Ziftci, C., Zappi, P., Quick, N., Aghera, P., Verma, N., Demchak, B., Patrick, K., Shacham, H., Rosing, T.S. and others, CitiSense: Adaptive Services for Community-driven Behavioral and Environmental Monitoring to Induce Change (2011), Department of Computer Science and Engineering, University of California, San Diego
- Poduri, S., Nimkar, A. and Sukhatme, G.S.: Visibility monitoring using mobile phones, Technical report, Department of Computer Science, University of Southern California (2010)
- Steed, A., Spinello, S., Croxford, B. and Greenhalgh, C.: e-Science in the streets: urban pollution monitoring, UK e-science all hands meeting (2003)
- Stevens, M. and DHondt, E.: Crowdsourcing of pollution data using smartphones, Workshop on Ubiquitous Crowdsourcing (2010)
- Whitney, M. and Richter Lipford, H.: Participatory sensing for community build- ing, CHI ’11 Extended Abstracts on Human Factors in Computing Systems, 1321- 1326 (2011)
- Zappi, P., Bales, E., Park, J.H., Griswold, W. and Rosing, T., The CitiSense air quality monitoring mobile sensor node (2012), Proceedings of the 11th ACM/IEEE Conference on Information Processing in Sensor Networks, Beijing, China
- Acrobotic Industries Smart Citizen Overview, http://acrobotic.com/ smart- citizen
- AirBase, http://www.myairbase.com
- AirBase Sensors Map, http://sensors.myairbase.com/
- AirBase Sensor Data Download, http://sensors.myairbase.com/Sensors/xls/1
- AirCasting, http://aircasting.org
- AirNow, U.S. EPA O327ce of Air Quality Planning and Standards, http://airnow.gov
- Air Quality Egg, http://airqualityegg.com/
- Air Quality Egg Blog, http://aqe.wickeddevice.com
- Air Quality Egg Kickstarter Campaign, http://www.kickstarter.com/projects/edborden/air- quality- egg
- Air Quality Egg Wiki, http://airqualityegg.wikispaces.com
- Air Quality Egg Google Group, https://groups.google.com/forum/?fromgroups#!forum/airqualityegg
- Alphasense B4 sensors, http://www.alphasense.com/industrial-sensors/alphasense_sensors/B4_sensors.html
- AQE:Youcanhelpbuildanopenairqualitysensornetwork,http://blog.xively.com/2011/12/07/you-can-help-build-an-open-air-quality-sensor-network/
- AQE Wicked Device, http://wickeddevice.com/index.php?main_page=index&cPath=28
- Air Quality in Europe, CITEAIR, http://www.airqualitynow.eu
- CitizenSensor, http://thesis.jmsaavedra.com/
- Citizen Mobile Environmental Sensing, http://www.ecomobilecitizen.com/
- Council Directive 1999/30/EC of 22 April 1999 relating to limit values for sulphurdioxide, nitrogen dioxide and oxides of nitrogen, particulate matter and lead in ambient air
- CubeSensors, http://www.cubesensors.com
- CubeSensors Blog, http://blog.cubesensors.com 52. Dylos Corporation, http://www.dylosproducts.com 53. Dylos Reviews,
- DustDuino: http://publiclab.org/wiki/dustduino
- http://www.air-purifier-power.com/dylosdc1100proreview.html, http://www.revieweur.com/dylos-dc1100-laser-air-quality-monitor-review. html,
- http://www.americanallergysupply.com/dylos/
- EveryAware Air Quality Case Study, http://www.everyaware.eu/activities/case-studies/air-quality/
- EveryAware AirProbe Sensor Map, http://cs.everyaware.eu/event/airprobe/map2
- FacultyRow: Small, Portable Sensors Allow Users to Monitor Exposure to Pollution on Their Smart Phones, http://facultyrow.com/profiles/blogs/ ucsd-innovation-measuring-air-pollution-with-iphones

- Flickr CitiSense Photo Set, http://flickr.com/photos/jsoe/sets/72157632248508332/with/8273330584/
- HabitatMap, http://habitatmap.org
- iSPEX, http://ispex.nl/en/ (2013)
- LaboCitoyen Wiki, http://wiki.labocitoyen.fr/index.php?n=Hardware. Gasser
- La montre verde (The green watch), CityPulse, Fing http://fing.org/Green-Eyes-Montre-verte-CityPulse-?lang=fr (2009)
- Landesanstalt fu¨r Umwelt, Messungen und Naturschutz Baden-Wu¨rttemberg, http://mnz.lubw.baden-wuerttemberg.de/messwerte/aktuell/
- Matter Aerosol DiSCmini, http://www.matter-aerosol.ch/index.php/features/jquery- superfish- menu
- MAQS Wiki, http://maqs.pbworks.com/
- MobileDust, http://www.teco.edu/research/mobiledust/
- netatmo, http://www.netatmo.com
- OpenSense ETH Zu¨rich, http://www.opensense.ethz.ch/trac/
- OpenSense Live Data Browser, http://data.opensense.ethz.ch/
- PM-Air, Preemptive Media (Beatriz da Costa, Jamie Schulte and Brooke Singer), http://www.pm-air.net (2006)
- PM-Air readings, http://www.pm-air.net/dataVis/ (accessed 19/05/2013)
- Project Budburst, http://budburst.org/
- Sensaris, http://www.sensaris.com
- Sensordrone, http://www.sensorcon.com/sensordrone-1/
- Sensordrone Kickstarter Campaign, http://www.kickstarter.com/projects/453951341/sensordrone-the-6th-sense-of-your-smartphoneand-be
- Sensordrone Android API, http://developer.sensordrone.com/android/api/
- Sensordrone Android Apps Github, https://github.com/Sensorcon
- Sensordrone Developers Forum, http://developer.sensordrone.com/forum/
- Smart Citizen, http://smartcitizen.me/
- Smart Citizen Kickstarter Campaign, http://www.kickstarter.com/projects/acrobotic/the-smart-citizen-kit-crowdsourced-environmental-m
- Smart Citizen Github Repository, https://github.com/fablabbcn
- Smart Citizen Live Beta, http://test.smartcitizen.me/
- Statistisches Landesamt Baden-Wurttemberg, http://www.statistik.baden-wuerttemberg.de/Pressemitt/2013160.asp
- thingstream, http://www.thingstream.net
- TSI Dust Monitors, http://www.tsi.com/Dust-Monitors/
- United States Environmental Protection Agency http://www.epa.gov/airquality/
- http://www.everyaware.eu/resources/deliverables/D1_1.pdf
- http://cs.everyaware.eu/event/airprobe/map2
- http://variableinc.com/product/new-clima-climate-and-weather-sensor/
- http://www.netatmo.com/en-US/product
- http://www.davidholstius.com/author/holstius/
- http://www.notimpossiblenow.com/tools/wepo-pollution-monitor-might-save-delhi
- http://sdsu-dspace.calstate.edu:9000/bitstream/handle/10211.10/5627/Gamble_sdsu_0220N_10043.pdf?sequence=1
- https://sites.google.com/site/airsensors2014
- https://sites.google.com/site/airsensors2013

- ANNEX 3: PROJECT PROPOSAL

URBAN HOT-SPOTS PROJECT

A SMART REAL-TIME SENSOR NETWORK FOR

URBAN CLIMATE STRESS & AIR QUALITY MAPPING

Abstract

European cities are putting efforts in improving their environmental and health performances. While air quality remains a big concern, in cities like Milan (among the poorest air quality in EU) emissions of many air pollutants have decreased substantially over the past decades, and keep decreasing thanks to direct policy and indirect factors (car fleet improvement, economic crisis). However, Climate Change and summer Heatwaves are increasing and expected to happen more frequently, affecting urban quality, exacerbating ozone pollution and Urban Heat Islands, with serious effects on health, especially for older people and children, or those with asthma and other respiratory problems. Additionally, heatwaves are responsible for economic loss (industry, retail, tourism), increased energy consumption, buildings stock damages (even historical), besides citizens and tourists discomfort.

In big cities like Tokyo, London, Hong Kong, which fist studied UHI issues and their high heat stress, and in new megacities and developing countries cities, urban climatic consideration has far had a low impact on planning.

While recent studies are exploring mitigation and especially adaptation solutions to be applied to target locations, data and models are only available are the regional/city level, with little information available at the street level, at the people's level.

The main scope of the project is identifying and understanding sensitive urban-climatic and environmental problem areas ("Hot-spots") so that relevant strategic planning recommendations cab be made to assist planners in taking appropriate action. The idea is to build a mobile participatory smart real-time sensor network, in order to gather climate and environmental data at a local level, to be combined with geographic and planning data in a GIS-platform, based on the superficial energy balance Model.

The project aim at contributing in bridging the gap between urban climatology, environmental planning, town planning and urban design, and to transfer the climatic knowledge into planning languages. With the help of the smart information platform thus created for interdisciplinary communication and collaboration, ultimately used by planners and decision makers, cities will became more "Senseable", Sentient, Resilient, Adaptive, Responsive.

OBJECTIVE

The aim of the project is identifying and understanding "urban hot-spots" through the collection and monitoring of extreme temperature data at the street level, integrating air quality environmental data, through a mobile participatory smart real-time sensor network, based on personal and participatory sensing.

The project will show to be capable of producing high spatial and temporal resolution measures of climate and air quality level which could contribute to scientific understanding, as well as addressing economic, policy and regulatory issues spanning climate change, air pollution and human exposure (and health) responses.

RESEARCH/MEDIA ATTENTION

Climate Change is affecting all EU cities agenda, and most recently with adaptation plans and programmes.

Heatwaves are the center of media attention during summer (intense and hot summer are predicted in EU in the coming years), especially for national media and particularly for Milan, with the highest UHI in Italy.

Smart City and smart networks are key words for many projects today, and cities like Milan are profiting of funds to change their image and efficiency (Expo 2015 is seen as an opportunity to make Milan a smart city)

Air quality sensing interest is high, participatory sensing is increasing especially in the last 2-5 years (air quality projects like AirCasting, Air Quality Eggs, CamMobSens are flourishing, and being featured in scientific journals and wide spread magazines and newpapers).

EPA and Weather services are interested at local data and are including users data for forecasting (www.wunderground.com, a cwordsourced-based weather map, recently became part of The Weather Channel Companies).

Meteorology and urban climatology scientific research are struggling understanding UHI phenomena and the superficial energy balance with little data at local level, and are interested in quality real-time fine-grained data (factors: radiation, sensible heat, latent heat, anthropogenic heat).

STATUS (from PhD research)

Data for the platform is being implemented for the case of Milan city: indicators were previously selected based on the international urban energy balance models comparison project (Grimmond et al., 2010), and calculated and visualized for all city areas divided into a number of frames (800x800m) - Elaborations done in MatLab and ArcGIS environment at the Urban Simulation Lab, Politecnico di Milano).

Why Milan? *Milan is a good study case because of its thorough availability of data coming from the valuable municipal geo-database (with detailed info at the building level), the municipal green public database (with info for each tree element), the 3D and digital elevation model. Additionally, it has the highest UHI in Italy and among the highest in EU, and is a good case for studying "climate modification by urban area" being a place which lacks "extraneous effects due to topography", "water bodies", "and the downwind effect" (Oke, 1987).*

However, environmental and weather data from regional EPA comes from only 4 weather stations, and no other local data is available (besides some data coming from an hobbyist association, and university station).

The smart mobile network, as proposes in the next paragraphs, will provide fine-grained real-time data useful for the platform, in order to identify and understand sensitive urban-climatic and environmental problem areas; it will show it's potential and it could be easily replicable for other cities

Potential names: Urban Hot-Spots, Breath-Taking Cities, Climate-scapes, ...
Keywords: urban microclimate, urban model and simulation, climate change, UHI, heatwaves, urban energy balance, mitigation and adaptation, monitoring system, integrated assessment, smart sensor network, mobile sensing, personal and participatory sensing.

CASE STUDY AND TECHNOLOGY REFERENCES

Available techniques to monitor temperature and air quality in cities, are direct and indirect measurements.

<table>
<tr>
<td rowspan="2">Indirect measurements systems
Remote sensing and satellites data, infrared observations, sky observations, are useful to identify thermal urban surface and infer particular matter concentration in the air. However, they cannot replace direct measurements, as there is no fixed relation between surface and air temperature, and between dust estimates and air quality (Sun et al., 2013).</td>
<td colspan="2">Direct measurements systems
Traditional fixed monitoring stations provide high quality data, they are focused more on long-time analyses rather than spatial analysis, being sparse, and high costly. Recent smart networks aim at gathering local real time data but some are not succeeding because of lack of precise goal and usage of the data collected, permission and implementation cost, high maintenance cost, vandalism (Muller et al., 2013) (See Annex 1).
New technologies such as lidars, sodars, and fiber optical temperature measurements provide the opportunity to obtain atmospheric variables in greater spatial detail both horizontally and even more critically vertically. A wide range of new instruments including unmanned aerial vehicles (UAVs) and small self-contained instruments such as motes, HOBOs, and Tinytags have become available. Low cost air sensors are becoming more easily available, and its usage is expected to increase in the near future (such as temperature/humidity sensors in smartphones) (Chen et al, 2012).</td>
</tr>
<tr>
<td>(top-down) Fixed stations network
official networks
EPA monitoring stations (only regional level)
other meteo+environment networks
UScan, Luce, etc. (test campains), Sensor City Assen, Sensing City CristophChruch, Smart City Santander, CitySense Cambdridge, etc.</td>
<td>(bottom-up) Mobile devices as sensor units
personal sensing & participatory sensing
The Copenhagen Wheel, AirCasting, Air Quality Egg, CitiSense, MAQS, SmartCitizen, EveryAware, AirBase, Dylos, Smart Citizen, ... , hobbyits, volunteering associations, www.weathersignal.com, ...</td>
</tr>
</table>

Mobile sensing is certainly the most promising technique, thanks the availability of cheaper sensors and pervasive network systems, with increasing participatory sensing and user-generated content aggregators (EveryAware project Report, 2012). *(see also **Annex 1**)*

Technology for mobile sensors and networks

Different stakeholder such as researchers, hobbyists and companies have tried their approaches on sensor platforms and data management backends for air quality sensing, especially in the last five years. A few working systems available for purchase already exists, provided with different sensors, devices and platforms/architecture:

Sensors units	**Devices**	**Platform/Architecture**
Measurements: - temperature, humidity, pressure, solar radiation - air quality (CO, NO_x, PM_{10}, $PM_{2.5}$, O_3, SO_2, VOC) - other (noise, light) Data quality: - accuracy/precision, response/stabilization time Cost: - low-cost vs high-performance	Technology: - integrated "multi-sensors" devices = sensors + GPS + datalogger + microprocessor + streaming hardware - sensors connected to smartphones (using its GPS, connectivity, microprocessor/App) - sensors inside smartphones (i.e. Galaxy 4S includes STS21 Sensirion) or watches Design ("handheld" size and weight) Power management (life battery) Usability components (shields, ventilation)	Applications - Data management - Processing node - Aggregating - GIS spatial-temporal analysis - Visualization Platform - public/private sensing - integrated/not integrated with other data

Issues and constrains

Mobile air quality sensing carries many issues that extend beyond building a reliable sensor platform and that all need to be addressed in a fully working system. All existing systems seem to have covered deal with only a part of these issues and even ambitious projects like CitiSense have planned to solve many problems but did not include all solutions in their prototype because of the work involved (Sun et al., 2013). *(see **Annex2**)*

Issue and constrain:	**relevant in case of:**
high price	unaffordable for diffuse participatory sensing (more than 300$)
poor data quality	lack of calibration, poor quality sensors (low accuracy, high stabilization time), incorrect usage (lack of shield/ventilation), lack of data harmonization between different sources
lack of specific purpose	only "hobbyists", too many sensors with different purposes (CO, PM10, etc.)
lack of coverage, of coordination	no resolution at local level for portion of city areas (only single spots, although at international level)
poor power management	low battery life (less than 1 day)
bad design	not portable with size and weight (> ... kg, > handheld size)
lack of differentiation of use cases	no difference between indoor/outdoor measurements
complexity of wireless sensor network	issues in the internal platform and underlying operating systems, in the communication protocol stack, in networking services, provisioning, and deployment
bad connectivity	lack of ad-hoc network connections or self-healing mechanism
lack of privacy and security	no explicit privacy policy (possible unpredicted use of data for commercial purposes), no possibility for aggregating data
lack of integration/harmonization with other data	no calibration/confrontation with data coming from monitoring stations, no integration among different systems
lack of data sharing	no involvement of city managements, EPA and other stakeholders (and careless of potential impact on housing market, insurance sector)

IDEA and INNOVATION

The idea is to identify and understand "urban hot-spots" through to collection and monitoring of extreme temperature data at the street level, integrating other environmental data, through a mobile participatory Smart real-time sensor network (using mainly, but not only, sensors on bike sharing systems: *see below*).
The novelty consist in being the first working and useful network for urban climate mapping, and being a smart network that combines data coming from different sources (including official measurements stations for reference data ad calibration) with a single but open data management backend (heterogeneous mixture of sensor platforms will form a coherent map). The specific purpose, identifying urban hot spot collecting wide data ad local level, keeps the project focused in solving all the issues and constraints (experienced in other ambitious but failed project) with low compromise. It will put the base for environmental (personal and participatory) sensing, creating a local sensing community. Additionally, the smart information platform thus created will be a novel platform for interdisciplinary communication and collaboration between meteorologist and climatology, the environmental community and the urban planning decision makers.
Official monitoring systems and data exist, but the project will provide higher spatial and temporal resolution that could improve modeling and predictive analysis via big data analysis, only experienced in limited (in time and space) field campaign tests.

It will be the first real-time climate mapping (i.e. for a city like Milan), and the first smart public data network integrated with the bike sharing data, a system that promotes a green and smart image of a city, and is increasing worldwide in usage, thanks also to recent bike-oriented mobility policies.

The project will use mobile sensor devices: though low-cost air quality sensing network is not a novelty, only recent technologies and studies demonstrates that they are now feasible and quite reliable for widespread use of monitoring at ambient levels, complementing other measurements technologies, and are now rapidly emerging as a feasible measurement technique for inclusion in air quality monitoring and regulation, source attribution and humane exposure studies. (Mead at al. 2013)
An example of device that could be used in the project is the new EcoPM by Sensaris, to be released in Jan-Feb 2014 (featured with PM, humidity and temperature sensors), and it will be provide new precise measurements in respect to previous experiments.

A specific designed App available to the public, will let citizens participate to the network and show data in augmented reality. The innovative App can also be useful for citizens and tourist in suggesting most comfortable areas and routes (i.e. highlighting green areas, shaded areas, better microclimate pedestrian/biking streets, etc.).
A dedicated server and a web-based platform will display urban visualization with real-time data after a process of harmonization and calibration of data coming from different sources (mobile devices from bike sharing, mobile devices from citizens, EPA stations, university monitoring station, volunteer association station, etc.).
In addiction, a GIS-based Model will elaborate, mesh, and render the processed real-time data with the indicators coming from the urban data already calculated; morphology (temperature (T) and sky view factor), land use (T and green areas), buildings density (T and heat storage), anthropogenic waste heat (T and mobility, T and energy consumption and cooling cost estimation).

Data visualization will identify "Climate-scapes", will underline sensitive urban-climatic and environmental problem areas ("Hot-spots" or "Breath-Taking" maps), and will let build a "UHI map" (difference urban-rural), a "Heat stress map" (extreme heat), and a "Heat risk map" (overlapping T data to people exposure, GIS based, data about elderly). Reliable air pollution data, will let build a "Air quality map".
Data analysis and PET (Physiological Equivalent Temperature) calculation, could bring to new insight about the Heat vulnerability (HWV, Heat Wave Vulnerability index).
Additional potential availability of mobile cellular data, could let building 2 differentiated maps (day/night), which represents different situations: extreme day heat at urban center coinciding with the time when most people (resident and commuters) are present in the city center areas, will probably exactly correspond to the previously identified urban hot-spots (while at night both temperature and people exposure decrease in central city areas).
A further potential analysis could be the integrated study of "extreme heat" vs "air pollution increase" map (i.e. ozone), comparing different temporal data (before and after heatwaves).

A specific innovative climate platform would for the first time collect the interest of citizens, businesses, media, politicians, NGOs, as already proven by existing but partial projects (i.e. weathersignal.com)

A city (like Milan) could profit from this project, even if only implemented as a demo pilot version during summer, and could for the first time advocate being a smart, sentient, resilient, adaptive, "senseable", responsive city.

PROJECT MAIN FEATURE : Sensors devices on bike sharing system (case of Milan City)

why on Bike sharing?

- *promotes a "green" image of a city (together with traditional bike and car-free mobility) and a "smart" image of a city*
- *deliver fine-grain data coverage: bikes move around covering high resolution; Milan has 5000 average users a day (24000 frequent users), and more than 3400 bikes and 190 active stations (being the the 12th biggest bike sharing system in the world, and the 5th in EU)*
- *is successful and suitable for participatory sensing and mobile sensing: given its diffusion, its public utilization, its mobile nature*
- *is a mobile system appropriate for mobile sensing: proper ventilation through the sensor device provides more reliable data compared to fixed devices*
- *is a smart system: real-time bike usage is monitored at bike stations and a web-platform shows real-time availability*
- *is increasing worldwide: in Milan there is an ongoing expansion development project for 1000 new electric bikes and 100 new stations ready for EXPO 2015*

1. TECHNOLOGY: devices and platform

Sensors devices are already mentioned in a previous paragraph and in Annex_1 and Annex_2.
For the purpose of this study, there are two alternative options:

using commercial available "assembled" devices	**building ah-hoc DIY devices**
- i.e. Sensaris EcoPM and SensePods (to be installed to the bike front)	- i.e. Sensirion SHT21+arduino+streaming

The first solution is preferable, coming with acceptable precision (at least for temperature and humidity data - a preliminary comparison test has to be done), usability (unit sensors are shielded in a box, ventilation is ensured by biking movements), affordable cost, and energy requirements (ideally the device will not gather GPS data, therefore saving battery life - new electric bikes could implement direct battery charging). Recent devices, such as the ones from Sensirion, should provide reliable data for air quality parameters (i.e. EcoPM)
All devices will need accurate calibration before deployment, and during systematic maintenance (together with battery charging on-site or at maintenance site). DIY have shown more issues compared to the commercial devices (cost, reliability, stability - See **Annex 1**)



An additional important characteristic will be the calibration done with official EPA monitoring stations data, to be done directly while devices pass by, or done at the server data management level.
The selected devices will come in a labeled SCL "box" and will be installed to selected bikes (for public usage with an smartphone App), and will be additionally provided to selected "superusers" (such as urban climatologist and hobbyist). The demo version will last 3/4 months.
It could be possible to use the server and web-based platform (and App) from the device company if available (i.e. SensDot by sensirion). However, its is necessary to create an ad-hoc system (at SCL), integrated or substitutive of the company one, in order to implement data form other stations (EPA, university, association) and to visualize data in an advanced style (including real-time video).

2. NETWORKING the sensor devices

There are three main options to network the devices and gather their air measurements:

using smartphones network	**using bike-sharing poles network**	**creating ad-hoc cellular network**
- devices connected via Bluetooth, and designed App - data streaming to the server	- data is accumulated during the bike journey and transmitted to the poles at the end of the day - the poles stream data to the server via existing infrastructure (*feasibility to be verified)*	**-** ad-hoc devices with ad-hoc hardware (modem) or adding a cellular unit to commercial devices

The first solution is preferable, it allows <u>active</u> participatory sensing: users have to download the App and connect via Bluetooth the device before starting the bike journey (being therefore aware of their spatial data tracking). Second option should be verified in feasibility, and the third one implies high infrastructure cost not suitable at least for the pilot version of the project (though the DIY would potentially lead to a wider spread of the system usage - *See **Annex2***).

Additionally, the same device and App can be used by single citizens in their private bikes, or just waking around outdoor (they will be the "superusers" for the demo launch of the project; specifications will be provided for proper usage). Same system could be delivered and used (borrowed) by visitors at reception desks of public events (i.e. Expo 2015 in Milan)

3. DEPLOYMENT of the sensors

After selecting the best device, for the purpose of "demonstration", a small number of devices and can be mounted on bikes (i.e. 10) and provided to users (i.e. 10), still covering a significant part of city area. Future collaboration and funding will implement a full and stable smart sensor network:

test field campaign	**(potential) future full and stable implementation**
- testing different commercial available devices, and eventually building one, in a field campaign - selecting the "best" device, design a proper labeled sensor "box" - install the sensor boxes in selected bikes, and run a small test **developing the server/platform and the App** - developing the server, the platform, the App **enhancing a specific promotion campaign** **launch the demo and deploy the pilot prototypes** - mounting the sensor boxes on selected bikes, providing devices to selected users - data management: collecting data, integration and calibration with other monitoring station data (EPA, university, hobbyist) - data analysis, visualizations, scientific and media dissemination of results	- thanks to the expected success of the pilot prototypes, a collaboration with stakeholders (Sensor company, municipality, etc.) and possibly with EXPO funds, will establish a permanent smart network *(to be further investigated)*

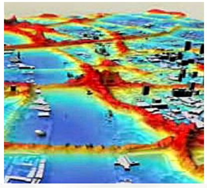
Notes:

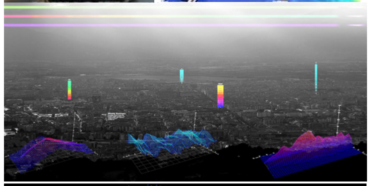
<u>Potential challenges</u> - need for active participation of the Municipality and its Agencies - lack of coverage in some less busy areas - data reliably in case of lack of sensors maintenance or calibration - integration of environmental data (PM or air gases) might be challenging because of harder and more delicate calibration in respect to temperature	<u>Alternative to bike sharing</u> (in case bikesharing is not feasible) Installing sensors on other public infrastructures - light poles: potential collaboration with A2A (ongoing project on replacing Milan light poles with smart LED by 2015 (EXPO) - public vehicles: car sharing, cars (taxi, police, ...), bikes (postmen), buses and bus stops, working people (postman, etc.) - *...(to be further explored)*

4. OUTCOME

Outcome for citizens and tourists

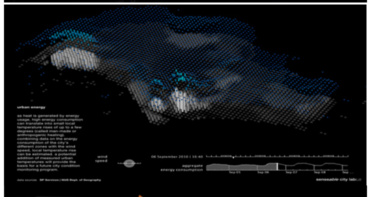
- App showing data in augmented reality (informative) useful for citizens and tourist in suggesting most climate-comfortable areas and routes (i.e. highlighting green areas, shaded areas, better microclimate pedestrian/biking streets, etc.).
- active public participatory sensing, excitement especially among hobbyist ("meteo-philist")
- same outcomes with potential integration of reliable air quality data (i.e. visualization of PM or air gases concentration)

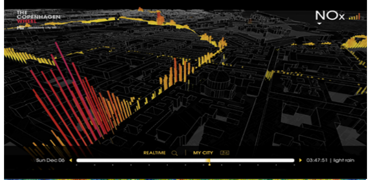




Media outcome

- website implementation with powerful visualizations *(see below)*
- magazine and newspaper article press about the project and other outcomes *(see below)*





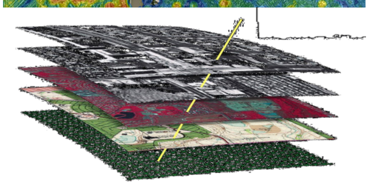
Other outcomes

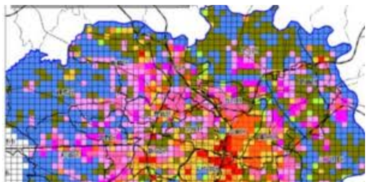
- for the city: the project will show the potential to identify real-time urban hotspots, therefore actively implementing solutions and policies to address the problem
- weather services will understand the potential to take part to the full project or buy the data for better weather forecasting
- city and Expo will benefit of the smart image of the city, and would likely implement the full network
- with the potential integration of reliable environmental data, interest from EPA and many NGO's will increase

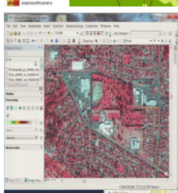
Visualizations: *"Breath-Taking Maps"*

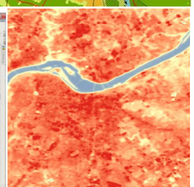
- UHI map: will show the highest difference in temperature between the areas, also urban-rural (around sunset)
- Heat stress map: will show the highest temperature at the extreme heat (around midday)
- video with a real-time combination of the two above: will show the difference overtime and "heat trapping" inside city center
- several maps with overlapping of UHI and:
  - morphology (sky view factor): will show contribution of urban design in trapping solar radiation (GIS data is available)
  - land use: will show contribution of green areas and water (GIS data is available)
  - buildings density: will show the contribution of buildings mass (compactness vs density) (GIS data is available)
  - anthropogenic waste heat (mobility/energy): will potentially show the contribution of mobility and waste from air conditioning to UHI (as a cause), (both GIS data is available)
  - cost from energy consumption: will potentially show higher energy consumption for cooling in hotspots
- *"Climate-scapes"* maps: a map with climatopes, the basic spatial unit for presenting areas with similar climatic conditions and features

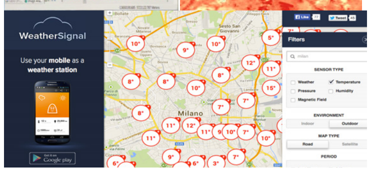
  Heat risk map: will show exposure with overlap of temperature with elderly residents (GIS data is available), based on the thermal loads index PET (Physiological Equivalent Temperature, an indicator used also for evaluating impacts of climate change on thermal comfort of humans) (potential) Heat risk video: will show "exposure" with overlap to "where the people are" (mobilephones tracking data needed) with day/night difference (showing the most heat affecting the highest amount of citizens and commuteters during the day)
- air quality map (i.e. PM10, PM2.5, if data is reliable)
- (potential) "Extreme heat & air pollution increase" map: overlapping ozone data and temperature data will potentially show the direct link between them











- visualization showing the platform and the potential integration with social data: mapping HotSpots and data from twitter about extreme heat/discomfort, or data coming from crowd-sourced services (weathersignal)

Scientific outcome: contribution to ongoing research

- general paper about the project
- paper about urban UHI and energy balance in Milan
- paper about heat exposure and risk index (evaluation of the Heat Wave Vulnerability)
- paper about other potential findings in air quality

Target journals

- Environment and Planning: B, International journal of climatology, Urban climate, Land use policy, Cities, Sensors, Weather and climate extremes, Sustainable cities and society

REFERENCES

See bibliography included in Annex1, Annex2

LIST OF MAIN POSSIBLE ACTORS

Senseable City Laboratory - MIT *senseable.mit.edu* project leading and management collaboration: server/platform, App, data visualization, data analysis		

Urban Simulation Laboratory, Politecnico di Milano *www.labsimurb.polimi.it*		AMAT, Mobility-Environment-Territory Agency of Milan *www.amat-mi.it*	
Campus Sostenibile: Politecnico di Milano and Università degli Studi di Milano *www.campus-sostenibile.polimi.it*		ATM, public Transport Company of Milan *www.atm.it*	
Clear Channel (Bike sharing operator) *www.clearchannel.com*		Municipality of Milan *www.comune.milano.it*	
Regional Environmental Protection Agency ARPA Lombardia www.arpalombardia.it		EXPO, Universal Exposition of 2015 in Milan *www.expo2015.org*	
Sensaris *www.sensaris.com*		A2A utilities company of Milan *www.a2a.eu*	
Citizens, Tourists, Expo visitors, NGO Associations, Funding opportunities (i.e. CARIPLO Foundation), other Sensors companies			

ROADMAP *(indicative)*

(planning further steps and) contacting selected stakeholders — month 1
- shared interest, need for cooperation with (Municipality, Clear Channel, EPA, EXPO) and authorization in using bikes from bikesharing

selecting the best sensor device — month 1
- testing different commercial available devices, and eventually building one, in a specific short field campaign (riding a bike and waking, in Cambridge)
- contacting sensor companies for buying or borrowing the devices (i.e. EcoPM Sensaris)

designing the sensor box — month 1
- designing a SenseableCityLab labeled sensor box (and 3D printing)

running a 'test' field campaign — month 2
- trying the devices functionality (i.e. 10) in bikes for specific time (i.e. 2 weeks, in Cambridge)

refining the project — month 3
- data analysis from the test campaign, solving eventual issues (design, calibration, power management)

developing the project components — month 3-4
- developing the server, the platform
- developing the App
- finalize the SCL labeled sensor box (3D printing 20 boxes)

launching the DEMO with pilot prototypes — month 5
- final launch as a Demo with the sensor boxes in selected bikes (i.e. 10, in proximity of EPA stations, AreaC city center, Campus sostenibile Città Studi, where some sensors exist for calibrations), covering different land use and urban texture and a urban-suburban-rural 'transect'
- providing boxes to selected volunteers/superusers (i.e. 10 from NGOs, university, etc.)
- media campaign

visualizations of data — month 5
- Breath-Taking maps: UHI map, Heat stress map, heatmaps with combination of data from the GIS Model (UHI and green areas, UHI and cars, UHI and building mass, UHI and sky view factor, etc.)
- Climate-scapes map, Air quality map
- Heat risk map, exposure map (day-night change in temperature and also in people in city center)
- videos with maps in timeline
- visualization of the senseable city:, sentient, adaptive/resilient, responsive

dissemination of results: media and scientific publication — month 6
- articles for media, paper(s) for selected journals

ACKNOWLEDGMENTS

I would like to express my special appreciation and thanks to my supervisor Eugenio Morello, for encouraging my research and for allowing me to grow as a research scientist, also for believing in my ideas and suggesting the visiting period at MIT. Working at the Urban Simulation Laboratory under his supervision, also within the SENSE UHI project, helped me define my goals and explore useful models and tools for my work. His support was invaluable and unwavering throughout my entire PhD experience, and without his continuous support this work would not have been possible.
Additionally, I want to thank the Lab members, Laura Cibien, Barbara Piga, Valerio Signorelli and Mattia Rudini for the fruitful exchange of ideas during my years at Politecnico di Milan.
I need to thank my tutor Angela Poletti, whose acute comments and effective advice helped me tremendously during the PhD years, in particular in helping me organize and edit my ideas, and especially in increasing my critical perspective during the thesis-writing process and the presentation of results.
I would also like to thank the PhD professors' board, and the coordinator Rossella Salerno, for the comments and suggestions received during the semesters reviews.

My visiting period at MIT lent a tremendous boost to my research, and I have to thank Carlo Ratti and Rex Britter for letting me be a part of a world-leading research group, and for the opportunity to work on case studies for my research. This thesis clearly owes so much to Rex Britter's guidance and mentorship during my eight months at Senseable City Laboratory. Under his supervision, I was able to test sensors and work on air sensing projects that contributed to the development of my research, being able to better explore local air pollution, and the impact on health, despite the uncountable issues coming from the sensors. More than anything, the countless afternoon chats spent together were invaluable to me in sharpening my critical lense and giving focus to my work, such as the invaluable supervision to the analysis later included in chapter 5.
Additionally, I also want to thank the Lab members, Tracey Li, Sebastian Grauwin and Luis Carli in particular, for their help in teaching me how to better analyze and visualize the sensors (big) data gathered for my research.

I need to espress a special thanks to Rosanna Zavattini, Monica Marchi, and Alessandro Di Stefano from the Environmental Department of Regione Emilia Romagna, for the support given to my research, and also for helping me to explore and better understand air quality plans and policies.

A final thank to my family and friends for their support during the PhD years. In particular to Guido Minucci, Aloke Sengupta and Linda Cossa for growing together through the "stalemate" moments and helping each through the constant research challenges, to Francesco Cattani for his thoughtful efforts to keep me sane and motivated. A special thanks to Raymond Fiore who supported me through the writing process, and always pushed me to be ambitious and to strive towards my goals, believing in me since the beginning of the PhD journey.

Aldo Treville