Politecnico di Milano
Polo Territoriale di Como
A.A 2012-2013

Scuola di Ingegneria Civile, Ambientale e Territoriale
Master of Science in Environmental and Geomatic Engineering

The Impact of Atmospheric Particulate Matter Pollution on Visibility

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The Impact of Atmospheric Particulate Matter Pollution on Visibility

By

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Thesis

Presented to the School of Civil and Environmental Engineering

of

Politecnico di Milano

In partial fulfillment of the requirements for the degree of

Environmental and Geomatic Engineering

POLITECNICO DI MILANO

July 2013

In the Name of the Almighty Allah, the most Gracious, the most Merciful

Dedicated to

My adoring Parents

Md Zainal Abedin & Zulekha Khanam &

Dr Nusrat Islam (Shuvra)
My Heartiest gratitude for your love and inspiration &

endless supports and prayers. And for being my side always…

Acknowledgement

First and foremost I would like to take the opportunity to express my eternal gratitude to the almighty Allah for blessing which made it possible to work out the thesis.

I would like to express my sincere appreciation to my supervisor **Prof. Giovanni Lonati**, whose generous guidance and precious advice, adroit supervision always kept my thoughts towards an appropriate focus. His involvement with his originality has triggered and nourished my intellectual maturity.

I am grateful to all the **POLIMI teachers** for their precious knowledge. I would also thank to all my colleagues, friends and well wisher for their warm friendship and memorable time in Italy.

I owe to my wonderful **parents** for their everlasting love, affection, encouragement and support throughout my life.

Bottom line is that this thesis work is for very special person Dr Nusrat Islam (Shuvra) who always inspired me with her intuition, encouragement, cooperation and sympathy.

Abstract

The Impact of Atmospheric Particulate Matter Pollution on Visibility

Md Masroor Abedin, degree sought M.Sc in Environmental and Geomatic Engineering

Politecnico di Milano, 2013

Supervisor: Prof Ing. Giovanni Lonati

This paper describes overall visibility impairment situation of Milan city by atmospheric particulate matter pollution and its chemical composition during the time duration from August'02 to December'03.

Visibility impairment is a basic form of air pollution that people can see and recognize without special instruments. Visibility impairment is a major atmospheric pollution problem in many mega cities around the world. The impact of air pollution by anthropogenic sources on human health and visibility has been studied for decades. Many analyses have been conducted worldwide not only to estimate the health benefits from air pollution abatement but also to identify scientific and technical understanding of how the air pollutants impair visibility. It is known that visibility impairment can result directly or indirectly from particle emission and is dominated by fine particulate matter (PM).

Air pollutants can be roughly divided into two classes: gases and particles. Particles are composed of liquids or solids and are collectively referred to as particulate matter (PM). Most gaseous pollutants are invisible to the human eye including ozone, sulfur dioxide, and carbon dioxide. The individual particles in PM are so small that they are invisible (or nearly invisible) to the human eye but collectively they create haze. The visibility effects of haze are similar to the effects of fog; the main distinctions being that smog particles are smaller and are composed primarily of air pollutants not water. Examples of PM include diesel exhaust from motor vehicles, smoke from chimneys, and sulfuric acid droplets formed in the atmosphere. Although the PM from individual sources seems to disappear as it disperses in the atmosphere, it does not – it is merely diluted. In the process, the distinct plumes from individual sources merge into a featureless, uniform haze. PM can persist in the atmosphere for several days or weeks and be transported thousands of miles, affecting visibility locally, regionally, and globally.

Particle pollution (also called particulate matter or PM) is the term for a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope. Particle pollution includes "inhalable coarse particles," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "fine particles," with diameters that are 2.5 micrometers and smaller.

The chemical compositions stated are based on results collected in studies in most parts of the United States. The results indicate that sulphate, ammonium, hydrogen ions, elemental carbon, primary and secondary organic compounds from cooking and combustion, as well as certain transition metals are predominantly found in the fine particle mode, while crustal materials such as calcium, aluminium, silicon, magnesium, and iron are mostly discovered in coarse particles. Also found in the coarse mode are primary organic materials such as pollen, spores, and plant and animal debris. Furthermore, nitrate and potassium are found in both the fine and the coarse modes as their sources and mechanisms of formation may vary.

Traditionally, visibility has been defined by meteorologists as the visual range defined as the furthest distance at which a black object can be distinguished against the horizon sky (EPA, 1979). As a consequence, visibility can only be quantified for a sight path and depends on the illumination of the atmosphere and the direction of view. When determining it as a quantity, the concentration of particles in the atmosphere plays a key role. Particles and gases in the atmosphere attenuate light on its way from an object to the observer.

Visual range is the distance at which a given object can be seen with the unaided eye. The deciview scale is zero for pristine conditions and increases as visibility degrades. Each deciview change represents a perceptible change in visual air quality to the average person. Generally, a one deciview change in the haze index is likely perceptible by a person regardless of background visibility conditions.

Table of Contents

List of Figures

List of Tables:

1.0   Introduction

1.1   Background:

In recent years, the health and environmental effects of particulate matter air pollution have been the subject of much research and discussion by scientific and policy professionals in the air quality community. Significant regulatory programs are under way to address these effects and are expected to result in decreasing ambient particulate matter concentrations (PM) and improved visibility over time. Implementation of the acid rain program is expected to reduce annual sulfur oxide emissions by more than 10 million tons (from 1980 levels) by 2010. In July 1997, the Environmental Protection Agency (EPA) promulgated new primary and secondary national ambient air quality standards for PM2.5 (particulate matter less than 2.5 μm) and EPA proposed a national program to reduce regional haze visibility impairment in more than 150 Class I areas across the country. Implementation of these programs over the coming years will require additional technical assessment and strategy development. Monitoring of particulate matter concentrations, visibility levels, and analysis of trends over time are critical activities needed to develop and evaluate strategies to reduce acid rain, attain national health standards, and make reasonable progress in reducing visibility impairment. Impairment of visibility by atmospheric haze is an environmental problem that can significantly impact the 'quality of life' in many regions. Although improvement of impaired visibility and preservation of pristine visibility are desirable goals, significant reductions of relevant precursor emission are not, as a rule, cost-free. Thus, evaluation of the effectiveness of various control options in improving visibility is vital.

Too often we neglect to take note of our surroundings, but consciously or unconsciously, they affect us. Life keeps most of us focused intently on the modern, constructed world. The majority of our lives are spent indoors, and many people are more familiar with the atmosphere of their office than their neighborhood. While most of us are distracted from it ''there is not a moment of any day of our lives, when nature is not producing scene after scene, picture after picture, glory after glory'' (Ruskin, 1906). When we take the time to experience nature, it can be harrowing and exhilarating, but even when we do not take the time, there is comfort in knowing that these events are occurring. We are often most aware of our surroundings when we are on vacation - when we have the time to relax and enjoy the scenery. Vacations offer an escape from the routine and stress of our daily lives. Vacation destinations are often chosen based on their scenery; vacations are spent gazing at monuments, mountains, clouds, and oceans. Good visibility allows clear observation of distant features and appreciation of the inherent beauty of these scenes. Scenic

photographs displayed in books, pamphlets, and advertisements depict the clearest atmospheric conditions and can set high expectations for the visitor. Artists and photographers are acutely aware of the importance of color contrast, saturation, and brightness. Air pollution, which is often present in both our cities and parks, interferes with these attributes and can ruin the views vacationers travel to enjoy. Visibility refers to the clarity or transparency of the atmosphere and the associated ability to see distant objects. The terms haze and smog describe the effects of air pollution on visibility. Haze is defined as ''an aggregation in the atmosphere of very fine, widely dispersed, solid or liquid particles, or both, giving the air an opalescent appearance that subdues colors'' (''Haze'', 2008). The opalescent appearance refers to the loss of contrast in a scene, which means a loss of ability to distinguish physical features, depth, and texture. Viewing distant landmarks offers the most straightforward measure of visual air quality. The visual range, or longest distance at which landmarks are visible, varies widely depending on the humidity and concentration of particles in the air. On clear days in remote areas of the world, visual range can be over 300 km in dry climates and over 100 km in humid climates; on the haziest days, visual range can be less than a few km in any climate. Not every location provides landmarks needed to gauge visibility; sky color is an indicator of visual air quality that is accessible in flat terrain with no prominent landmarks and in natural or urban canyons where long-distance vistas are blocked. On a clear day, when particle concentrations are low, the sky is a deep azure color. Particles scatter sunlight which dilutes colors; therefore, on a hazy day, when particle concentrations are high, the sky appears light blue, white, or gray, depending on the concentration. The eyes can be calibrated by comparing the sky color before and after a rainstorm following a dry period. Once attuned to the differences, the eyes are effective instruments for assessing particulate air pollution.

Air pollutants can be roughly divided into two classes: gases and particles. Particles are composed of liquids or solids and are collectively referred to as particulate matter (PM). Most gaseous pollutants are invisible to the human eye including ozone, sulfur dioxide, and carbon dioxide. The individual particles in PM are so small that they are invisible (or nearly invisible) to the human eye but collectively they create haze. The visibility effects of haze are similar to the effects of fog; the main distinctions being that smog particles are smaller and are composed primarily of air pollutants not water. Examples of PM include diesel exhaust from motor vehicles, smoke from chimneys, and sulfuric acid droplets formed in the atmosphere. Although the PM from individual sources seems to disappear as it disperses in the atmosphere, it does not – it is merely diluted. In the process, the distinct plumes from individual sources merge into a featureless, uniform haze. PM can persist in the atmosphere

for several days or weeks and be transported thousands of miles, affecting visibility locally, regionally, and globally. Some level of air pollution is inevitable but it must be controlled to limit the aesthetic and health problems it causes. Establishing policies to protect visibility involves a complex mixture of philosophy, psychology, public policy, and science. Psychological research demonstrates that people are emotionally affected by visibility. Public policy research shows that people think it is important to protect visibility and are willing to pay for the protection. The causes of visibility reduction are known and visibility can be measured by several different techniques. Visibility is affected by global, regional, and local pollution sources. PM concentrations are regulated in many parts of the world for health protection but these regulations are lenient in terms of visibility. Visibility conditions have been studied throughout the world, and visibility trends vary by location.

1.2 Particulate Matter

"Particulate matter," also known as particle pollution or PM, is a complex mixture of extremely small particles and liquid droplets. Particle pollution is made up of a number of components, including acids (such as nitrates and sulfates), organic chemicals, metals, and soil or dust particles.

The size of particles is directly linked to their potential for causing health problems. EPA groups particle pollution into two categories:

- "Inhalable coarse particles," such as those found near roadways and dusty industries, are larger than 2.5 micrometers and smaller than 10 micrometers in diameter.

- "Fine particles," such as those found in smoke and haze, are 2.5 micrometers in diameter and smaller. These particles can be directly emitted from sources such as forest fires, or they can form when gases emitted from power plants, industries and automobiles react in the air.

Particle pollution (also called particulate matter or PM) is the term for a mixture of solid particles and liquid droplets found in the air. Some particles, such as dust, dirt, soot, or smoke, are large or dark enough to be seen with the naked eye. Others are so small they can only be detected using an electron microscope. Particle pollution includes "inhalable coarse particles," with diameters larger than 2.5 micrometers and smaller than 10 micrometers and "fine particles," with diameters that are 2.5 micrometers and smaller.

These particles come in many sizes and shapes and can be made up of hundreds of different chemicals. Some particles, known as *primary particles* are emitted directly from a source, such as construction sites, unpaved roads, fields, smokestacks or fires. Others form in complicated reactions in the atmosphere of chemicals such as sulfur dioxides and nitrogen oxides that are emitted from power plants, industries and automobiles. These particles, known as *secondary particles*, make up most of the fine particle pollution in the country. The PM impact has been stated below:

- **Health**: Particle pollution contains microscopic solids or liquid droplets that are so small that they can get deep into the lungs and cause serious health problems. The size of particles is directly linked to their potential for causing health problems. Small particles less than 10 micrometers in diameter pose the greatest problems, because they can get deep into your lungs, and some may even get into your bloodstream.
- **Visibility**: Fine particles (PM$_{2.5}$) are the main cause of reduced visibility (haze) in parts of the United States, including many of treasured national parks and wilderness areas in USA.
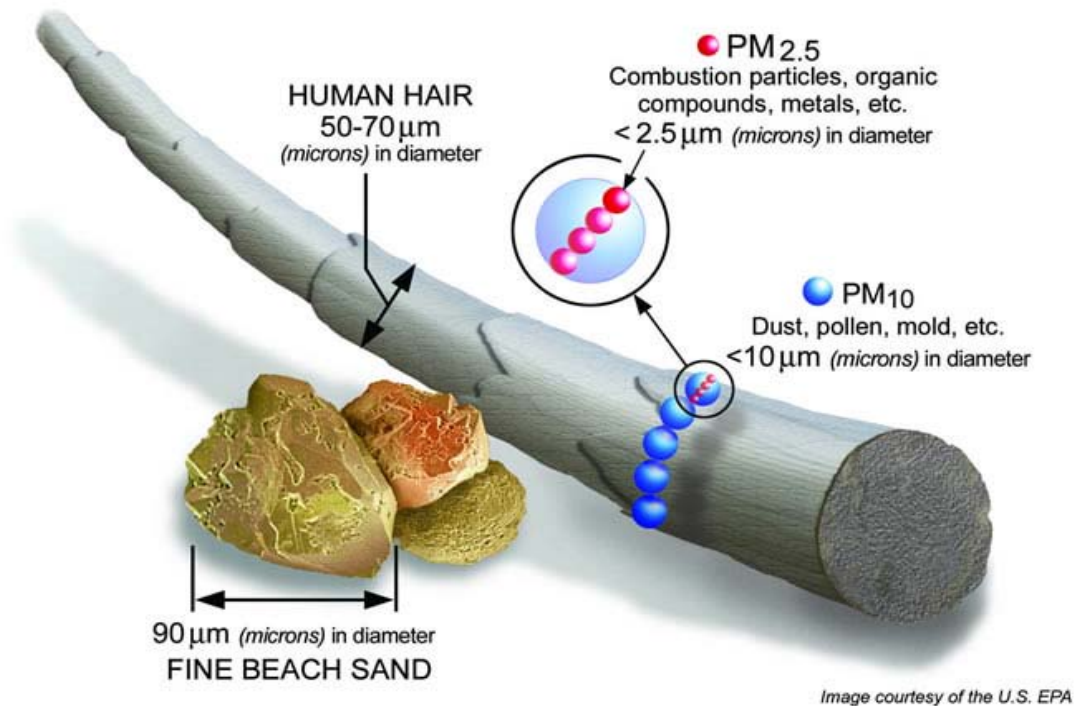
Figure1.1: How big is particle pollution?

1.3 What is Visibility? :

Visibility, as it relates to management of the many visual resources found in national parks, is a complex and difficult concept to define. Should visibility be explained in strictly technical terms that concern themselves with exact measurements of illumination, threshold contrast, and precisely measured distances? Or is visibility more closely allied with value judgments of an observer viewing a scenic vista? Historically, "visibility" has been defined as "the greatest distance at which an observer can just see a black object viewed against the horizon sky." An object is usually referred to as at threshold contrast when the difference between the brightness of the sky and the brightness of the object is reduced to such a degree that an observer can just barely see the object. Much effort has been expended in establishing the threshold contrast for various targets under a variety of illumination and atmospheric conditions. An important result of this work is that threshold contrast for the eye, adapted to daylight, changes very little with background brightness, but it is strongly dependent upon the size of the target and the time spent looking for the target.

Nevertheless, visibility is more than being able to see a black object at a distance for which the contrast reaches a threshold value. Coming upon a mountain such as one of those shown in Figures Ia and Ib, an observer does not ask, "How far do I have to back away before the vista disappears?" Rather, the observer will comment on the color of the mountain, on whether geological features can be seen and appreciated, or on the amount of snow cover resulting from a recent storm system. Approaching landscape features such as those shown in Figures Ic and Id, the observer may comment on the contrast detail of nearby geological structures or on shadows cast by overhead clouds.

Visibility is more closely associated with conditions that allow appreciation of the inherent beauty of landscape features. It is important to recognize and appreciate the form, contrast detail, and color of near and distant features. Because visibility includes psychophysical processes and concurrent value judgments of visual impacts, as well as the physical interaction of light with particles in the atmosphere, it is of interest to understand the psychological process involved in viewing a scenic resource, the value that an observer places on visibility, and to be able to establish a link between the physical and psychological processes.

Whether we define visibility in terms of visual range or in terms of some parameter more closely related to how visitors perceive a visual resource, the preservation or improvement

of visibility requires an understanding of what constituents in the atmosphere impair visibility as well as the origins of those constituents.

Scientists know that introduction of particulate matter and certain gases into the atmosphere interfere with the ability of an observer to see landscape features. Monitoring, modeling, and controlling sources of visibility-reducing particulate matter and gases depend on scientific and technical understanding of how these pollutants interact with light, transform from a gas into particles that impair visibility, and are dispersed across land masses and into local canyons and valleys.

(a) The farthest scenic feature is the 130 km distant Navajo Mountain, as seen from Bryce Canyon National Park.

(b) The La Sal Mountains, as seen from the Colorado River, are a dominant form on the distant horizon.
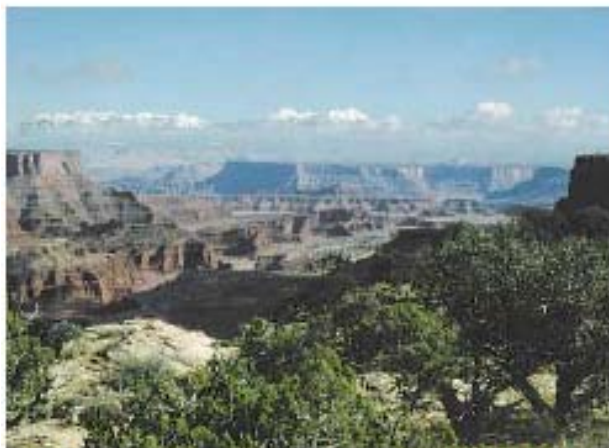
(c) This view in Canyonlands National Park shows the highly textured foreground canyon walls against the backdrop of the La Sal Mountains. The La Sals are 50 km away from the observation.

(d) Bryce Canyon as seen from Sunset Point. Notice the highly textured and brightly colored foreground features.

1.4   What is haze/reduced visibility?

Haze is caused when sunlight encounters tiny pollution particles in the air. Some light is absorbed by particles. Other light is scattered away before it reaches an observer. More pollutants mean more absorption and scattering of light, which reduce the clarity and color of what we see. Some types of particles such as sulfates scatter more light, particularly during humid conditions.

1.5   Where does reduced visibility/haze-forming pollution come from?

Air pollutants come from a variety of natural and manmade sources. Natural sources can include windblown dust, and soot from wildfires. Manmade sources can include motor vehicles, electric utility and industrial fuel burning, and manufacturing operations. Particulate matter pollution is the major cause of reduced visibility (haze) in parts of the United States, including many of our national parks.

Some haze-causing particles are directly emitted to the air. Others are formed when gases emitted to the air form particles as they are carried many miles from the source of the pollutants.

1.6   What else can these pollutants do to you and the environment?

Some of the pollutants which form haze have also been linked to serious health problems and environmental damage. Exposure to very small particles in the air has been linked with increased respiratory illness, decreased lung function, and even premature death. In addition, particles such as nitrates and sulfates contribute to acid rain formation which makes lakes, rivers, and streams unsuitable for many fish, and erodes buildings, historical monuments, and paint on cars.

1.7   Atmospheric PM Effects on Visibility:

Traditionally, visibility has been defined by meteorologists as the visual range defined as the furthest distance at which a black object can be distinguished against the horizon sky (EPA, 1979). As a consequence, visibility can only be quantified for a sight path and depends on the illumination of the atmosphere and the direction of view. When determining it as a quantity, the concentration of particles in the atmosphere plays a key role. Particles and gases in the atmosphere attenuate light on its way from an object to the observer. The fractional attenuation of light per unit distance is termed light extinction coefficient (b) and

expressed in unit 1/distance. It is composed of the sum of light scattering and light absorbing coefficients of particles and gases:

$$b_{ext} = b_{ap} + b_{ag} + b_{sg} + b_{sp} \qquad \text{with p, g (particles, gases)}$$

$$\text{s, a (scattering, absorption)}$$

The light scattering (**Rayleigh scattering** – caused by molecular components of the air, which diameter is much smaller than the wavelength of the incident light) and absorption (mostly NO_2 – absorbs blue - looks yellow, brownish) of gases only dominate the light extinction under pristine atmospheric conditions. Otherwise, it is the particles that have the greatest effect on visibility. The corresponding extinction coefficient can be determined when the particle size, refractive index, and shape of the particles are known.
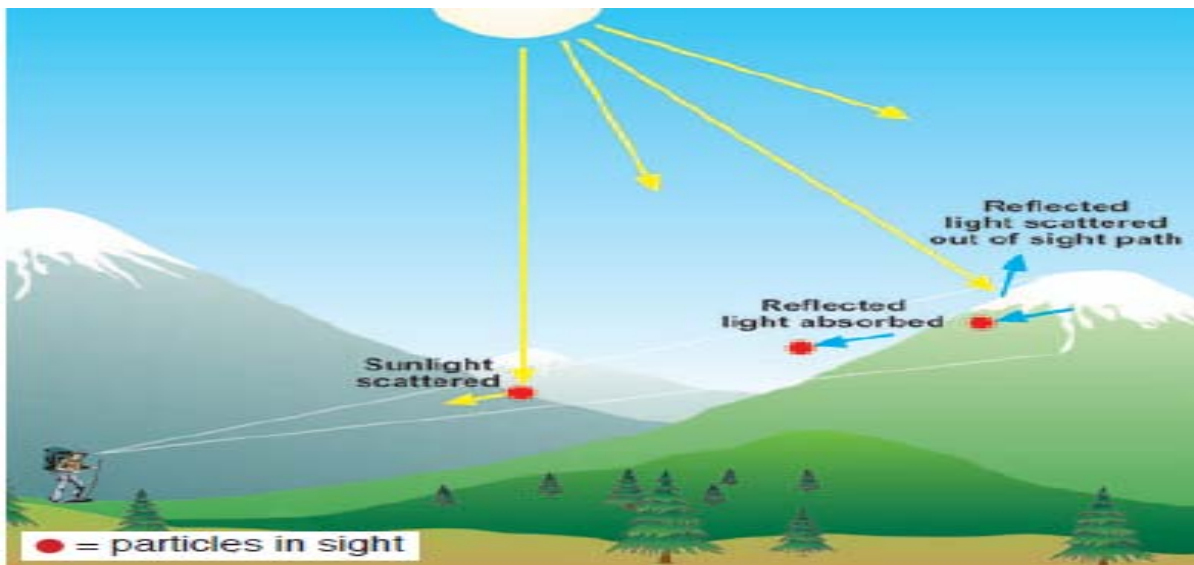
Figure 1.2: Pollution particles in the air absorb or scatter the light so the view is not as clear or as far as it should be.

The whole situation is illustrated in a simple way in figure 1.2. Light absorption by particles is predominantly caused by soot (black carbon) and to a lesser extent by minerals in crustal particles. **Mie scattering** is caused by particles with diameters larger than the wavelength of the light (Quaschning, 1999). The single most important factor determining the amount of light scattered by a particle is its size and the maximum single-particle scattering efficiency (i.e. scattering per cross-sectional area of a particle) is achieved by particles with diameters of about the wavelength of visible light, centered at around 0.53µm. Therefore, the effects of relative humidity on particle size will significantly affect the amount of particle light scattering.

1.8   Chemistry of Atmospheric Particulate Matter

Atmospheric particulate matter can be divided into several **major categories**, such as **nitrates**, **sulfates**, **ammonium**, **hydrogen ions**, **particle-bound water**, **elemental carbon** and **organic compounds**, **crustal material**, **sea salts** (at coastal locations), and a large amount of **elements** in numerous compounds and concentrations.

1.8.1 Chemical Composition

The chemical compositions stated are based on results collected in studies in most parts of the United States. The results indicate that sulfate, ammonium, hydrogen ions, elemental carbon, primary and secondary organic compounds from cooking and combustion, as well as certain transition metals are predominantly found in the fine particle mode, while crustal materials such as calcium, aluminum, silicon, magnesium, and iron are mostly discovered in coarse particles. Also found in the coarse mode are primary organic materials such as pollen, spores, and plant and animal debris. Furthermore, nitrate and potassium are found in both the fine and the coarse modes as their sources and mechanisms of formation may vary.

While potassium in coarse particles originates from soil, the potassium in the fine particle mode comes from burning wood or cooking meat. The nitrate in fine particles is caused by the reaction of gas-phase nitric acid with gas-phase ammonia forming particulate ammonium nitrate. Reactions of gas-phase nitric acid with pre-existing coarse particles lead to nitrate ending up in the coarse mode (EPA, 2004).

1.8.2 Primary and Secondary Particulate Matter

The two major types of particulate matter, defined in section 3.0, not only differ in their pathway of formation but also in their chemical composition. *Primary coarse particles* are usually formed by mechanical processes including windblown dust, sea salt, road dust, and combustion-generated particles such as fly ash and soot. *Primary fine particles* can either be emitted directly as particles or as vapours that quickly condense forming nucleation-mode particles. Included in this category is soot from diesel engines, a large range of organic compounds from incomplete combustion or cooking, and compounds of As, Se, Zn, etc which condense from vapour formed during combustion or smelting.

Condensable vapours generated by chemical reactions of gas-phase precursors are the source of fine secondary particulate matter. Most sulphates and nitrates along with some of the organic compounds in atmospheric particles are formed in these chemical reactions. It

is, however, much more difficult to trace ambient secondary species back to their origins, as the entire formation process depends on numerous factors, such as the concentration of precursors and other gaseous reactive species, e.g. ozone, hydroxyl and peroxy radicals, or hydrogen peroxide, and atmospheric conditions such as solar radiation and relative humidity (EPA, 2004).

1.8.3 Particle-Bound Water (PBW)

Some atmospheric aerosols are in equilibrium between the gas phase and the condensed phase and are therefore called semi-volatile. Examples of this kind are water, ammonium nitrate and certain organic compounds. The equilibrium between water vapour and liquid water in **hygroscopic particles** is the reason why many ambient particles contain particle-bound water. In order not to measure PBW as a part of the particle mass, it has to be removed by drying. PBW has a large impact on the chemistry and physics of the atmospheric particles, such as:

• Particle size and light scattering;

• Aerodynamic properties, which play an important role in dry deposition to surfaces, deposition to airway surfaces during breathing, and deposition in sampling instruments;

• Provides medium for reactions of dissolved gases;

• Acts as carrier for potentially toxic species to the respiratory system.

1.9 Atmospheric Chemistry affecting the visibility:

Particulates and gases in the atmosphere can originate from natural or man-made sources. Table 1.1 includes the terms that are usually used to describe airborne particles; Table 1.2 shows the size range of typical atmospheric aerosols. The ability to see and appreciate a visual resource is limited, in the unpolluted atmosphere, by light scattering of the molecules

that make up the atmosphere. These molecules are primarily nitrogen and oxygen along with some trace gases such as argon and hydrogen. Other forms of natural aerosol that limit our ability to see are condensed water vapor (water droplets), wind-blown dust, and organic aerosols such as pollen and smoke from wild fires.

Aerosols, whether they are man-made or natural, are said to be primary or secondary in nature. Primary refers to gases or particles emitted from a source directly, while secondary refers to airborne dispersions of gases and particles formed by atmospheric reactions of precursor or primary emissions. Examples of primary particles are smoke from forest and prescribed fires, soot from diesels, fly ash from the burning of coal, and windblown dust.

Primary gaseous emissions of concern are sulfur dioxides emitted from coal burning, nitrogen oxides that are the result of any type of combustion such as coal-fired power plants and automobiles, and hydrocarbons, usually associated with automobiles but are also emitted by vegetation, especially conifers.

These gases can be converted into secondary particles through complex chemical reactions. Furthermore, primary gases can combine to form other secondary gases. Atoms and molecules of special interest along with their relative sizes are shown in Figure 1.2. Five atoms, in order of their size, that play significant roles in determining air quality are hydrogen (H), oxygen (O), nitrogen (N), carbon (C), and sulfur (S). Sulfur dioxide (SO_2) is ultimately converted to sulfates, such as ammonium sulfate ($(NH_4)_2SO_4$), nitrogen oxides (NOx) convert to nitrates such as nitric acid or ammonium nitrate (NH_4NO_3), hydrocarbons convert to larger organic or hydrocarbon molecules, and hydrocarbon gases interfere with a naturally occurring cycle between hydrocarbon and NO_2 to yield ozone (O_3).

Table 1.1: *Definitions of terms that describe airborne particulate matter*

Term	Definition
Particulate matter	Any material, except uncombined water, that exists in the solid or liquid state in the atmosphere or gas stream at standard condition.
Aerosol	A dispersion of microscopic solid or liquid particles in gaseous media.
Dust	Solid particles larger than colloidal size capable of temporary suspension in air.
Fly ash	Finely divided particles of ash entrained in flue gas. Particles may contain unburned fuel.
Fog	Visible aerosol.
Fume	Particles formed by condensation, sublimation, or chemical reaction, predominantly smaller than 1 micron (tobacco smoke).
Mist	Dispersion of small liquid droplets of sufficient size to fall from the air.
Particle	Discrete mass of solid or liquid matter.
Smoke	Small gasborne particles resulting from combustion.
Soot	An agglomeration of carbon particles.

The gas-to-particle conversion process takes place by essentially three processes: condensation, nucleation, and coagulation. Condensation involves gaseous vapors condensing on or combining with existing small nuclei, usually called condensation nuclei. Small condensation nuclei may have their origin in sea salts or combustion processes. Gases may also interact and combine with droplets of their own kind and form larger aerosols. This process is called homogeneous nucleation. Heterogeneous nucleation occurs when gases nucleate on particles of a different nature than themselves. Once aerosols are formed, they

can grow in size by a process called coagulation, in which particles essentially bump into each other and "stick" together.

Table 1.2: *Typical size ranges of a number of aerosols commonly found in the atmosphere*
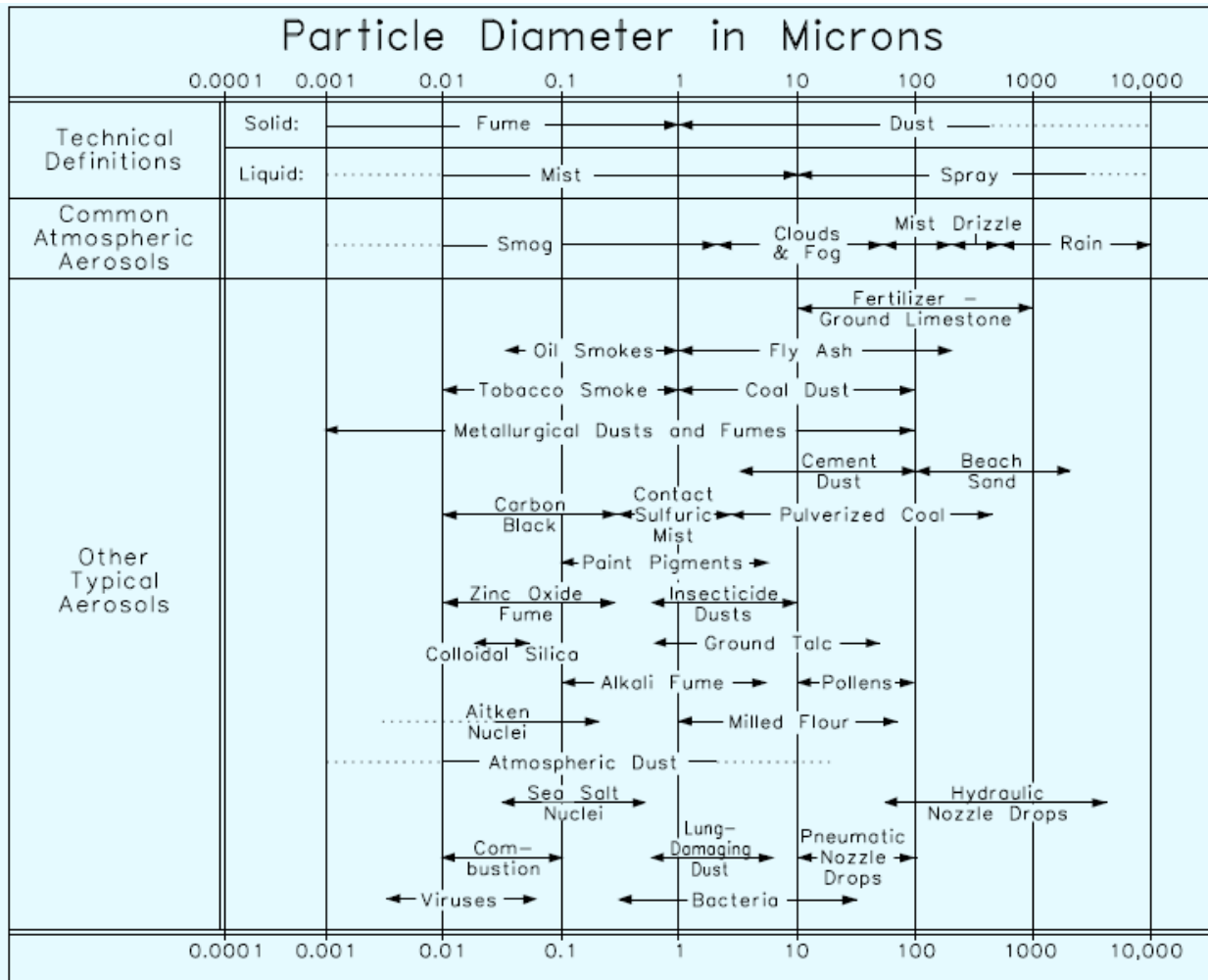
Figure 1.4 schematically shows the conversion of sulfur dioxide to sulfate, the growth of sulfate molecules into sulfate particles and the very important process of water absorption by the sulfate particle. Some inorganic salts, such as ammonium sulfate and nitrate, undergo sudden phase transitions from solid particles to solution droplets when the relative humidity (RH) rises above a threshold level. Thus, under higher RH (>70%) levels, these salts become disproportionately responsible for visibility impairment as compared with other particles that do not uptake water molecules. The size of most secondary particle ranges between 0.1 and 1.0 microns. For reference, the relative size of beach sand, a grain of flour, and a secondary particle is shown in Figure 1.5.
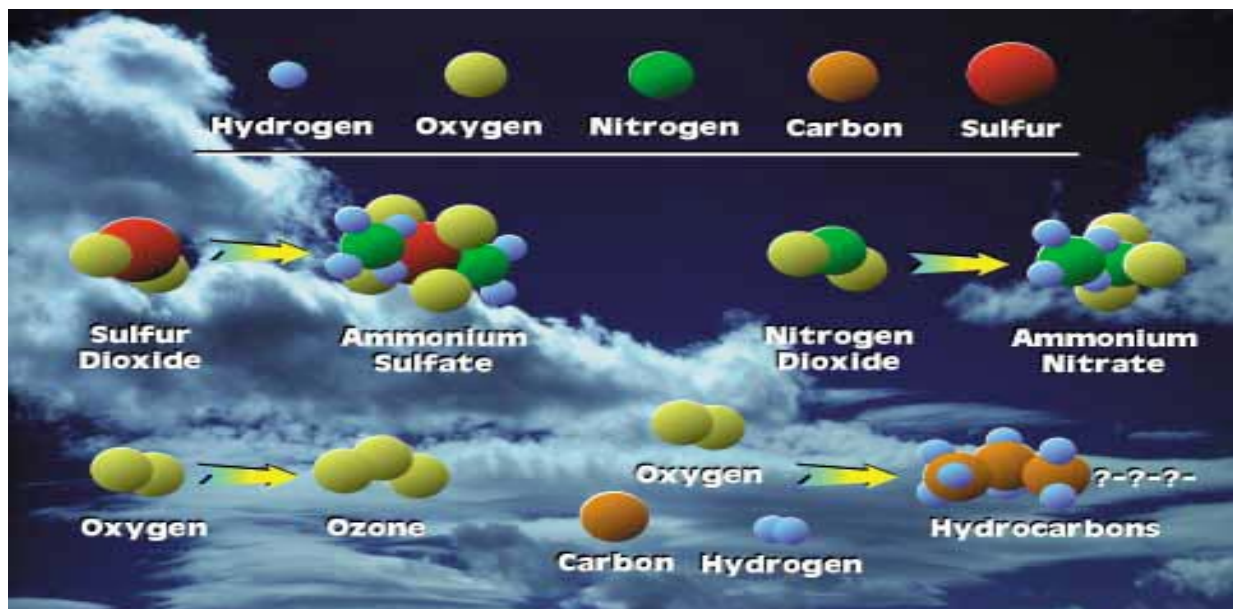
Figure 1.3: *The top row shows five atoms, in order of size, that play a significant role in determining air quality. They are hydrogen, oxygen, nitrogen, carbon, and sulfur. Through complex sets of chemical reactions, gases are formed that, in some cases, react to form visibility reducing particles. Sulfur dioxide reacts to form ammonium sulfate, nitrogen oxide forms ammonium nitrate, oxygen is converted to ozone, and carbon, hydrogen, and oxygen form hydrocarbon particles.*

Figure 1.6 shows a typical mass size distribution for particles found in the atmosphere. Those particles less than about 2.5 microns are usually secondary in nature and are referred to as fine particles. Fine particles tend to be man-made, while particles larger than 2.5 microns, referred to as coarse particles, tend to have a natural origin. It is the fine particles that cause most of the visibility impairment and have the greatest adverse health effects. The formation mechanisms are also schematically shown in figure 1.6. Near a source (within 0-100 km), such as an urban center, power plant, or other industrial facilities, haze is usually a mixture of gases and secondary and primary aerosols. After these pollutants have been transported hundreds of kilometers, gaseous emissions have either deposited to aquatic or terrestrial surfaces or converted to secondary aerosols. Thus, in remote areas of the United States, man-made components of haze are usually composed of secondary particles. However, in some parts of the forested United States, fire emissions can contribute significantly to primary carbon particles.
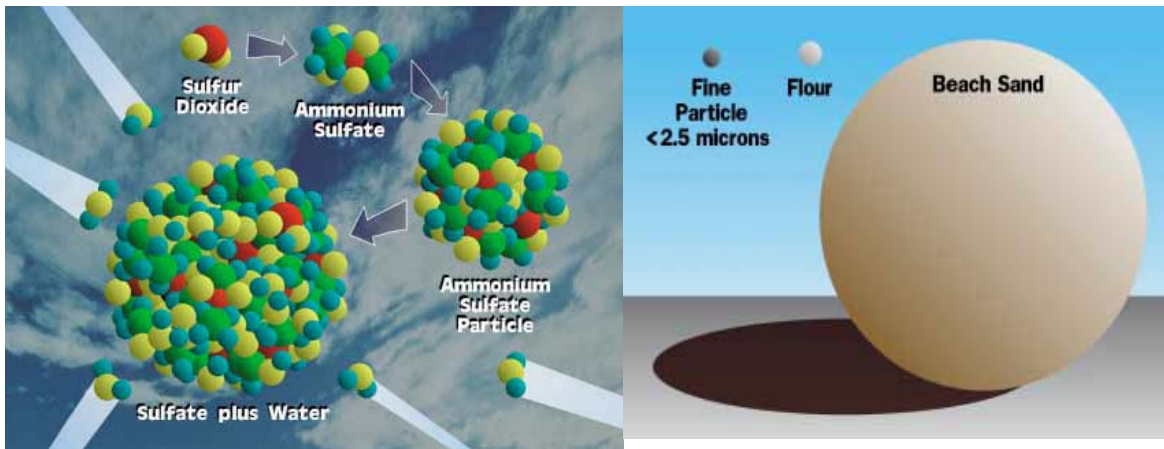
Figure 1.4: *Sulfur dioxide gas converts in the atmosphere to ammonium sulfate particles. These particles are hygroscopic, meaning they grow rapidly in the presence of water to reach a size that is disproportionately responsible for visibility impairment. Figure 1.5: Relative size of beach sand, a grain of flour, and a secondary fine particle.*
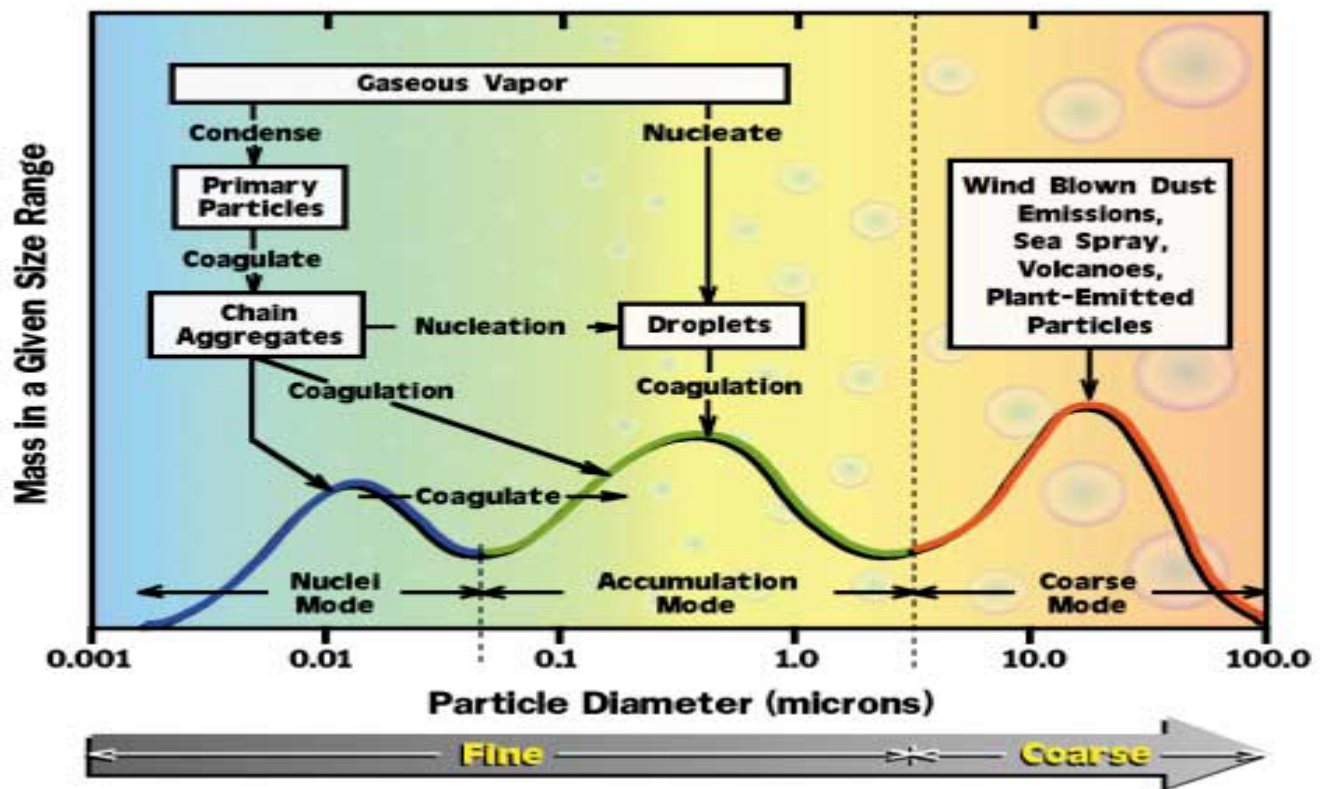
Figure 1.6: *The particles are arranged by their typical mass/size distribution in the atmosphere. Coarse particles tend to have natural origins and deposit out close to the source. Fine particles are usually man-made, can transport great distances, and cause the greatest visibility impairment.*

2.0   Literature Review:

Visibility usually refers to the horizontal distance, at which the contrast between a target and its sky background equals the threshold of the human eye (Koschmieder, 1926). In an unpolluted atmosphere, visibility would be often in the range of 145-225 km (Environmental Protection Agency, 2001). However, at polluted sites, atmospheric visibility could be decreased by air pollutants via light scattering and absorption by fine particles and gases in the atmosphere (Malm et al., 1994, 1996). At some severely polluted sites, the visibility can be even less than 1 km (Husar et al., 1981). Due to the adverse effects of air pollution on human lives, visibility has been a major concern in air pollution studies and climatology (Malm and Kreidenweis, 1997; Yuan et al., 2002; Lee et al., 2005; Che et al., 2007; Deng et al., 2011).

The impact of air pollution by anthropogenic sources on human health and visibility has been studied for decades. Many analyses have been conducted worldwide not only to estimate the health benefits from air pollution abatement but also to identify scientific and technical understanding of how the air pollutants impair visibility (Dzubay et al., 1982; Larson et al., 1988; Johnson et al., 1990; Wilson and Suh, 1997; Kim et al., 2001; Clancy et al., 2002). It is known that visibility impairment can result directly or indirectly from particle emission and is dominated by fine particulate matter (PM). The PM Science Assessment Report (North American Research Strategy for Tropospheric Ozone (NARSTO), 2004) published by the NARSTO suggested that the chemical and physical properties of PM with an aerodynamic diameter less than 2.5 mm have to be better characterized, as they are responsible for adverse health effects linked to chronic respiratory diseases (Dockery and Pope, 1994) and visibility impairment (Malm, 1999).

A multi-year field study, 'Fine Particles and Visibility Impairment in Urban Area' was funded by the Ministry of Environment of Korea in 2003.Changing trend of atmospheric visibility, as well as the influences of air pollution on visibility trend, has attracted worldwide attention, and lots of studies have been carried out to evaluate visibility trends at local, regional, continental, and global scales (Craig and Faulkenberry, 1979; Sloane, 1982a, 1982b; Lee, 1994; Husar et al., 2000; Schichtel et al., 2001; Doyle and Dorling, 2002; Ghim et al., 2005; Tsai, 2005; Park et al., 2006; Mahowald et al., 2007; Tsai et al., 2007; Molnar et al., 2008). In China, visibility condition has also become an important issue that concerns both the public and the scientific community. Many studies on visibility trend and its causes have been carried out (Che et al., 2007; Chang et al., 2009). Those studies were primarily focused on the polluted areas such as the Pearl River Delta (PRD) region (Deng et al., 2008;

Chang et al., 2009), the Yangtze River Delta (YRD) region (Deng et al., 2011;Gao et al., 2011), and the Beijing-TianjinHebei (BTH) region (Fan et al., 2005; Fan and Li, 2008; Zhao et al., 2011). Che et al. (2007) evaluated the trend of visibility across entire China between 1981 and 2005, and identified a rapid decrease in visibility during the latest 15 years (2.1 km/decade from 1990 to 2005). Chang et al. (2009) investigated the visibility trends for six major megacities in China during 1973-2007.

It is to be expected that the visibility will be correlated with the aerosol concentrations near the surface, though meteorological influences might also play a significant role (e.g. Sloane, 1987). Several studies (e.g. Ferman et al., 1981) have found that sulfate aerosols account for over 50 % of the visibility reduction, and can be a good indicator of long term (sulfate) aerosol changes (Trijonis, 1984). Gomez and Smith (1987) for example argue that the frequency of "very good visibility" days (defined as days where the visibility exceeds 19 km) in summer is a good indicator for long range transportation of air pollution. This simple method has been used in this and other studies too. Several other studies have also shown good correlations with aerosol (SO2) emissions, and visibility changes can often be linked to economical events and environmental policies. In the United Kingdom, Doyle and Dorling (2002) found that in the United Kingdom, visibility increased after 1973 due to the oil crisis and implementation of environmental policies in the UK. Aerosols outside the UK were found to have much less influence than from sources inside the UK. In a much larger study, using many stations located all over Europe Vautard et al. (2009) found a decline of fog, mist and haze over the past 30 years. They determined that the frequency of low visibility conditions declined in all season and for all visibility ranges between 0 and 8 km. This decline was spatially and temporally correlated with trends in SO2 emissions, suggesting a significant contribution to air quality improvements. Besides visibility trends, also (much smaller) negative trends in cloud cover were discovered. Most substantial changes occurred in West-Central and Eastern Europe. A similar study was done by Oldenborgh et al. (2010). Focusing on the effect of changes in aerosol emissions and atmospheric circulation on dense foggy days, they also found a significant decline which was spatially and temporally correlated with SO2 emissions. The decline of days with low visibility started in De Bilt in 1985. No significant trend was found before this date.

3.0 Description and Methodology for Assessing Impact of Atmospheric Particulate Matter Pollution on Visibility

3.1 Study Area:

Milan is the second-largest city in Italy and the capital of Lombardy. The city proper has a population of about 1.35 million, while its urban area is the 5th largest in the EU and the largest in Italy with an estimated population of about 5.2 million. Milan is located in the north-western section of the Po Valley, approximately half-way between the river Po to the south and the first reliefs of the Alps to the north, with the Ticino river to the west and the Adda to the east. The municipal territory is entirely flat, the highest point being at 122 m (400.26 ft) above sea level. According to the Köppen climate classification, Milan has a humid subtropical climate (Cfa); the Mediterranean Sea is too far to exert any influence, so Milan's climate is similar to much of northern Italy's inland plains, where sultry summers and cold, rainy winters prevail.
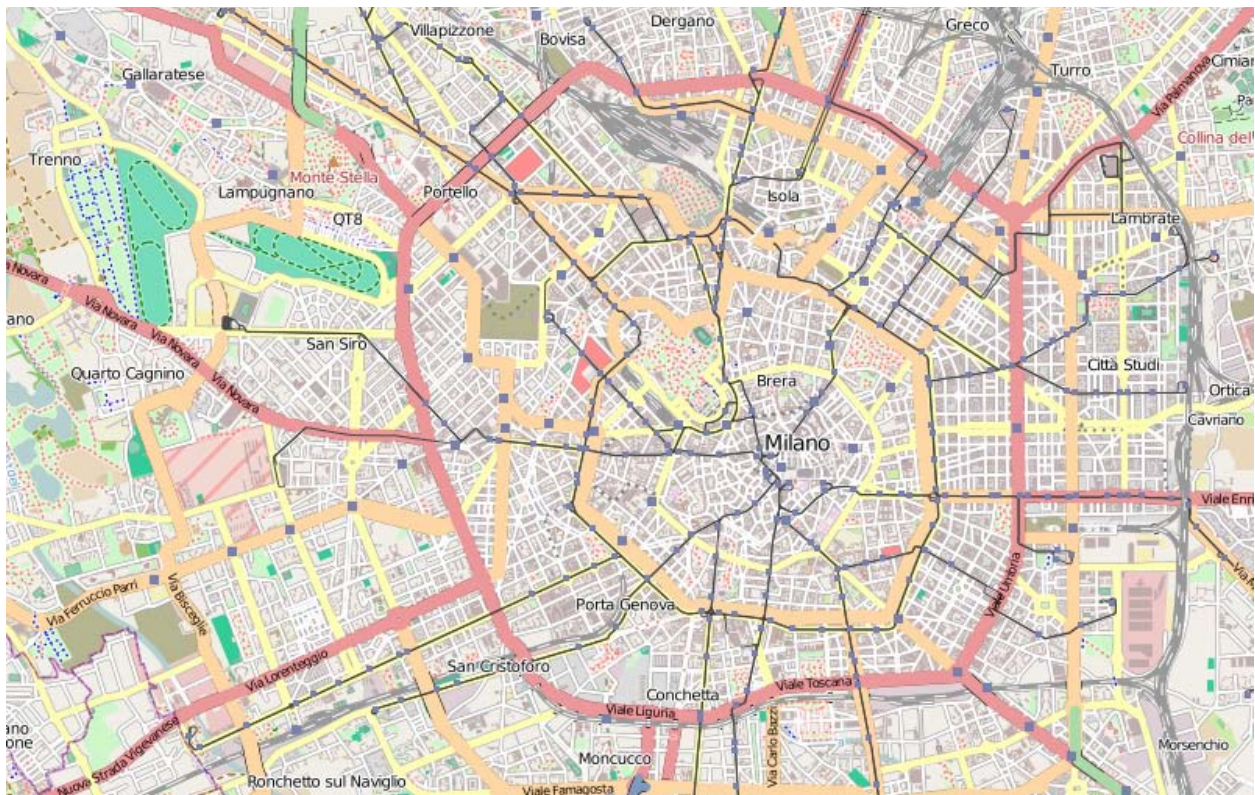
Figure 3.1: Map of Milan

3.2 Methodology for assessing visibility:

The light extinction coefficient, b_{ext}, is defined as the sum of the $PM_{2.5}$ scattering (b_{sp}), $PM_{2.5}$ absorbing (b_{ap}), gas (NO_2) absorption (b_{ag}), and Rayleigh scattering (b_{sg}).

where:

$$b_{ext} = b_{sp} + b_{ap} + b_{Ray} + b_{ag} \qquad\qquad (1)$$

where b_{ext} =   light extinction coefficient

         b_{sp} =   light scattering coefficient due to particles

         b_{ap} =   light absorption coefficient due to particles

         b_{Ray} =   Rayleigh light scattering coefficient due to gases

         b_{ag} =   light absorption coefficient due to gases

Rayleigh scattering can be theoretically computed (vandeHulst, H.C. *Light Scattering by Small Particles'1981)* and varies with altitude from 9-12 Mm^{-1} with the lower values at mountain tops. The IMPROVE program assumes a standard value of 10/Mm*.* Absorption due to gases is primarily due to NO_2. Ozkaynak *et al.*, (1985) found that in Eastern US cities the NO_2 contribution to b_{ext} was less than 1% and b_{ag} is assumed to be negligible. The particle light absorption is primarily due to elemental carbon or soot and soil particles. Estimates of light absorption in the Eastern US range from ~10% in rural areas to 30% in urban areas (Malm *et al.*, 1994).

Reconstructed total light extinction was then calculated using the modified IMPROVE (Interagency Monitoring of Protected Visual Environments) program (Kim et al., 2001) according to the following equation:

$$b_{ext} = a\,[NHSO] + b[NHNO] + c\,[OMC] + d\,[Fine\ Soil] + e\,[CM] + b_{ap} + b_{Ray} \qquad (2)$$

where a, b, c, d, and e are mass extinction efficiencies for particulate matter components, as summarized in Table 3.2.

Table 3.1: Composite variables for particulate matter used by the IMPROVE (Interagency Monitoring of Protected Visual Environments) program

Component	Specification	Composite equation
NHSO	$(NH_4)_2SO_4$	$4.125\ [SO_4^-]$
NHNO	NH_4NO_3	$1.29\ [NO_3^{\ -}]$
OMC	Organic mass by carbon	$1.4\ [OC]$
FS	Fine soil	$2.20[Al]+2.49[Si]+1.63[Ca]+2.42[Fe]+1.94[Ti]$
CM	Coarse mass	$[PM_{10}] - [PM_{2.5}]$
b_{aps}	Absorption co-efficient	$10\ [EC]$
b_{Ray}	Rayleigh scattering coeff.	Altitude dependent

Mass extinction coefficient of hygroscopic aerosol composes a RH-dependent scaling factor, which represents the relationship between RH and the scattering efficiency. In this analysis, the growth of hygroscopic carbonaceous particles was calculated using the RH-dependent function proposed by IMPROVE (1996). b_{aps} in Eq. (2) was taken from 24-h-time-based EC measurements in this study as shown in Table 3.1.

Table 3.2: Functions of mass extinction efficiency of various Particulate Matter components

Constituent	IMS95* (m^2g^{-1})
NHSO	$2.1 \times (1 - RH)^{-0.7}$
NHNO	$2.1 \times (1 - RH)^{-0.7}$
OMC	$2.8 \times (1 - RH)^{-0.2}$
EC	10
FS	2
CM	0.6

  * IMPROVE (1996)

Gaseous NO_2 absorption is estimated by using the absorption efficiency of Hodkinson (1966):

$$b_{ag}\ (Mm-1)=0.33\times[NO_2](ppb) \tag{3}$$

The U.S regional haze rule stipulates that reasonable progress is to be measured in terms of changes in a deciview haze index or simply "deciviews"(dv). Deciviews are defined as the natural logarithm of the ratio of the extinction coefficient to Rayleigh scattering (Pitchford and Malm, 1994)

$$\text{Deciview} = 10 \ln(b_{ext}/10)$$

$$(4)$$

where

b_{ext} represents total light extinction expressed in inverse megameters(i.e.$Mm^{-1} = 10\text{-}6\ m^{-1}$)

The relationship between units of light extinction (Mm^{-1}), haze index (dv), and visual range (km) is indicated by the scale below (Figure 3.2). Visual range is the distance at which a given object can be seen with the unaided eye. The deciview scale is zero for pristine conditions and increases as visibility degrades. Each deciview change represents a perceptible change in visual air quality to the average person. Generally, a one deciview change in the haze index is likely perceptible by a person regardless of background visibility conditions.
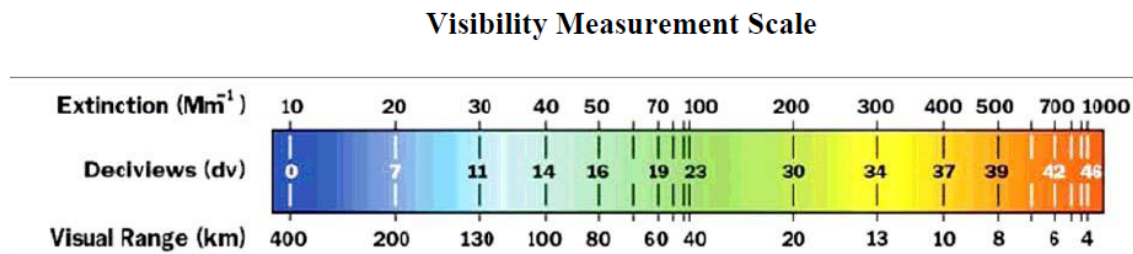
Figure 3.2: Visibility Measurement Scale

As the scale indicates, the deciview value gets higher as the amount of light extinction increases. The ultimate goal of the U.S regional haze program is to reduce the amount of light extinction caused by haze species from anthropogenic emissions, until the deciview level for natural conditions is reached.

3.3 Data Analysis and calculation:

In this thesis paper the particulate matter and its chemical composition data from Milano via Messina station, Juvara and Verziere stations of Milan have been used. More precisely for visibility impairment, the daily concentration data of PM_{10}, $PM_{2.5}$, EC, OC, NO_3, SO_4, NO_2, Al, Si, Ca, Ti, Fe and relative humidity (RH) have been used. The duration of the formerly collected data applied in this thesis is approximately 1.5 years from 10/8/2002 to 13/12/2003 and total 113 days of data have been analyzed. PM2.5 samples were collected at Milano via Messina station and speciated for the main chemical species, including carbonaceous species (Elemental and Organic carbon), ionic species (Chlorides, Nitrates, Sulfates, Ammonium), and the main elements.

Data for metals are somewhat limited both in terms of numbers of species and in actual data availability. This has two main implications when accounting for the crustal term of the calculation. There was missing data of some days, since there is a "hole" in the data time series for specific metals/elements. In this case missing data have been estimated based on linear regression between a complete time series (K, Fe, and Pb) and the less complete ones, provided that having a reasonable value for R^2.

In particular, missing values for Al, Ti and Si have been calculated by linear regression with the most correlated among K, Fe, Pb (in general the most correlated species can be different); however, in those few cases when the regression coefficients with K, Fe, Pb were very low regression with $PM_{2.5}$ mass, EC, OC, ionic species was considered for missing values replacement.
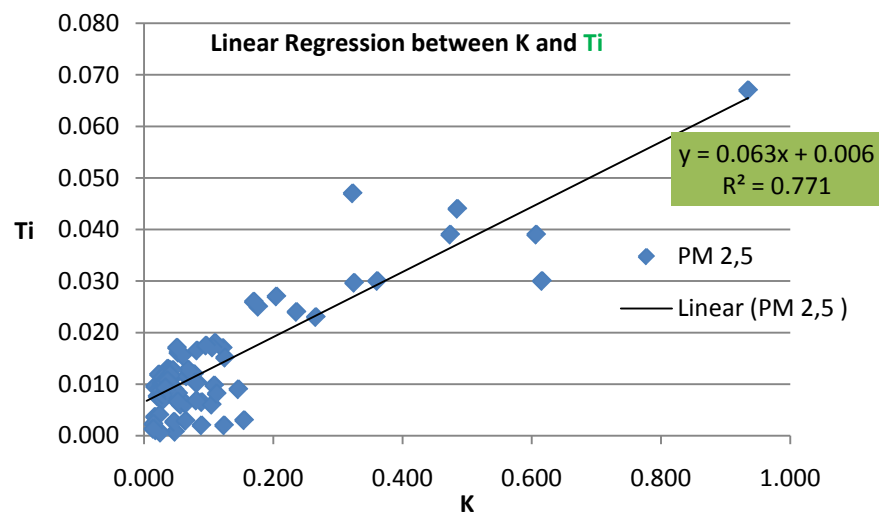
Figure 3.3: Linear Regression between K and Ti

Linear regression between Fe and Al (µg/m³)

y = 0.197x + 0.033
R² = 0.592
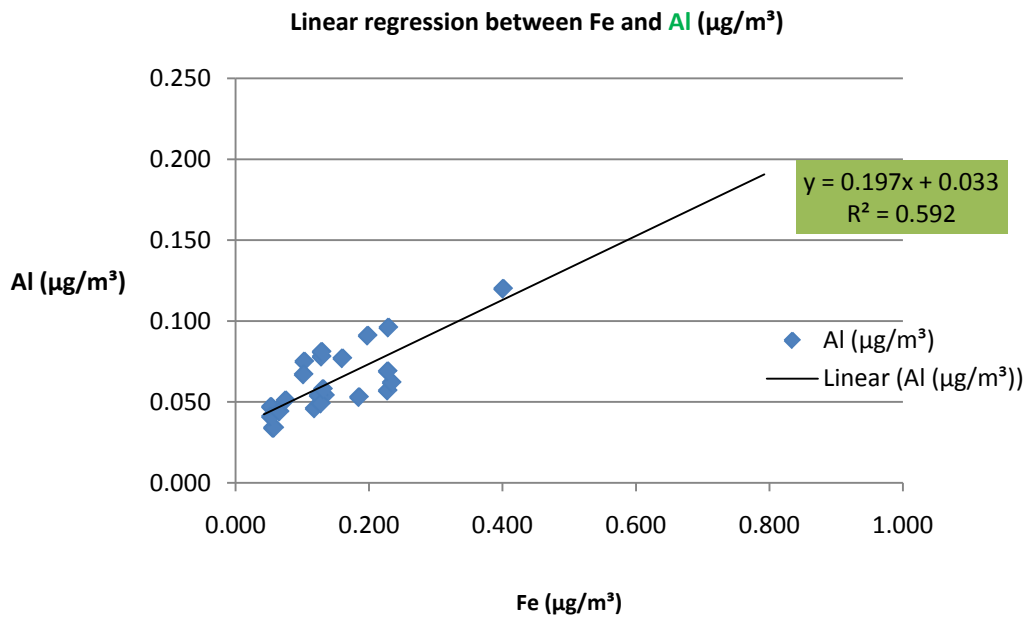
Figure 3.4: Linear Regression between Fe and Al

PM_{10} data were not available for the same monitoring station (Milano via Messina) of speciated PM2.5 data. Therefore, in this work PM10 data from Milano Juvara and Milano Verziere monitoring stations have been collected and the daily averages of the two station's data have been used for calculations based on the hypothesis that the spatial variability of PM10 concentration levels is rather limited within the urban area of the city. The main drawback of this approach was that about 20% (19 data out of 115) of PM10 data where abnormal in comparison of PM2.5 data, i.e. PM10 daily average was lower than the PM2.5 average. This situation could depend on three reasons:

1. The monitoring sites are different and PM10 data might be influenced by emissions at the the very local scale; in fact, despite its location in the city centre, Milano Verziere station is a kerbside station where traffic emissions could determine PM10 peaks

2. The PM measurement principle and was different: namely, PM2.5 data derived from gravimetric measurements whereas PM10 data were collected by automated monitors (TEOM monitors)

3. The operational conditions (namely, the air sample flow rate) of the monitors could be different.

So this unusual data were not considered for the calculation of light extinction coefficient, b_{ext}.

NO$_2$ data was also used but the data found in **µg/m³** unit and conversion of units to **ppb** performed by the simple formula:

ppb = µg/m³ *(22.414 * T$_m$)/(Mw * T$_{std}$)

Here T$_m$ = Measured temperature (20˚C = 293 K)

T$_{std}$ = Standard temperature (0˚C = 273 K)

Mw = NO$_2$ molecular weight (46 g mole^{-1})

The 17-months PM2.5 study provides additional information, particularly on chemical composition (Figures 3.4-3.7).
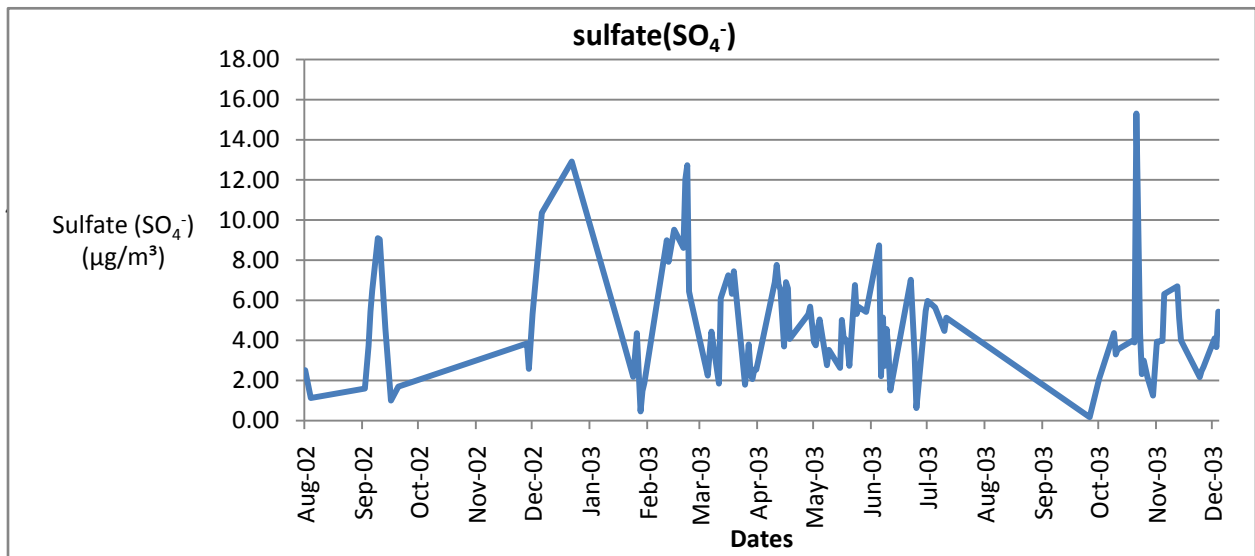
Figure 3.5: *Time series of sulfate concentrations measured from August 2002 to December 2003*
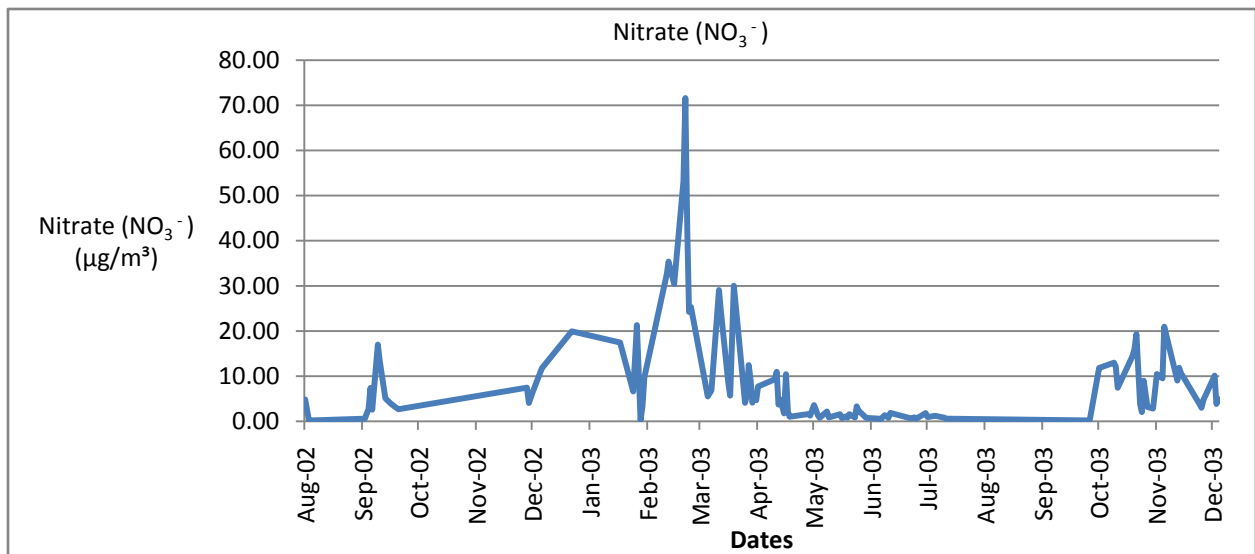
Figure 3.6: *Time series of Nitrate concentrations measured from August 2002 to December 2003*

From the time series of figure 3.3 and 3.4, it can be seen that average value of sulfate is 4.68 μg/m³ and for nitrate is 8.61 μg/m³ during the 17ᵗʰ month time duration. The concentration of sulfate is little bit higher during the warmer period. Nitrate concentration also increasing and reached the maximum concentration during the cold season.
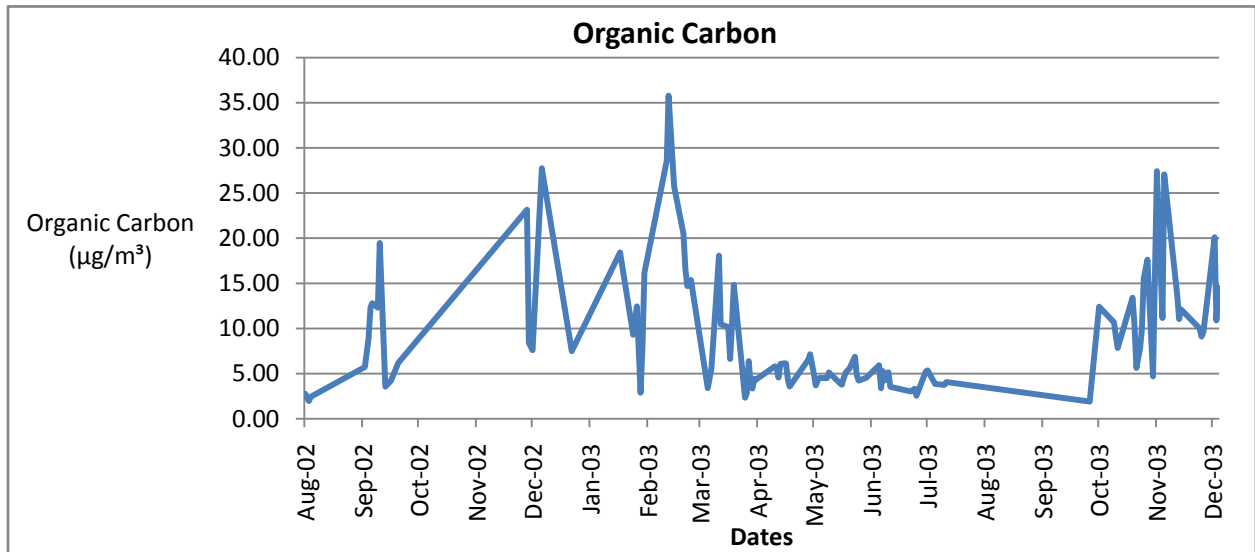
Figure 3.7: *Time series of Organic Carbon concentrations measured from August 2002 to December 2003*
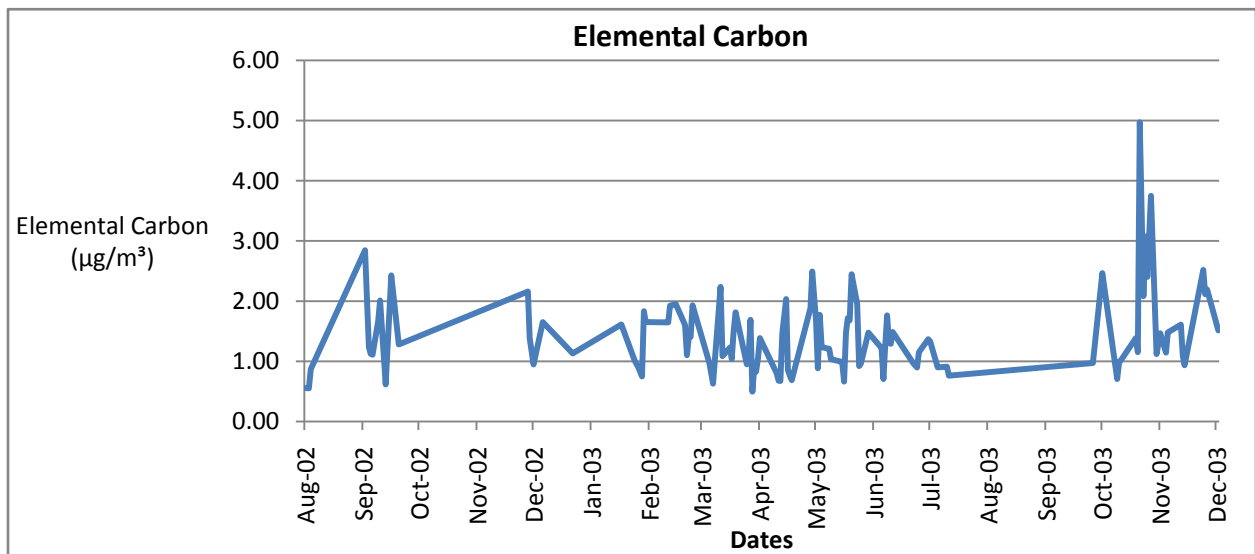
Figure 3.8: *Time series of Elemental Carbon concentrations measured from August 2002 to December 2003*

From the figure 3.6 and 3.7, the time series of Organic carbon and Elemental carbon give an idea about the average concentrations which are 8.99 µg/m³ and 1.92 µg/m³ respectively. The concentrations of organic carbon are higher during the month of October 2002 to March 2003 compare to other moths of the time series duration.

4.0 Results and Discussion:

The maximum and minimum value of light extinction was found to be 849.57 Mm^{-1} and 34.87 Mm^{-1} respectively which corresponds to deciviews (dv) of 44.42 and 12.49.
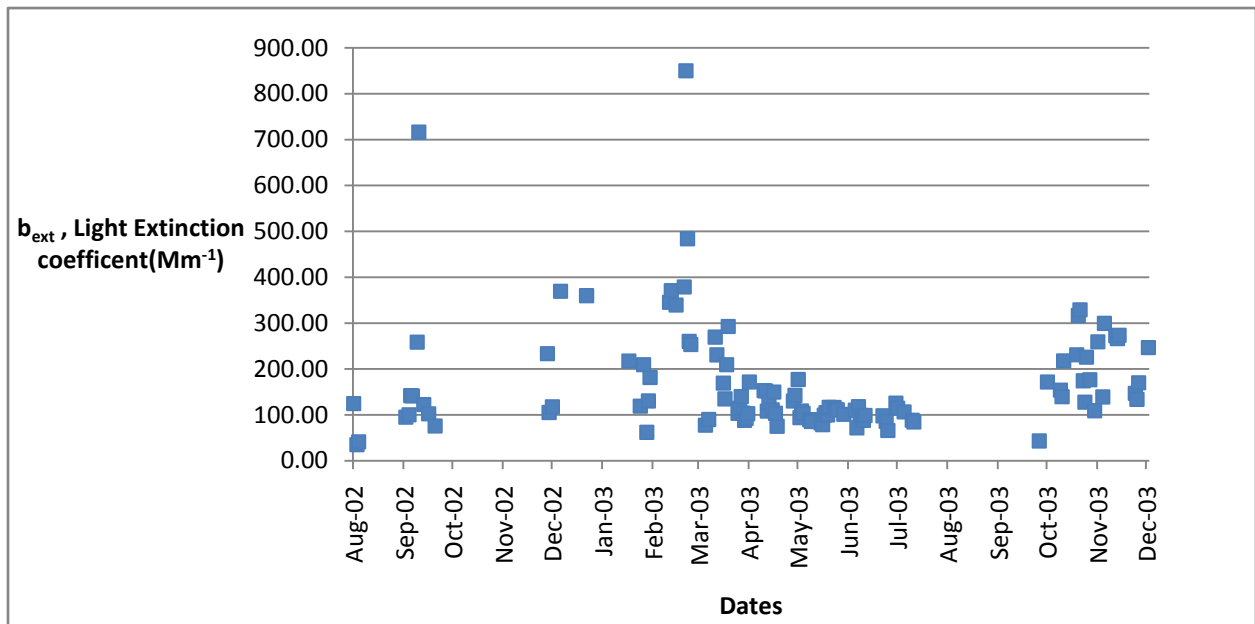
Figure 4.1: *Time series of b$_{ext}$ (Light extinction coefficient) from August 2002 to December 2003*

The maximum visibility impairment observed in mid of September '02 and from December 2002 to March 2003, November'03 and December'03 as well compare to other months of the study periods.

Table 4.1: Summary values of b$_{ext}$

Maximum (Mm^{-1})	Minimum (Mm^{-1})	Average (Mm^{-1})	Standard deviation
849.57	34.87	168.61	120.61
Cold Period (October to March)			
849.57	43	229.46	130.63
Warm Period (April to September)			
715.91	34.87	118.63	84.38

From the table 4.2, it's interesting to notice that around 46 % of the data fall in the visual range of 20-40 Km which corresponds to light extinction coefficient of 100-200 Mm^{-1}. 21% extinction value fall in the visual range of 40-60 Km and approximately 16% data contribute to the visual range of 13-20 km. These moderate visibility conditions represent the need for air quality improvement in the Milan city.

Table 4.2: Stratified presentation of the results by visual range

Visual range (in Km)	No of Data found
<6	02
8-6	01
10-8	02
13-10	08
20-13	19
40-20	52
60-40	24
80-60	02
100-80	02
100 - 400	01

It can be noticed from the table listed below that 55% of the total warm period (April to September) data and 33% data of the total cold period data fall in the 40-20 Km visual range and 36% warm period data are in the visual range of 60-40 km. On the contrary, 33% of the total cold period data accounted in the 20-13 Km visual range.

Table 4.3: Stratified presentation of the results by visual range and season

Visual range (in Km)	Cold (October to March)	Warm (April to September)
<6	1	1
8-6	1	0
10-8	2	0
13-10	8	0
20-13	18	1
40-20	18	34
60-40	2	22
80-60	1	1
100-80	1	1
100 - 400	0	1

The pie chart below delineates the contribution of different PM2.5 chemical composition such as sulfate, nitrate, organic carbon, fine soil, elemental carbon on light extinction coefficient (b_{ext}). It's worth notices that nitrate was found to be the largest contributor to the light extinction, followed by sulfate, Organic carbon. At Milan city, Nitrate (NO_3), sulfate (SO_4) and Organic carbon (OC) accounted for 73.84%, 12.4% and 8% of the total chemical extinction, respectively.

b_{ext} = 849.57 (Mm^{-1})
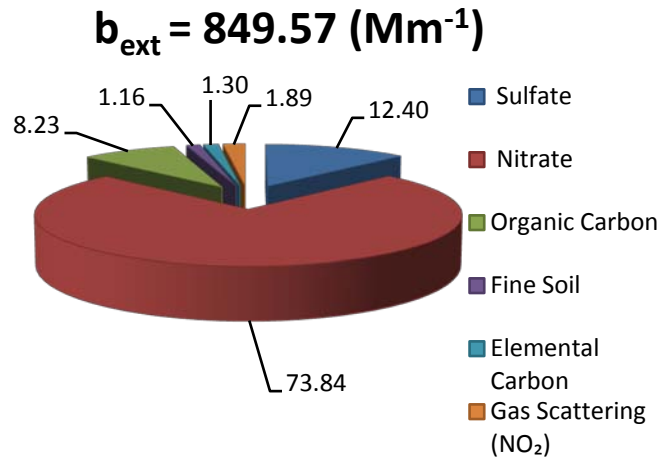
Figure 4.2 Average contributions to highest light extinction value (Visual range 5-4 Km)

b_{ext} = 181.18 (Mm^{-1})
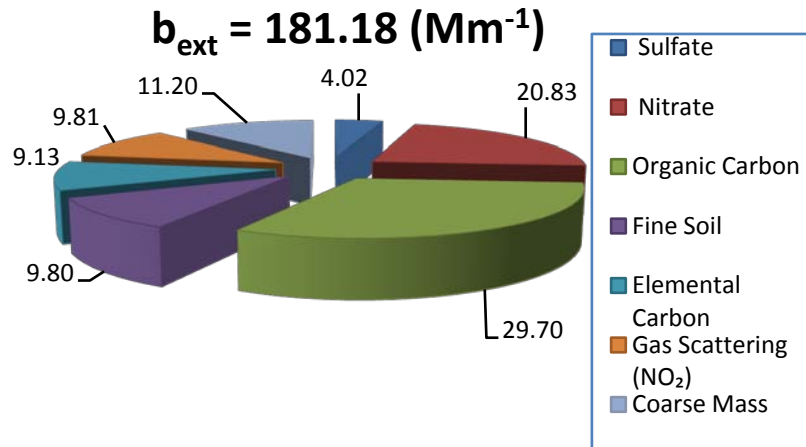
Figure 4.3: Average contributions to visual range of 40 – 20 Km

I would like to stress a little bit about the pie chart in figure 4.6, as earlier mentioned in the table 4.2 around 46% of the extinction coefficient value falls in the range of 100-200 Mm^{-1} with visual range of 40-20 Km, We can see that major contributors are organic carbon, nitrate, fine soil, EC and NO_2.

b_{ext} = 34.87 (Mm^{-1})
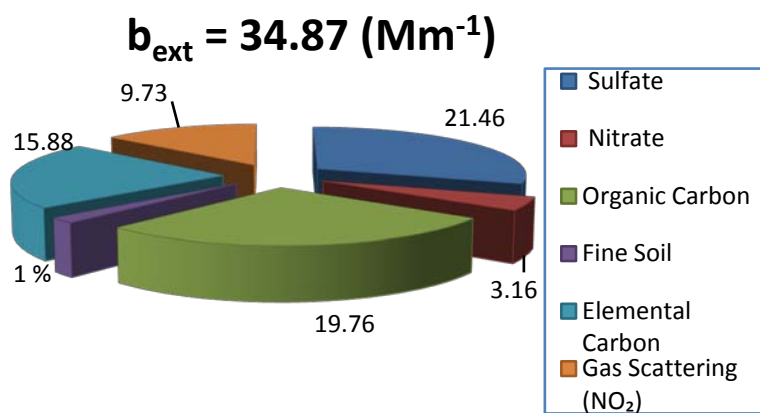
Figure 4.4: Average contributions to lowest light extinction value and visual range of 130 – 100 Km

For the lowest extinction value (visual range 130-100 Km) the contribution of gas scattering (NO$_2$) increased up to 20%. Organic carbon and elemental carbon have dominance in the visibility impairment contribution. But the nitrate effects reduced considerably.

Table 4.4: Relative contribution from various chemical species of particulate matter on b_{ext}

	Sulfate	Nitrate	Organic Carbon	Fine Soil	Elemental Carbon	Gas Scattering (NO$_2$)	Coarse Mass
Warm (April to September) (in %)							
Average	19.10	13.99	16.35	11.88	11.82	9.45	8.28
Standard deviation	7.64	13.06	4.54	6.54	5.13	2.99	4.32
Cold (October to March)							
Average	13.35	33.21	22.90	5.33	8.66	7.02	5.01
Standard deviation	6.71	14.77	7.89	6.01	5.17	3.13	4.43

Considering the average contribution of the chemical species of the particulate matter we observed that sulfate has the higher contribution of 19.10% during warm period and then organic carbon, nitrate, fine soil, elemental carbon respectively.

On the contrary, nitrate contributes the highest percentage of 33.21% on light extinction during cold season. Organic carbon also plays a significant role contributing about 22.90%.

Average contribution of cold and warm period also represented in the pie chart (figure 4.5 and figure 4.6).
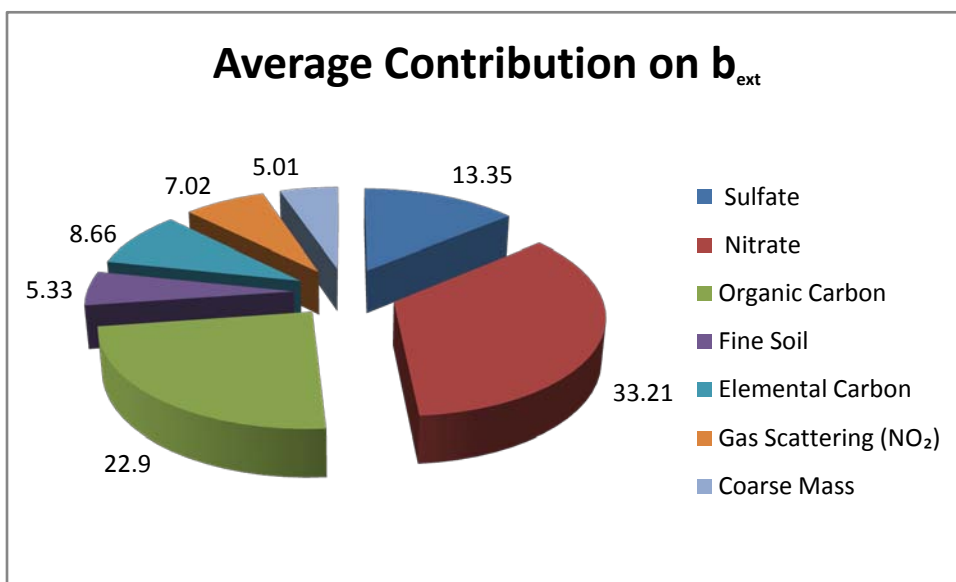
Figure 4.5: Average Contribution of Chemical species on light extinction coefficient (b_{ext}) (Warm period)
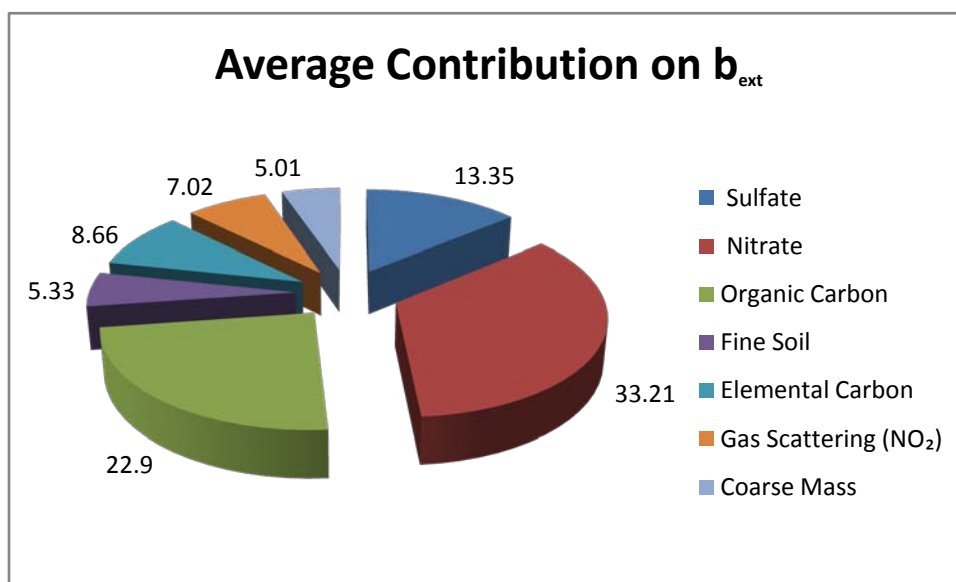
Figure 4.6: Average Contribution of Chemical species on light extinction coefficient (b_{ext})

(Cold period)

During this period, humidity also moderate value approximately 60% which can also have affect on visibility impairment.
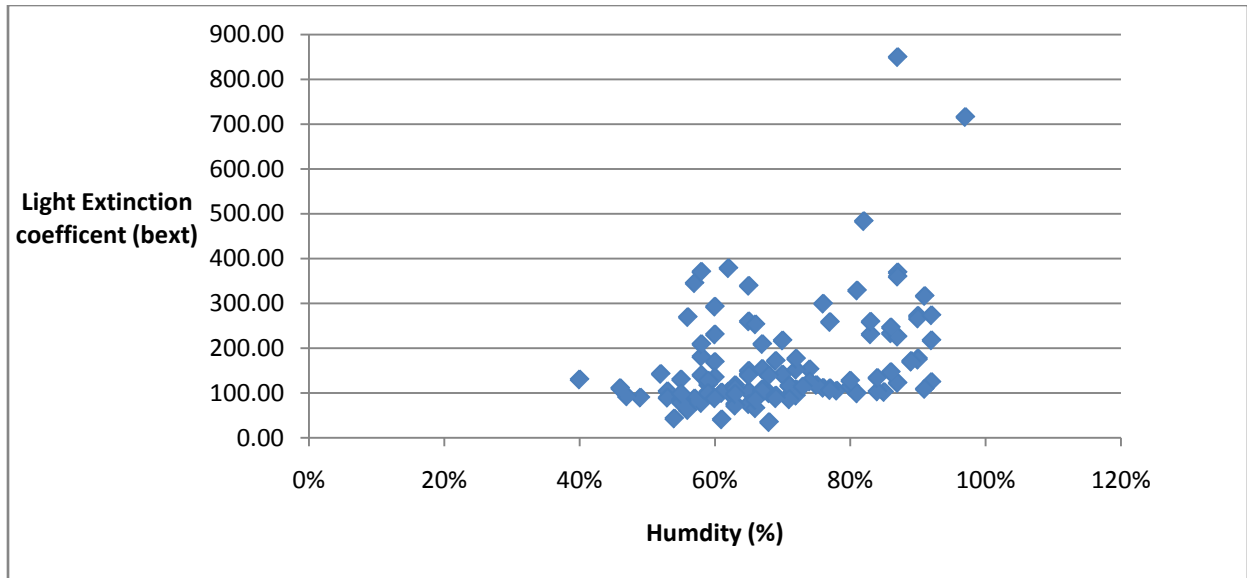
Figure 4.7: *Light extinction vs Humidity from August 2002 to December 2003*
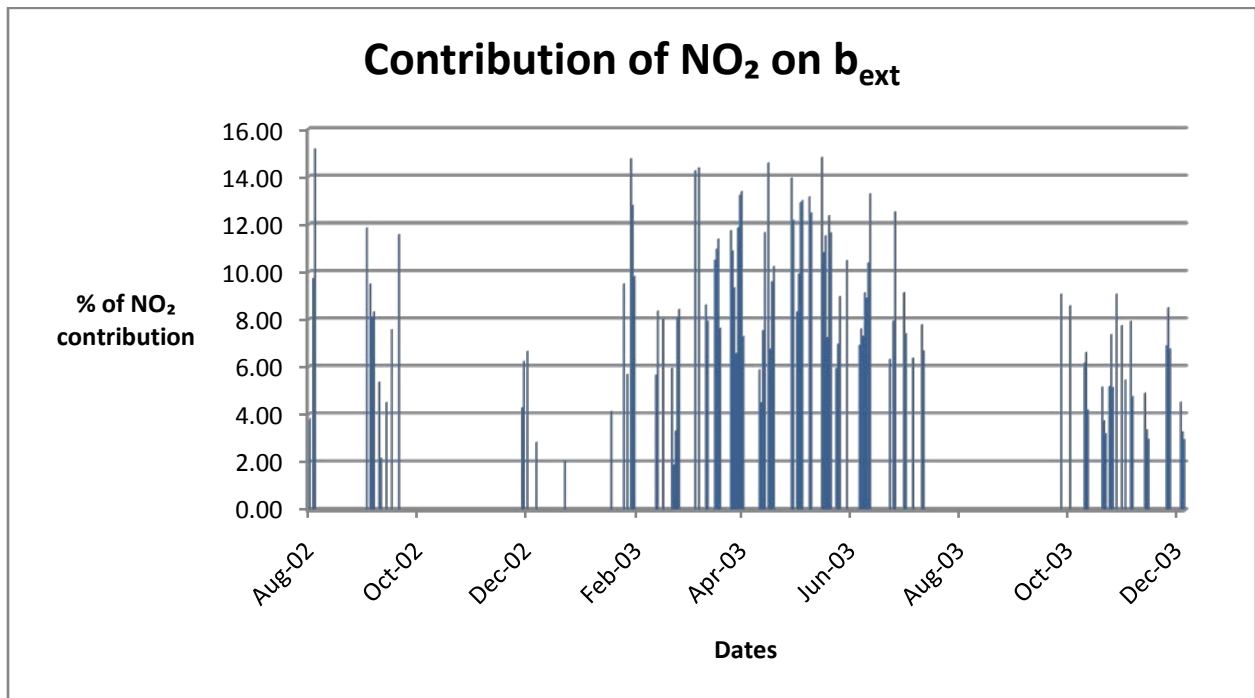
Figure 4.8: Time series of Contribution of Gas Scattering (NO$_2$) on Light extinction (b$_{ext}$)

Gaseous NO$_2$ contribution an average of 9% to light extinction in Milan city area. This result was based on the data collect on the days with aerosol samples. Figure 4.8 shows the contribution of gas scattering on light extinction. It can be seen that during the time series of study period NO$_2$ contribution never exceeded 16% of the total light extinction (the highest was 15.16%). NO$_2$ contribution is higher to some extent than eastern US where NO$_2$ contribution found to be less 4%.

Contribution of Coarse Mass on b_{ext}
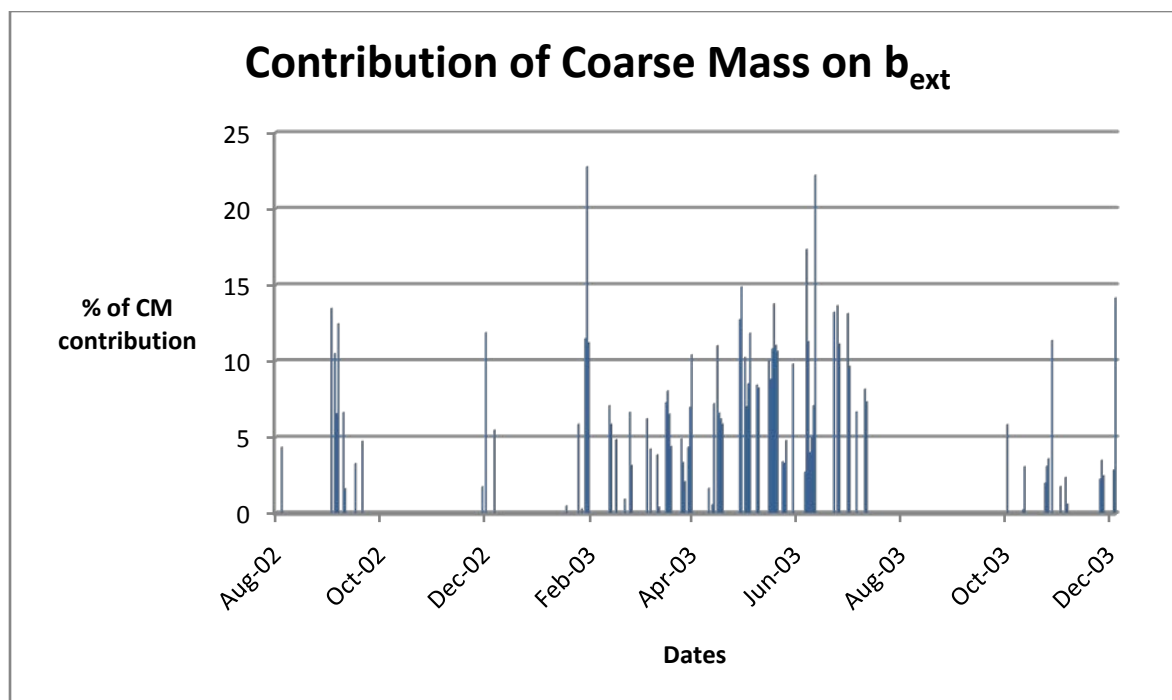
Figure 4.9: Time series of Contribution of Coarse Mass (CM) on Light extinction (b_{ext})

The contribution of coarse mass in not that significant on light extinction. Average contribution was found to be 6.96% on light extinction.

In the calculation, nitrate (NO_3^-) was found to be the largest contributor to light extinction, followed by Organic Carbon (OC) and sulfate ((SO_4^-). At Milan city, Nitrate, OC and sulfate accounted for 22.65 %, 19.30 % and 16.51 % of the total light extinction respectively. The contribution of element carbon is around 10.40 % and for fine soil and NO_2 was found 8.96% and 8.36% correspondingly.

The significant contribution of nitrate to visibility degradation in Milan is due to a relatively high concentration of nitrate and its ability to absorb water vapor which enhances light scattering. The contribution of PM2.5 in Milan is not similar to the situation in the eastern US where sulfate has been found to be the dominant component for light extinction (Watson 2002). Previously estimates of NO_2 contribution in other cities showed that NO_2 accounted for 4.7% of light extinction in Houston, Texas (Dzubay et al., 1982), 7% in Denver, Colorado (Groblicki et al., 1981), 7% in Los Angeles, California (Appel et al., 1985), and 4% in Sydney (Williams et al., 1982). In Milan city NO_2 contribution accounted for 9% which is little bit higher than cities in US.

So far there is no specific regulation exists in EU for visibility impairment. US employ well established haze rule. The ultimate goal of the U.S regional haze program is to reduce the amount of light extinction caused by haze species from anthropogenic emissions, until the deciview level for natural conditions is reached.

5. Conclusion:

The scope of the work was to assessment of visibility impairment due to atmospheric particulate matter pollution in Milan city. At present EU regulations do not consider visibility impairment whereas in the US the "haze rule" (or similar regulations) are in force for given areas.

Environmental Protection Agency (EPA) of US and other Agencies have been monitoring visibility in national parks and wilderness areas since 1988. In 1999, the U.S. Environmental Protection Agency announced a major effort to improve air quality in national parks and wilderness areas. The Regional Haze Rule calls for state and federal agencies of US to work together to improve visibility in 156 national parks and wilderness areas such as the Grand Canyon, Yosemite, the Great Smokies and Shenandoah.

Reconstructed total light extinction was calculated using the modified IMPROVE (Interagency Monitoring of Protected Visual Environments) program (Kim et al., 2001). In a typical urban atmosphere, fine aerosol species contributing to visibility degradation can be classified into five major types: sulfates, nitrates, OC, EC, and soil dust. The mass concentration of each component was calculated from the masses of the measured elements and ions.

In this study the particulate matter and its chemical composition data from Milano via Messina station, Juvara and Verziere stations of Milan have been used. More precisely for visibility impairment, the daily concentration data of PM_{10}, $PM_{2.5}$, EC, OC, NO_3, SO_4, NO_2, Al, Si, Ca, Ti, Fe and relative humidity (RH) have been used. The duration of the formerly collected data applied in this thesis is approximately 1.5 years from 10/8/2002 to 13/12/2003 and total 113 days of data have been analyzed. PM2.5 samples were collected at Milano via Messina station and speciated for the main chemical species, including carbonaceous species (Elemental and Organic carbon), ionic species (Chlorides, Nitrates, Sulfates, Ammonium), and the main elements.

Nitrate (NO_3^-) was found to be the largest contributor to light extinction, followed by Organic Carbon (OC) and sulfate (SO_4^-). The highest deciviews (dv) found to be 44.42 and lowest deciview (dv) was 12.49. 46 % of the data fall in the visual range of 20-40 Km which corresponds to light extinction coefficient of 100-200 Mm^{-1}. 21% extinction value fall in the visual range of 40-60 Km and approximately 16% data contribute to the visual range of 13-20 km. In Milan city, Nitrate (NO_3), sulfate (SO_4) and Organic carbon (OC) accounted for 73.84%, 12.4% and 8% of the total chemical extinction, respectively. Gaseous NO_2

contribution was an average of 9% to light extinction. NO_2 contribution never exceeded 16% of the total light extinction (the highest was 15.16%).

Sulfate has the higher contribution of 19.10% during warm period and then organic carbon, nitrate, fine soil, elemental carbon respectively.

On the contrary, nitrate contributes the highest percentage of 33.21% on light extinction during cold season. Organic carbon also plays a significant role contributing about 22.90%.

Particulate matter pollution on visibility of Milan showed moderate affect which indicates the necessity of air quality improvement in Milan city.

The data set was limited in this study and also recent data was not available due to the fact that the availability of fully speciated PM data and of concurrent PM10 and PM2.5 data is still very limited in Europe since the need for routinary speciation measurements has been introduced in EU regulations only recently.

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Appendixes

Atmospheric Particulate Matter data set

T1	293.15	22.414
T2	273.15	46.00

Date	PM10 (Average)	PM 2,5	EC	OC	NO$_3$	SO$_4$	NH$_4$	Al	Si	K	Ca	Ti	Fe	Relative humidity	NO$_2$		b Ray
	(µg/m³)	µg/m³	µg/m³	µg/m³	µg/m³	µg/m³	µg/m³	(µg/m³)	µg/m³	µg/m³	µg/m³	µg/m³	µg/m³		PPb	(µg/m³)	(Mm-1)
8/10/2002	16	23.0	0.56	2.78	4.86	2.52	1.90	0.034	0.042	0.122	0.028	0.017	0.056	92%	14.37	27.48	10.00
8/12/2002	13.5	16.2	0.55	1.96	0.24	1.60	0.48	0.034	0.070	0.039	0.039	0.008	0.058	68%	10.28	19.66	
8/13/2002	19.5	16.5	0.87	2.44	0.22	1.13	0.35	0.047	0.114	0.004	0.033	0.006	0.053	61%	18.83	36.00	
9/11/2002	37.5	16.2	2.85	5.73	0.60	1.60	0.50	0.054	0.104	0.057	0.037	0.006	0.134	71%	34.03	65.08	
9/13/2002	47	29.5	1.24	8.91	2.82	3.72	1.90	0.078	0.127	0.177	0.067	0.025	0.129	61%	28.76	55.00	
9/14/2002	62.5	47.1	1.13	12.33	7.40	5.45	3.70	0.077	0.108	0.236	0.069	0.024	0.160	65%	34.84	66.63	
9/15/2002	57	27.7	1.11	12.80	2.60	6.50	3.60	0.075	0.096	0.146	0.045	0.009	0.103	70%	35.58	68.04	
9/18/2002	71.5	43.1	1.67	12.31	17.00	9.10	5.60	0.091	0.133	0.205	0.075	0.027	0.198	77%	41.88	80.08	
9/19/2002	86	66.6	2.01	19.47	13.37	9.03	5.60	0.081	0.162	0.155	0.039	0.003	0.129	97%	47.15	90.17	
9/22/2002	22	27.0	0.62	3.54	5.10	4.60	2.50	0.067	0.123	0.089	0.022	0.002	0.102	87%	16.67	31.88	
9/25/2002	22	16.4	2.43	4.21	3.90	1.00	1.10	0.046	0.090	0.090	0.034	0.007	0.119	85%	23.40	44.75	
9/29/2002	28.5	22.5	1.28	6.19	2.70	1.70	1.30	0.054	0.094	0.124	0.038	0.002	0.125	63%	26.49	50.66	
12/7/2002	62.5	63.7	2.16	23.16	7.48	3.85	3.10	0.057	0.128	0.474	0.081	0.039	0.228	86%	30.22	57.79	
12/8/2002	33.5	30.4	1.39	8.40	4.09	2.58	1.70	0.041	0.091	0.105	0.030	0.006	0.053	78%	19.85	37.96	
12/10/2002	47	23.8	0.95	7.58	6.42	5.32	3.20	0.049	0.117	0.266	0.069	0.023	0.128	63%	23.64	45.21	
12/15/2002	95.5	61.8	1.65	27.74	11.78	10.35	6.10	0.062	0.128	0.607	0.074	0.039	0.234	87%	31.77	60.75	
12/31/2002	32.5	42.1	1.13	7.48	19.94	12.92	9.60	0.043	0.070	0.030	6.829	0.008	0.052	87%	22.51	43.04	
1/26/2003	59.5	57.7	1.61	18.43	17.49	4.53	5.50	0.077	0.079	0.059	4.312	0.010	0.226	70%	27.13	51.88	
2/2/2003	52	40.4	1.02	9.30	6.61	2.19	2.20	0.074	0.077	0.053	8.462	0.008	0.210	59%	34.14	65.29	
2/4/2003	62	61.0	0.90	12.46	21.34	4.36	5.90	0.097	0.087	0.083	9.563	0.010	0.325	67%	36.02	68.88	
2/6/2003	24	12.2	0.75	2.87	0.25	0.46	0.08	0.073	0.076	0.047	9.272	0.009	0.204	56%	27.61	52.79	
2/7/2003	76.5	27.1	1.83	7.98	3.34	1.48	1.00	0.078	0.074	0.042	9.456	0.009	0.228	40%	50.37	96.33	
2/8/2003	92.5	58.7	1.65	16.15	9.79	1.89	2.80	0.109	0.085	0.078	10.028	0.012	0.384	58%	53.84	102.96	
2/20/2003	150	109.5	1.65	28.61	32.64	9.00	8.17	0.189	0.100	0.125	11.927	0.015	0.792	57%	59.09	113.00	
2/21/2003	166.5	130.3	1.92	35.78	35.39	7.92	9.45	0.120	0.352	0.935	0.163	0.067	0.401	58%	93.69	179.17	

Appendixes

2/24/2003	127.5	100.0	1.95	25.71	30.41	9.52	7.66	0.096	0.525	0.616	0.114	0.030	0.229	65%	82.23	157.25
3/1/2003	118	112.1	1.61	20.50	53.16	8.61	10.96	0.069	0.165	0.485	0.120	0.044	0.228	62%	68.22	130.46
3/2/2003	84	133.4	1.10	16.60	71.62	12.03	16.16	0.066	0.086	0.080	5.567	0.010	0.166	87%	48.76	93.25
3/3/2003	82.5	97.3	1.39	14.70	42.39	12.74	11.16	0.058	0.117	0.323	0.074	0.047	0.131	82%	48.70	93.13
3/4/2003	94	65.4	1.41	14.75	24.24	6.44	5.73	0.084	0.095	0.109	6.865	0.010	0.261	65%	63.73	121.88
3/5/2003	78	64.7	1.93	15.37	25.35	5.98	5.07	0.053	0.122	0.361	0.094	0.030	0.185	66%	64.54	123.42
3/14/2003	27.5	19.5	0.97	3.40	5.53	2.25	1.10	0.044	0.087	0.110	0.068	0.018	0.066	58%	33.42	63.92
3/16/2003	33	26.7	0.63	5.59	6.86	4.44	2.37	0.051	0.140	0.170	0.065	0.026	0.075	49%	39.00	74.58
3/20/2003	100	82.7	2.24	18.06	29.11	1.85	6.63	0.156	0.094	0.106	16.056	0.017	0.624	56%	70.20	134.25
3/21/2003	71.5	70.0	1.09	10.46	24.76	6.10	4.48	0.140	0.086	0.082	18.633	0.017	0.545	60%	55.41	105.96
3/25/2003	64	43.6	1.23	10.15	8.70	7.25	1.73	0.102	0.081	0.066	10.944	0.012	0.349	60%	53.78	102.83
3/26/2003	51	33.0	1.04	6.62	5.71	7.02	2.99	0.082	0.074	0.041	9.015	0.011	0.247	60%	44.73	85.54
3/27/2003	74.5	51.8	1.51	10.28	17.24	6.32	3.18	0.124	0.082	0.068	12.203	0.013	0.462	58%	72.14	137.96
3/28/2003	104.5	83.0	1.81	14.84	30.04	7.44	6.89	0.160	0.091	0.096	16.972	0.017	0.647	60%	67.59	129.25
4/3/2003	21.5	13.0	0.95	2.34	4.11	1.79	0.87	0.051	0.067	0.021	7.309	0.008	0.093	84%	36.76	70.29
4/4/2003	24	17.6	1.13	2.81	5.60	2.64	1.49	0.057	0.066	0.017	7.390	0.010	0.124	80%	37.72	72.13
4/5/2003	40	35.1	1.69	6.38	12.46	3.81	3.83	0.080	0.072	0.035	7.394	0.009	0.237	58%	39.50	75.54
4/6/2003	33	33.7	0.50	3.92	9.07	2.33	1.81	0.116	0.077	0.053	16.644	0.016	0.422	53%	20.66	39.50
4/7/2003	29	22.6	0.91	3.34	4.13	2.08	1.10	0.087	0.072	0.037	11.479	0.013	0.274	57%	31.53	60.29
4/8/2003	32	21.3	0.83	4.42	5.52	2.55	1.57	0.070	0.072	0.037	8.720	0.010	0.187	47%	36.98	70.71
4/9/2003	38.5	20.8	1.05	4.34	4.70	2.54	1.48	0.067	0.068	0.023	8.473	0.012	0.173	59%	41.42	79.21
4/10/2003	22	25.5	1.39	4.49	7.73	2.93	2.61	0.050	0.069	0.026	6.195	0.007	0.086	89%	37.78	72.25
4/19/2003	41.5	37.3	0.80	5.81	9.34	6.90	4.37	0.068	0.073	0.040	8.327	0.011	0.179	74%	27.17	51.96
4/20/2003	37	40.2	0.68	5.62	10.98	7.77	5.06	0.053	0.070	0.029	7.034	0.009	0.102	72%	20.70	39.58
4/21/2003	28.5	27.5	0.68	4.57	3.73	6.80	2.87	0.054	0.072	0.037	7.084	0.008	0.104	72%	24.64	47.13
4/22/2003	47	31.7	1.47	6.07	4.84	6.54	2.97	0.066	0.073	0.038	8.184	0.010	0.166	59%	45.10	86.25
4/24/2003	43.5	23.2	2.04	6.14	1.79	3.70	1.08	0.085	0.072	0.037	8.549	0.010	0.263	46%	48.94	93.58
4/25/2003	57	40.7	0.86	6.13	10.46	6.90	4.19	0.067	0.074	0.041	8.031	0.009	0.171	65%	30.57	58.46
4/26/2003	33.5	22.9	0.76	4.29	2.19	6.59	2.08	0.064	0.074	0.043	9.429	0.009	0.156	65%	30.03	57.42
4/27/2003	22	14.7	0.69	3.58	1.02	4.07	0.92	0.047	0.071	0.031	6.710	0.008	0.070	65%	23.25	44.46
5/7/2003	58	30.4	1.89	6.56	1.63	5.30	1.46	0.105	0.078	0.056	11.158	0.016	0.366	55%	54.95	105.08
5/8/2003	67	31.7	2.49	7.15	1.27	5.69	1.46	0.109	0.080	0.060	12.223	0.016	0.386	52%	52.45	100.29
5/10/2003	56.5	26.3	1.66	4.86	3.60	3.92	1.52	0.107	0.077	0.051	9.533	0.017	0.375	90%	44.60	85.29

5/11/2003	30	19.1	0.89	3.70	2.65	3.76	1.42	0.063	0.072	0.035	7.520	0.012	0.155	72%	28.19	53.92
5/12/2003	37.5	22.2	1.77	4.23	1.45	4.56	1.30	0.077	0.073	0.039	8.702	0.013	0.225	67%	42.29	80.88
5/13/2003	43	22.7	1.23	4.53	0.79	5.05	1.34	0.079	0.072	0.037	8.955	0.012	0.235	62%	40.48	77.42
5/17/2003	33.5	21.0	1.21	4.48	2.21	2.76	0.84	0.075	0.071	0.032	9.105	0.011	0.216	53%	35.58	68.04
5/18/2003	32	20.3	1.04	5.12	0.90	3.53	0.96	0.062	0.071	0.033	8.291	0.009	0.149	55%	32.20	61.58
5/24/2003	31.5	17.7	0.99	3.93	1.61	2.63	0.71	0.065	0.069	0.027	7.872	0.009	0.164	55%	36.95	70.66
5/25/2003	30	18.5	0.66	3.77	0.73	5.03	1.31	0.057	0.070	0.030	7.581	0.007	0.122	55%	25.75	49.25
5/26/2003	39.5	21.6	1.48	4.51	0.84	4.08	0.90	0.070	0.070	0.029	7.819	0.010	0.189	68%	34.68	66.32
5/27/2003	46.5	22.4	1.72	5.10	1.11	4.05	0.97	0.072	0.070	0.029	8.297	0.011	0.197	67%	23.01	44.00
5/28/2003	40.5	22.2	1.68	5.34	0.82	3.78	0.88	0.069	0.071	0.032	7.873	0.009	0.181	59%	37.24	71.21
5/29/2003	43	22.4	2.45	5.54	1.60	2.73	0.42	0.076	0.072	0.036	8.237	0.011	0.220	71%	41.01	78.42
6/1/2003	34.5	27.9	1.95	6.87	0.84	6.76	1.33	0.080	0.071	0.032	7.401	0.009	0.237	71%	20.87	39.92
6/2/2003	33	26.9	0.92	4.84	3.33	5.31	1.91	0.060	0.068	0.023	7.893	0.009	0.135	76%	23.49	44.92
6/3/2003	33	24.2	0.96	4.23	2.39	5.67	1.93	0.054	0.070	0.029	7.315	0.007	0.109	77%	30.00	57.38
6/7/2003	38	21.5	1.48	4.52	0.77	5.42	1.29	0.073	0.072	0.037	8.868	0.009	0.203	61%	32.07	61.33
6/14/2003	48.5	43.6	1.22	5.93	0.60	8.74	2.34	0.079	0.074	0.043	10.163	0.009	0.232	63%	23.01	44.00
6/15/2003	28.5	7.8	0.71	3.38	0.48	2.22	0.32	0.065	0.071	0.031	7.983	0.011	0.160	63%	16.49	31.54
6/16/2003	50	27.9	1.25	5.27	1.02	5.14	0.68	0.086	0.075	0.045	11.537	0.013	0.270	75%	26.04	49.79
6/17/2003	30.5	23.9	1.76	4.24	1.40	2.73	0.60	0.068	0.069	0.027	8.179	0.010	0.175	81%	27.34	52.29
6/18/2003	41	33.1	1.31	4.55	1.19	4.56	0.98	0.062	0.070	0.030	8.445	0.008	0.149	69%	25.38	48.54
6/19/2003	30	19.7	1.29	5.15	0.77	3.51	0.89	0.073	0.070	0.029	8.892	0.010	0.203	60%	27.69	52.96
6/20/2003	46	9.6	1.49	3.54	1.88	1.51	0.58	0.061	0.069	0.026	8.525	0.009	0.145	55%	39.57	75.66
7/1/2003	43	21.5	0.97	3.02	0.68	7.02	1.65	0.071	0.073	0.040	9.440	0.012	0.194	63%	18.67	35.71
7/3/2003	36	16.5	0.90	3.32	0.90	3.26	0.52	0.061	0.071	0.032	9.113	0.010	0.142	71%	20.61	39.42
7/4/2003	20.5	8.3	1.15	2.54	0.60	0.63	0.01	0.057	0.070	0.029	8.492	0.008	0.124	66%	24.95	47.71
7/9/2003	54	26.6	1.37	5.21	1.83	5.47	1.34	0.072	0.072	0.034	8.847	0.009	0.198	74%	34.62	66.21
7/10/2003	44	25.6	1.33	5.35	0.97	5.97	1.17	0.065	0.071	0.033	9.126	0.010	0.164	73%	25.62	49.00
7/14/2003	36.5	24.8	0.90	3.85	1.25	5.64	1.23	0.071	0.074	0.042	10.896	0.010	0.192	77%	20.50	39.21
7/19/2003	30.5	18.5	0.91	3.75	0.82	4.47	0.99	0.067	0.072	0.036	9.683	0.011	0.171	69%	20.79	39.75
7/20/2003	30	19.7	0.76	4.07	0.62	5.13	1.17	0.063	0.071	0.033	8.855	0.009	0.152	66%	17.06	32.63
10/5/2003	8	36.7	0.97	1.90	0.22	0.17	0.07	0.041	0.066	0.016	6.970	0.007	0.042	54%	11.81	22.58
10/10/2003	64.5	47.8	2.47	12.42	11.85	2.08	3.70	0.104	0.076	0.048	0.287	0.001	0.362	69%	44.54	85.17
10/18/2003	38	59.3	0.71	10.68	13.02	4.37	2.77	0.053	0.069	0.025	6.101	0.008	0.102	67%	28.70	54.88

10/19/2003	48.5	48.0	0.99	9.20	12.14	3.30	2.57	0.052	0.064	0.010	6.202	0.007	0.095	65%	27.91	53.38
10/20/2003	36	24.9	1.02	7.85	7.45	3.55	2.40	0.059	0.066	0.015	5.650	0.007	0.133	92%	27.51	52.61
10/28/2003	51	59.5	1.39	13.40	14.50	3.99	3.68	0.083	0.067	0.018	3.922	0.001	0.253	83%	36.00	68.83
10/29/2003	36	54.3	1.15	10.39	16.08	3.90	4.54	0.062	0.065	0.012	5.463	0.007	0.146	91%	35.97	68.79
10/30/2003	41.5	62.2	4.97	5.63	19.36	15.31	10.11	0.121	0.162	0.325	1.106	0.030	0.447	81%	31.99	61.17
11/1/2003	38	32.2	2.08	7.81	3.86	4.36	2.77	0.061	0.065	0.013	5.537	0.007	0.141	90%	27.28	52.17
11/2/2003	37.5	30.9	3.07	9.86	2.05	2.32	1.45	0.086	0.066	0.017	3.664	0.007	0.270	80%	28.43	54.38
11/3/2003	65	51.5	2.40	15.54	9.02	3.00	2.27	0.093	0.072	0.037	0.029	0.008	0.303	87%	35.06	67.04
11/5/2003	78.5	45.1	3.75	17.63	3.21	2.17	1.28	0.123	0.075	0.047	0.095	0.003	0.459	72%	48.48	92.71
11/8/2003	14.5	19.6	1.12	4.68	2.85	1.25	1.17	0.042	0.063	0.006	6.893	0.006	0.048	91%	25.54	48.83
11/10/2003	86	78.4	1.47	27.42	10.48	3.94	3.98	0.120	0.081	0.065	0.014	0.003	0.443	83%	42.75	81.75
11/13/2003	58	52.5	1.15	11.15	9.53	3.98	3.71	0.078	0.067	0.019	0.030	0.007	0.228	68%	33.34	63.75
11/14/2003	110	107.0	1.48	27.07	20.99	6.31	6.64	0.128	0.081	0.065	0.144	0.006	0.480	76%	43.03	82.29
11/21/2003	63	63.2	1.61	13.52	9.05	6.70	5.05	0.086	0.066	0.017	3.684	0.004	0.269	90%	40.33	77.13
11/22/2003	58.5	61.0	1.09	11.02	11.88	5.14	5.20	0.074	0.068	0.024	4.541	0.007	0.210	90%	27.24	52.08
11/23/2003	44.5	57.1	0.93	12.12	10.68	3.99	4.04	0.065	0.069	0.026	5.193	0.001	0.165	92%	24.64	47.13
12/3/2003	41.5	36.0	2.52	9.99	3.78	2.17	1.38	0.085	0.068	0.024	3.785	0.004	0.262	86%	30.59	58.50
12/4/2003	40.5	32.7	2.11	9.10	3.02	2.47	1.49	0.076	0.066	0.015	4.410	0.002	0.219	84%	34.34	65.66
12/5/2003	44	37.0	2.19	9.61	4.74	2.67	1.80	0.083	0.065	0.015	3.929	0.001	0.252	89%	34.73	66.42
12/11/2003	81.5	69.8	1.52	20.10	10.14	4.11	4.17	0.094	0.077	0.052	0.008	0.007	0.310	86%	33.69	64.42
12/12/2003	107	1.96	26.40	10.88	3.88	3.67	0.133	0.086	0.081	0.173	0.007	0.505	0.505	80%	44.19	84.50
12/13/2003	139	1.44	32.99	14.51	4.98	5.44	0.137	0.096	0.113	0.199	0.008	0.529	0.529	87%	53.45	102.21

Appendixes

Calculation of Light Extinction and Deciview

[2.20[Al]+2.49[Si]+1.63[Ca]+2.42[Fe]+1.94[Ti]]	0.6*[[PM$_{10}$] − [PM$_{2.5}$]]	10 [EC]	a,b 2.1 x (1 - RH)$^{-0.7}$	c 2.8 x (1 - RH)$^{-0.2}$	bag = 0.33×[NO2](ppb)	bext = a [NHSO] + b[NHNO] + c [OMC]+ d [Fine Soil]+ e [CM] + b_{ap} + b_{Ray} + $b\ ag$	Deciview = 10 ln(b$_{ext}$/10)
0.394	-4.21	5.57	12.304	4.64	4.742	124.41	25.21
0.469	-1.59	5.54	4.662	3.52	3.393	34.87	12.49
0.581	1.78	8.71	4.060	3.38	6.213	40.99	14.11
0.774	12.76	28.46	4.995	3.59	11.231	94.77	22.49
0.958	10.49	12.38	4.060	3.38	9.491	99.97	23.02
0.985	9.26	11.26	4.379	3.45	11.497	141.86	26.52
0.744	17.57	11.11	4.878	3.56	11.742	141.16	26.47
1.185	17.06	16.66	5.875	3.76	13.819	258.31	32.52
0.963	11.62	20.11	24.447	5.65	15.560	715.91	42.71
0.740	-2.98	6.16	8.759	4.21	5.501	122.29	25.04
0.678	3.35	24.30	7.924	4.09	7.722	102.11	23.23
0.719	3.59	12.82	4.212	3.42	8.742	75.55	20.22
1.204	-0.71	21.61	8.316	4.15	9.973	233.13	31.49
0.506	1.83	13.88	6.061	3.79	6.550	105.07	23.52
0.866	13.93	9.48	4.212	3.42	7.802	117.40	24.63
1.218	20.22	16.52	8.759	4.21	10.484	369.09	36.08
11.542	-5.78	11.32	8.759	4.21	7.428	359.63	35.82
7.962	1.07	16.14	4.878	3.56	8.952	217.17	30.78
14.672	6.96	10.22	3.920	3.35	11.267	118.74	24.74
16.824	0.60	9.00	4.563	3.50	11.886	209.12	30.40
15.972	7.09	7.49	3.731	3.30	9.110	61.80	18.21
16.338	29.62	18.33	3.003	3.10	16.624	130.12	25.66
17.748	20.29	16.54	3.854	3.33	17.767	181.18	28.97
22.052	24.33	16.47	3.791	3.31	19.500	345.03	35.41
2.507	21.72	19.24	3.854	3.33	30.919	370.49	36.12
2.317	16.47	19.53	4.379	3.45	27.137	339.10	35.24

1.395	3.51	16.06	4.134	3.40	22.513	378.49	36.34
9.856	-29.65	11.02	8.759	4.21	16.092	849.57	44.42
0.948	-8.85	13.93	6.975	3.95	16.071	483.44	38.78
12.262	17.18	14.07	4.379	3.45	21.032	259.84	32.57
1.080	7.99	19.33	4.469	3.47	21.298	253.08	32.31
0.619	4.79	9.72	3.854	3.33	11.030	77.46	20.47
0.799	3.79	6.29	3.364	3.20	12.871	89.68	21.94
28.290	10.37	22.38	3.731	3.30	23.167	269.29	32.93
32.246	0.92	10.86	3.988	3.36	18.285	230.57	31.38
19.131	12.26	12.30	3.988	3.36	17.746	169.15	28.28
15.677	10.81	10.39	3.988	3.36	14.762	134.68	26.00
21.511	13.60	15.09	3.854	3.33	23.807	209.04	30.40
29.843	12.89	18.14	3.988	3.36	22.305	292.57	33.76
12.433	5.08	9.51	7.574	4.04	12.130	103.31	23.35
12.656	3.81	11.26	6.479	3.86	12.447	114.38	24.37
12.999	2.92	16.89	3.854	3.33	13.036	139.80	26.38
28.630	-0.41	4.97	3.562	3.26	6.816	103.81	23.40
19.771	3.82	9.14	3.791	3.31	10.404	87.75	21.72
15.018	6.42	8.29	3.275	3.18	12.202	92.41	22.24
14.570	10.65	10.53	3.920	3.35	13.669	102.28	23.25
10.603	-2.10	13.86	9.846	4.35	12.468	171.44	28.42
14.358	2.52	8.00	5.392	3.67	8.966	152.73	27.26
12.020	-1.93	6.77	5.119	3.61	6.831	151.89	27.21
12.113	0.61	6.76	5.119	3.61	8.132	108.01	23.80
14.084	9.17	14.67	3.920	3.35	14.884	127.73	25.47
14.960	12.20	20.36	3.233	3.17	16.150	110.86	24.06
13.853	9.81	8.56	4.379	3.45	10.088	149.52	27.05
16.089	6.39	7.63	4.379	3.45	9.908	103.29	23.35
11.401	4.40	6.88	4.379	3.45	7.672	75.00	20.15
19.531	16.55	18.87	3.673	3.28	18.134	130.08	25.66
21.327	21.20	24.95	3.510	3.24	17.307	142.39	26.56
16.906	18.13	16.64	10.525	4.44	14.718	177.08	28.74
12.974	6.56	8.86	5.119	3.61	9.304	93.84	22.39

15.106	9.19	17.73	4.563	3.50	13.957	108.18	23.81
15.543	12.18	12.34	4.134	3.40	13.360	102.93	23.31
15.726	7.52	12.08	3.562	3.26	11.742	89.39	21.90
14.208	7.01	10.37	3.673	3.28	10.627	85.32	21.44
13.562	8.27	9.90	3.673	3.28	12.194	82.38	21.09
12.966	6.91	6.64	3.673	3.28	8.499	78.54	20.61
13.551	10.72	14.82	4.662	3.52	11.445	99.33	22.96
14.355	14.45	17.19	4.563	3.50	7.593	104.96	23.51
13.617	10.98	16.79	3.920	3.35	12.289	99.56	22.98
14.329	12.36	24.47	4.995	3.59	13.532	116.18	24.53
13.006	3.94	19.54	4.995	3.59	6.888	115.98	24.51
13.512	3.67	9.21	5.703	3.72	7.751	111.46	24.11
12.493	5.31	9.64	5.875	3.76	9.901	110.60	24.03
15.305	9.89	14.79	4.060	3.38	10.584	100.98	23.12
17.503	2.97	12.23	4.212	3.42	7.593	109.91	23.97
13.738	12.43	7.08	4.212	3.42	5.443	71.59	19.68
19.860	13.28	12.48	5.542	3.69	8.592	117.79	24.66
14.096	3.96	17.64	6.716	3.90	9.024	98.99	22.92
14.454	4.76	13.09	4.767	3.54	8.377	94.20	22.43
15.339	6.20	12.92	3.988	3.36	9.139	87.99	21.75
14.570	21.86	14.88	3.673	3.28	13.057	98.46	22.87
16.220	12.92	9.67	4.212	3.42	6.162	97.74	22.80
15.529	11.70	8.98	4.995	3.59	6.802	85.74	21.49
14.458	7.32	11.52	4.469	3.47	8.233	65.84	18.85
15.255	16.44	13.70	5.392	3.67	11.425	125.25	25.28
15.613	11.04	13.32	5.251	3.64	8.456	114.36	24.37
18.583	7.05	8.99	5.875	3.76	6.766	106.35	23.64
16.545	7.18	9.11	4.767	3.54	6.860	88.19	21.77
15.134	6.16	7.64	4.469	3.47	5.630	84.42	21.33
11.732	-17.24	9.72	3.617	3.27	3.897	43.00	14.59
1.765	10.03	24.67	4.767	3.54	14.697	171.53	28.42
10.494	-12.76	7.08	4.563	3.50	9.470	153.74	27.33
10.626	0.31	9.90	4.379	3.45	9.211	139.43	26.35

9.840	6.68	10.20	12.304	4.64	9.079	217.50	30.80
7.354	-5.07	13.90	7.259	3.99	11.878	230.83	31.39
9.569	-10.99	11.53	11.331	4.53	11.871	316.35	34.54
3.609	-12.42	49.74	6.716	3.90	10.555	328.70	34.93
9.676	3.47	20.83	10.525	4.44	9.002	174.16	28.57
6.995	3.95	30.75	6.479	3.86	9.383	127.49	25.45
1.180	8.09	24.02	8.759	4.21	11.569	225.55	31.16
1.729	20.02	37.52	5.119	3.61	15.999	176.48	28.71
11.613	-3.04	11.23	11.331	4.53	8.427	108.93	23.88
1.566	4.57	14.66	7.259	3.99	14.108	259.01	32.54
0.953	3.29	11.47	4.662	3.52	11.001	138.89	26.31
1.889	1.79	14.79	5.703	3.72	14.201	299.23	33.99
7.017	-0.14	16.10	10.525	4.44	13.309	272.17	33.04
8.258	-1.50	10.90	10.525	4.44	8.988	266.12	32.81
9.181	-7.58	9.35	12.304	4.64	8.132	273.39	33.08
7.168	3.30	25.20	8.316	4.15	10.095	146.64	26.85
8.052	4.67	21.15	7.574	4.04	11.331	133.59	25.92
7.362	4.19	21.93	9.846	4.35	11.461	169.74	28.32
1.175	7.04	15.16	8.316	4.15	11.116	246.38	32.04
2.605	63.02	264.00	6.479	3.86	14.582	445.16	37.96
2.812	82.54	329.90	8.759	4.21	17.638	595.22	40.86

Appendixes

Individual Contribution (in %) of Chemical composition of particulate matter on Total Light extinction (b_{ext})

Sulfate	Nitrate	Organic Carbon	Fine Soil	Elemental Carbon	Gas Scattering (NO_2)	Coarse Mass
%	%	%	%	%	%	%
24.88	48.11	10.37	0.32	4.48	3.81	-
21.46	3.16	19.76	1.35	15.88	9.73	-
11.18	2.15	20.10	1.42	21.25	15.16	4.35
8.43	3.16	21.69	0.82	30.03	11.85	13.46
15.12	11.44	30.12	0.96	12.38	9.49	10.49
16.81	22.85	30.02	0.69	7.94	8.10	6.53
22.46	8.98	32.31	0.53	7.87	8.32	12.45
20.70	38.67	17.90	0.46	6.45	5.35	6.60
30.84	45.67	15.35	0.13	2.81	2.17	1.62
32.95	36.53	12.21	0.61	5.04	4.50	-
7.76	30.27	16.88	0.66	23.79	7.56	3.28
9.48	15.05	28.00	0.95	16.96	11.57	4.75
13.74	26.70	41.21	0.52	9.27	4.28	-
14.89	23.61	30.31	0.48	13.21	6.23	1.75
19.07	23.02	22.07	0.74	8.07	6.65	11.87
24.57	27.94	31.65	0.33	4.48	2.84	5.48
31.46	48.58	8.76	3.21	3.15	2.07	-
10.18	39.28	30.23	3.67	7.43	4.12	0.49
7.22	21.84	26.22	12.36	8.60	9.49	5.86
9.51	46.57	20.82	8.05	4.30	5.68	0.28
2.77	1.53	15.34	25.84	12.11	14.74	11.48
3.42	7.70	19.03	12.56	14.08	12.78	22.76
4.02	20.83	29.70	9.80	9.13	9.81	11.20
9.88	35.86	27.49	6.39	4.77	5.65	7.05
8.23	36.82	32.17	0.68	5.19	8.35	5.86
12.29	39.27	26.19	0.68	5.76	8.00	4.86
9.40	58.07	18.40	0.37	4.24	5.95	0.93
12.40	73.84	8.23	1.16	1.30	1.89	-
18.37	61.15	12.00	0.20	2.88	3.32	-
10.86	40.85	19.61	4.72	5.41	8.09	6.61
10.55	44.76	21.10	0.43	7.64	8.42	3.16
11.18	27.52	14.61	0.80	12.55	14.24	6.19
16.64	25.74	19.98	0.89	7.01	14.35	4.23
2.56	40.32	22.13	10.51	8.31	8.60	3.85
10.55	42.83	15.25	13.99	4.71	7.93	0.40
17.09	20.51	20.17	11.31	7.27	10.49	7.25
20.79	16.90	16.54	11.64	7.72	10.96	8.03

11.66	31.78	16.38	10.29	7.22	11.39	6.50
10.15	40.95	17.05	10.20	6.20	7.62	4.40
13.14	30.14	9.14	12.03	9.21	11.74	4.92
14.94	31.70	9.50	11.06	9.84	10.88	3.33
10.49	34.36	15.20	9.30	12.08	9.32	2.09
7.99	31.14	12.31	27.58	4.78	6.57	-
8.97	17.87	12.61	22.53	10.41	11.86	4.36
9.03	19.57	15.20	16.25	8.97	13.20	6.94
9.73	18.00	14.18	14.24	10.30	13.36	10.41
16.82	44.40	11.41	6.18	8.09	7.27	-
24.37	32.98	13.94	9.40	5.24	5.87	1.65
26.18	37.00	13.37	7.91	4.46	4.50	-
32.22	17.68	15.27	11.22	6.26	7.53	0.57
20.06	14.86	15.91	11.03	11.48	11.65	7.18
10.78	5.21	17.55	13.49	18.36	14.57	11.01
20.21	30.64	14.16	9.27	5.72	6.75	6.56
27.96	9.27	14.35	15.58	7.39	9.59	6.19
23.77	5.95	16.48	15.20	9.17	10.23	5.87
14.97	4.60	16.56	15.01	14.50	13.94	12.72
14.02	3.13	16.29	14.98	17.52	12.15	14.89
23.27	21.42	12.17	9.55	9.40	8.31	10.24
20.50	14.45	14.22	13.83	9.44	9.91	6.99
19.22	6.11	13.68	13.96	16.39	12.90	8.49
20.28	3.16	14.94	15.10	11.99	12.98	11.83
11.01	8.81	16.33	17.59	13.52	13.14	8.41
15.20	3.88	19.72	16.65	12.15	12.46	8.22
11.71	7.17	15.66	16.46	12.02	14.80	10.04
23.50	3.43	15.76	16.51	8.45	10.82	8.79
19.15	3.95	15.96	13.64	14.92	11.52	10.79
17.61	4.83	16.98	13.68	16.38	7.23	13.77
14.89	3.22	17.94	13.68	16.86	12.34	11.03
11.76	6.87	17.09	12.33	21.06	11.65	10.64
29.10	3.63	21.24	11.21	16.85	5.94	3.40
27.19	17.04	16.17	12.12	8.26	6.95	3.29
30.11	12.71	14.37	11.30	8.72	8.95	4.80
21.78	3.11	15.13	15.16	14.64	10.48	9.80
33.50	2.31	18.43	15.92	11.13	6.91	2.70
13.05	2.79	16.14	19.19	9.88	7.60	17.37
24.18	4.78	16.53	16.86	10.59	7.29	11.28
18.52	9.49	16.71	14.24	17.82	9.12	4.00
23.10	6.00	17.10	15.34	13.89	8.89	5.06
15.89	3.51	19.68	17.43	14.68	10.39	7.05
5.63	7.02	11.81	14.80	15.12	13.26	22.21
30.27	2.92	10.57	16.59	9.89	6.30	13.22
19.02	5.26	13.89	18.11	10.47	7.93	13.65

4.27	4.04	13.41	21.96	17.50	12.50	11.12
23.53	7.88	15.24	12.18	10.94	9.12	13.13
27.42	4.46	17.03	13.65	11.64	7.39	9.65
31.18	6.89	13.60	17.47	8.46	6.36	6.63
24.18	4.41	15.06	18.76	10.33	7.78	8.14
27.16	3.29	16.76	17.93	9.05	6.67	7.30
1.47	1.83	14.48	27.28	22.61	9.06	-
5.78	32.94	25.62	1.03	14.38	8.57	5.85
12.98	38.64	24.28	6.83	4.60	6.16	-
10.36	38.13	22.79	7.62	7.10	6.61	0.22
20.06	42.14	16.75	4.52	4.69	4.17	3.07
12.54	45.60	23.17	3.19	6.02	5.15	-
13.96	57.58	14.88	3.02	3.64	3.75	-
31.28	39.56	6.68	1.10	15.13	3.21	-
26.37	23.32	19.89	5.56	11.96	5.17	1.99
11.77	10.43	29.88	5.49	24.12	7.36	3.10
11.65	35.03	29.00	0.52	10.65	5.13	3.59
6.30	9.31	36.07	0.98	21.26	9.07	11.34
13.02	29.62	19.48	10.66	10.30	7.74	-
11.05	29.37	42.25	0.60	5.66	5.45	1.76
13.35	31.99	28.23	0.69	8.26	7.92	2.37
12.03	40.01	33.70	0.63	4.94	4.75	0.60
25.91	34.98	22.05	2.58	5.92	4.89	-
20.32	46.97	18.38	3.10	4.09	3.38	-
17.98	48.05	20.56	3.36	3.42	2.97	-
12.30	21.42	28.26	4.89	17.18	6.88	2.25
14.01	17.14	27.53	6.03	15.83	8.48	3.49
15.48	27.50	24.65	4.34	12.92	6.75	2.47
13.86	34.24	33.85	0.48	6.15	4.51	2.86
5.34	5.65	9.44	0.59	59.30	3.28	14.16
8.00	7.33	10.26	0.47	55.43	2.96	13.87