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Environmental and Land Planning Engineering

LAPSE RATE INVERSIONS IN THE PO VALLEY:
A 30-YEAR OVERVIEW

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SUMMARY

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1 ABSTRACT

1.1 English abstract

In this study some features of lapse rate inversions in the lower layers of the atmosphere over the Northern Italy area of the Po Valley have been investigated. Radiosonde data available at 12 UTC from four meteorological stations (Cuneo Levaldigi, Milano Linate, San Pietro Capofiume and Rivolto) located in this area have been taken into account considering a 32-year period from 1985 to 2016; Milano Linate's data have been found to be the most complete in terms of data coverage, so they have been used for a consistent part of the following evaluations. In particular, parameters like the number of occurrence of days with thermal inversion observed, the number of occurrence of "inversion events" (i.e. time periods formed by consecutive "inversion days) and their temporal features (i.e. time-span distribution) and the vertical structure of the temperature lapse rate on inversion days have been investigated; these evaluation has been carried on both annual and seasonal basis. Some analysis have shown that there are common features through this air basin, while there significant differences in other aspects; in addition, assessments on trend evolution (on annual and seasonal basis) of some phenomena have shown that there are different behaviours depending on the season considered. An empirical model for the distribution of thermal inversion events' duration has been developed; at last, a comparison between data from radiosonde and radon measurements made by the University of Milan has been carried on in order to evaluate if the two different methods are useful and consistent to determine the free mixing height generated from subsidence inversions.

1.2 Italian summary

Le inversioni termiche nei bassi strati dell'atmosfera sono fenomeni che si generano in condizioni di alta stabilità, che sono sfavorevoli alla dispersione degli inquinanti, con la conseguenza di un peggioramento delle caratteristiche della massa d'aria interessata e

delle condizioni dell'aria che respiriamo. Questo fenomeno può essere critico in particolare nei mesi invernali, quando spesso i limiti di qualità dell'aria vengono spesso superati. Da questo punto di vista, nel contesto europeo la Pianura Padana è un'area molto critica, sia per le sue caratteristiche orografiche e geografiche sia per il suo elevato grado di urbanizzazione e industrializzazione. I dati utilizzati, provenienti da quattro diverse stazioni meteorologiche distribuite nel territorio considerato (Cuneo Levaldigi, Milano Linate, San Pietro Capofiume e Rivolto), si riferiscono alle misure effettuate dai palloni sonda alle ore 12 UTC (le 13 in Italia), nel periodo 1985-2016; da questi dati sono state ricavate informazioni riguardanti alcune delle caratteristiche delle inversioni termiche (ad esempio: numero di giorni di inversione, numero eventi di inversione e loro durata, spessore delle inversioni, tipologia di inversione), in modo da valutare, ove possibile, eventuali andamenti significativi nel tempo, basandosi su valutazioni di tipo annuale e stagionale. Si è proceduto con le stesse modalità stazione per stazione, andando poi ad individuare eventuali similarità o differenze tra le varie stazioni e andando a definire un modello empirico che rappresentasse la distribuzione delle durate degli eventi nelle varie stazioni considerate; la maggior parte delle analisi si sono concentrate sui dati provenienti da Milano Linate, i migliori in termini di completezza nei 32 anni considerati. Inoltre, è stato possibile confrontare alcuni dati messi a disposizione dall'Università degli Studi di Milano, derivati da misure di concentrazioni di radon in atmosfera, con i dati dei radiosondaggi di Linate per valutare la coerenza e la consistenza dei due metodi per la stima dell'altezza di libero rimescolamento generata dalle inversioni termiche.

2 INTRODUCTION

This study is based on the analysis of historical data coming from soundings of four different stations located in the Po Valley region, considering a 32-year period from 1985 to 2016. Other assessments taken in this part of Italy have been carried on to evaluate air pollution concerns that are a common feature of this area, considering many aspects of this phenomenon, like aerosols and particulate matter. Here, some inversion characteristics have been studied considering both qualitative and quantitative aspects.

2.1 Location

The Po Valley region is a 46000 km^2 flat area in the Northern part of Italy. There are about 20 million people living in this region, between the Alps and the Apennines. It is the industrial and economical core of Italy, but especially in recent years it is dealing with air pollution concerns, with serious problems to meet the EU standards for air quality. It has also to be considered that there are an estimated 2.6–4,4 million premature deaths per year all over the world due to poor air quality causes (Horton et al., 2014), so this is not a major problem only in this specific region: in fact, more than 92% of population deals with air pollution effects and in 2012 there was a peak of 6,5 million of deaths for this reason (WHO, 2016). Those concerns are related both to high emissions of pollutants and to various periods of strong stability of the low atmosphere due to poor recirculation of air and also for weak vertical dispersion of pollutants. These unfavourable conditions very frequently occur in the Po Valley region: winds generally have an average speed between 1.4-2.5 m/s (considering 2006 - 2015 data), but they can decrease consistently during winter periods in some areas in Piedmont (ARPA Piemonte, 2016) and elsewhere, so that the advection factor is not so important; in addition, the lack of well-distributed rainfall events over time (with many “winter droughts” occurring) makes the wet removal mechanism like a palliative solution on which we cannot rely on so much to comply with EU standards of air quality.

Some studies have focused their attention on the relationship between PM_{10} air pollution and thermal inversions in Alpine valleys, where there are some effects due to particular orography (Largeron and Staquet, 2016), while others have assessed particular mechanisms of high-pressure systems or the presence of a nearby sea (Katsoulis, 1987; Iacobellis et al., 2010), which can lead to regional scale atmospheric circulation and unfavourable dispersion conditions, such as vertical inversion of temperature. In this case, it has been considered a very wide flat area that it seems like a "calm basin", that is not really affected by a particular orography and where the sea presence is not determinant, in particular in Piedmont and Lombardy regions.

2.2 Thermal inversions

In normal conditions, the ambient temperature tends to decrease with height with many lapse rates. In particular, three reference lapse rates can be take into account: the dry adiabatic lapse rate (-0,98 K/100m), the moist adiabatic lapse rate (about -0,6 K/100m) and the one of the International Standard Atmosphere (ISA), defined by the International Civil Aviation Organization (ICAO), which has a lapse rate of -0,65 K/100m on average. However, there are also situations where the environmental lapse rate is positive, so there is an increase of temperature with height: these situations are the so-called "thermal inversions". Thermal inversion layers can be formed basically in two ways. *Subsidence inversions*, that can occur when there is a high-pressure condition at ground level and a low turbulence in the near-surface atmospheric layer (typical anticyclonic state). This situation happens when there are upper tropospheric layers, heavier and cooler ones, which come down in place of the relatively warmer layers underneath them; typically, there is not heat exchange between the two air masses when these movements occur. *Radiation inversions* are typically ground-level phenomena that occur mainly during nights because of the differential lack of solar irradiation in the vertical profile of the atmosphere: layers close to the ground usually cool down very quickly compared to the upper ones; this kind of inversions can survive during early mornings but also in daylight hours (Iacobellis et al., 2009) if there are favourable conditions. Therefore, under thermal inversion conditions, vertical dispersion of pollutants is highly limited (Giuliacci et al., 2010) and this can lead to their concentration build-up, with the subsequent health concerns.

2.3 Measurements of vertical temperature profile

The atmosphere is constantly monitored all over the world using many techniques that have been developed since the late 19th century: meteographs bound with kites, radiosonde, dropsonde from airplanes, radio acoustic sounding systems (RASS) from ground level, and satellite data. Each of these techniques has its own strengths and weaknesses, depending on the type of analysis that it is aimed for. In this study, data coming from radiosonde soundings has been used; they are taken from the so called "weather balloons", that can reach over than 35000 m a.s.l.. These systems are composed by a balloon filled with helium (or hydrogen) that carries a radiosonde, which transmits meteorological data in real time to a radio receiver or and to a GPS system during the flight, in order to know its position and the characteristics of the atmosphere that is passed through; after the upward flight, a small parachute permits to the radiosonde the descent (Figure 2.3.1).

Figure 2.3.1: Typical weather balloon during a flight

Data collected are processed in order to give all the informations about the characteristics of the atmosphere in a precise time, like pressure, temperature, humidity, wind direction and intensity; results of these processing phase can be found in many representations, as text files or diagrams like Skew T-Log P (also called Herlofson diagram) and Stüve, emagrams and tephigrams. All of these are commonly used to represent meteorological variables in many ways and are very useful for weather forecasting purposes.

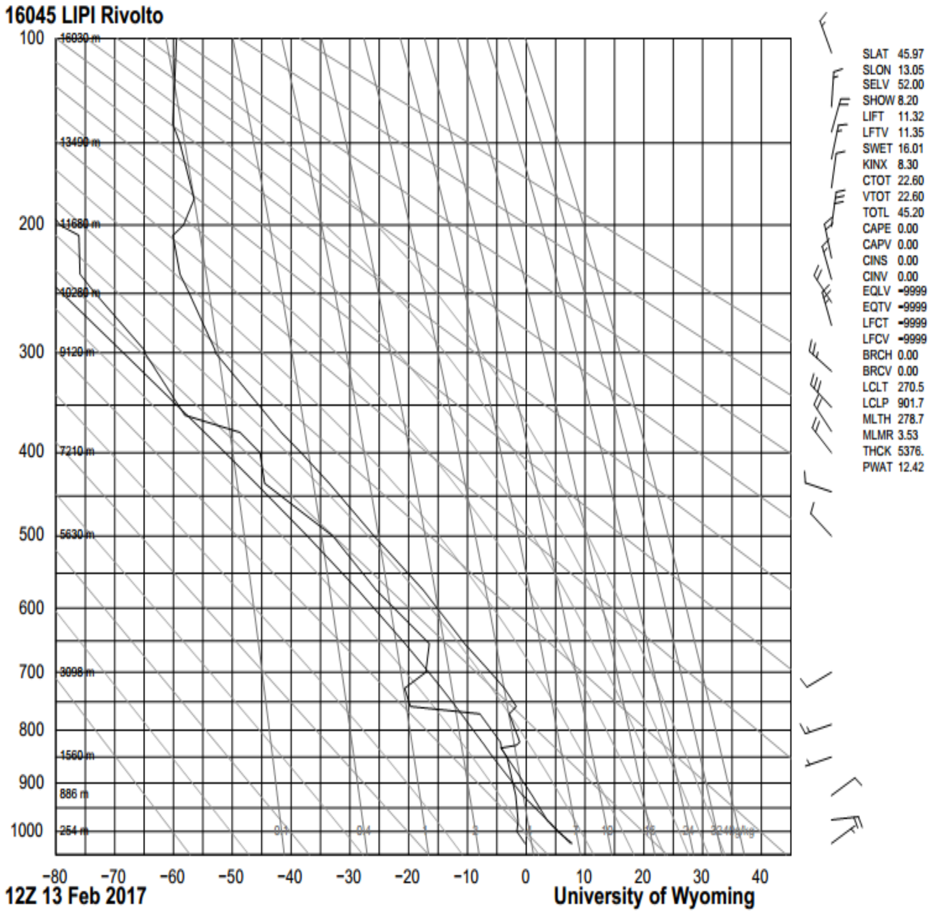


Figure 2.3.2: Example of a Stüve diagram; the left curve represents the dew point, the right curve the temperature and there are info about direction and strength of the wind at various geopotential heights

In this study, data have a great completeness about pressure levels in the vertical profile but there have not been many information about the height in metres related to them. There are physical relationships between these two variables, given by many organizations, such as WMO, ICAO and others. For example, considering the characteristics of the International Standard Atmosphere, defined in 1976 by ISO, various equations (obtained by the application of Stevin law and the ideal gas law) for different altitudes can be used; from a brief analysis of the soundings data considered, it was found that 1 hPa pressure decrease on the vertical corresponds to about 9 metres rise in altitude, on average.

In this work, the features of diurnal thermal inversions in the Po valley have been investigated based on 30 years of vertical soundings coming from the four meteorological stations mentioned before. In particular, the following aspects have been analysed:

- number and frequency of occurrence, on both annual and seasonal basis, of days with thermal inversion observed at 12Z;
- number and frequency of occurrence of “inversions events”, i.e. time periods formed by consecutive “inversion days”;
- temporal features of the "inversion events", i.e. their distributions in terms of time-span (number of consecutive “inversion days” forming each inversion event;
- vertical structure of the temperature lapse rate on inversion days, in terms of location of the base of the inversion, thickness of the inversion layer, number of layers occurred and the free mixing height generated (Figure 2.3.3).

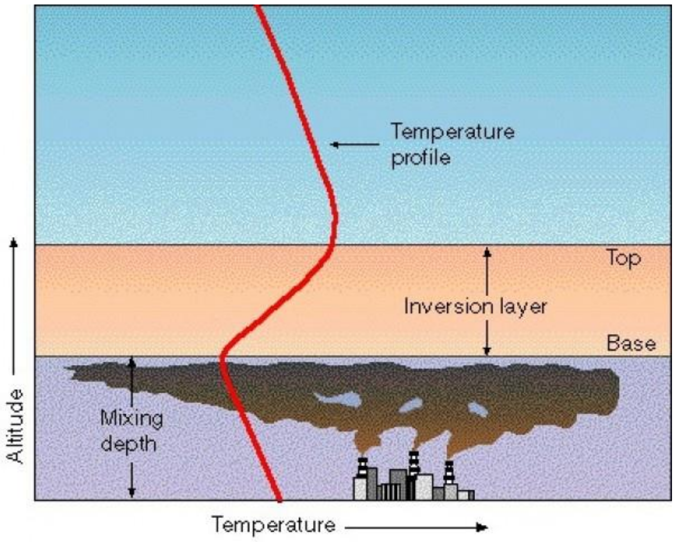


Figure 2.3.3: Thermal inversion example: variables involved in the study (base of inversion, thickness, mixing height/depth)

3 MATERIALS AND METHODS

3.1 Data selection

There are plenty of information available from radiosonde soundings, such as vertical profile of temperature, relative humidity, strength and direction of the wind at every pressure level considered. These soundings are taken all over the world from more than 800 stations at the same reference time, that is the UTC time at the 0° longitude in Greenwich (basically the so called "00Z" at midnight,"12Z" at noon), and they are released daily as vertical profiles of the atmosphere and collected into many databases (e.g. NOAA). In this study, the database of the Department of Atmospheric Science, University of Wyoming, has been examined; from this collection of measurements, data from the four meteorological stations in the Po Valley area, where soundings are routinely performed, have been retrieved: **Cuneo Levaldigi Airport** (ICAO: LIMZ), located at 44°32′49.27″N, 7°37′23.58″E, in the Western side of the Po Valley, **Milano Linate Airport** (ICAO: LIML) located at 45°26′58″N, 9°16′42″E, in the Central part, **San Pietro Capofiume** (SPC station), located at 44°39′13.63″N, 11°37′22.28″E, in the South-Eastern part, and **Rivolto Military Airport** (ICAO: LIPI), located at 45°58′54″N 13°03′03″E, in the very North-Eastern part of the Po Valley.

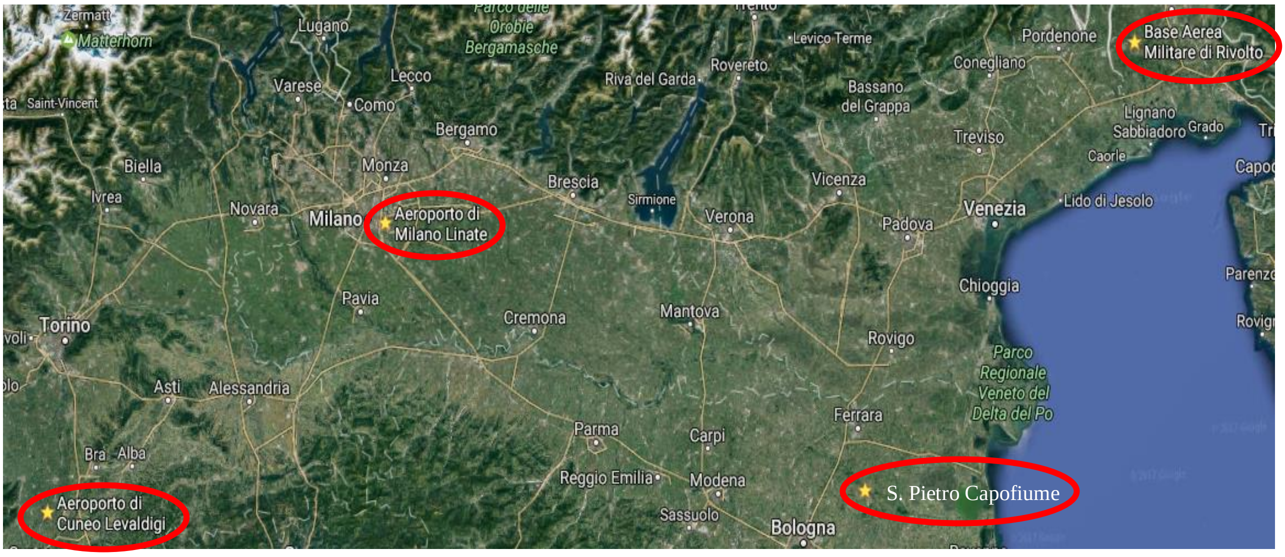


Figure 3.1.1: Location of the four station in the Po Valley

In this work, only the "12Z" measurements have been considered (this time corresponds to 1 p.m. in Italy), and it has been assumed that if a thermal inversion in the vertical profile at "12Z" time was found, it has to be present throughout all the day. Actually, only strong and persistent inversion events can last until noon and beyond, and these ones are the most related to air pollution concerns. In addition, another assumption has been taken: it has been considered the presence of a thermal inversion even if there was an isothermal condition in the vertical profile; in this case, in fact, the atmosphere has been evaluated as under stable condition: it has to be noticed that the typical temperature gradient that is used in basic meteorology to separate a stable atmosphere from an unstable one is the dry adiabatic lapse rate; so, the isothermal situation has been evaluated as a condition that guarantees a certain stability: for this reason, the vertical dispersion of pollutants is not facilitated anyway.

Then, a selection of the amount of soundings has been carried on; in fact, data that has been taken into account for the evaluation of the presence of a thermal inversion were below the 850 hPa level (that corresponds to about 1500 m a.s.l.), because in this low-layer the pollution events have great concerns about human and environmental health. It has been considered that the situation in the upper part of the atmosphere can be interest of study mainly for general circulation and continental/global scale considerations. So, upper atmosphere inversions were not considered in this study.

So all data coming from each station, collected each month in several text files, were imported in order to select the first seven levels of pressure for each sounding and other information such as the related height and temperature, as it was done in another study done before this one (Caserini et al., 2016). In this cited study, it has been noticed that the radiosonde data reach the 850 hPa pressure level after about 6 measurements on average, so this makes the system under easily processable conditions; of course, the use of this system sometimes may exclude the 850 hPa level if there is a denser measurement than expected: this situation has been verified, and it occurs for at maximum 5% of the overall data used, so it has been considered that this system was acceptable for this application anyway. The reference period that has been taken into account goes from 1985 to 2016, a 32-year period: this is a significant period for climatologic evaluations, so that seasonal variability does not affect heavily the results.

In literature studies, inversions have been classified by their strength, defined as the difference between temperatures at the top and the base of the inversion layer (Guèdjè et al., 2016; Wei et al., 2013) In this work, different features of inversion have been investigated: inversions have been classified by their position (ground-based or elevated ones), height of occurrence (considering the base of the inversion as the reference height), thickness (difference between the top and the base of the inversion layer, expressed in hPa) and duration of events (in days) and, so, it was possible to know the total number of events that have occurred in the period considered. It has to be highlighted the fact that it has been considered as an “event” a period when a thermal inversion has occurred consecutively for one or more days, without considering if it was the same layer of inversion that might has changed during the specific event or, instead, there was the occurrence of two (or more) different types of inversion one after the other.

In case of the presence of multiple inversion layers from ground-level to 850 hPa, the height of the nearest one to the ground inversion has been considered to evaluate the free mixing height, but all of the multiple layers has been taken into account in the overall study of thicknesses, so they have not been grouped together.

Daily data available have been grouped into two main reference periods (annual and seasonal) in order to carry on some evaluations about trends. The seasonal period that has been chosen is the typical meteorological splitting of the year: Spring (March, April and May: MAM), Summer (June, July and August: JJA), Autumn (September, October and November: SON) and Winter (December, January and February: DJF). It has to be highlighted that DJF periods are assigned to a specific year considering the continuous Dec - Jan - Feb year: so, for example, a "2004 DJF" period considers days between 01/12/2003 and 29/02/2004, even if some days are of the 2003 year. For this reason, seasonal evaluations start without December 1984 and end up with November 2016, so there is the exclusion of December 2016 data.

As it has been described earlier in this chapter, for each station daily data have been downloaded and treated properly. First of all, a normalization of data through the 1985-2016 calendar has been carried on to check the availability and to understand whether a thermal inversion has been occurred day by day; after that operation, *n*-consecutive days with a thermal inversion have been labelled as a *n*-days event, without considering the "00Z" data.

3.2 Statistical methods

At the end of this processing, an evaluation of possible trends of some of these variables has been carried on. In particular, trends have been calculated with linear regressions (they has been estimated with the Ordinary Least Squares method), giving a general relationship as:

$$Y = m * X + q$$

Subsequently two statistical assessments have been made (the F-test and the Mann-Kendall one) in order to understand whether the observed trends were statistically significant or not, assuming a 5% significance level (α) throughout all this study.

The F-test aims to give information about the *m* coefficient of the linear regression (the slope): the null hypothesis (H_0) and the alternative one (H_1) are listed here below:

$$H_0: m = 0$$

$$H_1: m \neq 0$$

So, if the null hypothesis is rejected, a linear relationship between X and Y subsists; otherwise, there is no evidence of a linear trend, but it has to be highlighted the fact that there may be different, non-linear, relationships (second-degree or higher). The statistic variable evaluated is defined as:

$$F_{(1,n-2)} = \frac{Variance\ of\ the\ regression}{Variance\ of\ the\ error}$$

where:

- n = number of data;
- Variances involved are evaluated from the corresponding deviances divided by their degrees of freedom (1 for the regression, n-2 for the error).

The value calculated has been compared with the statistical tables available on statistical books.

Non-parametric Mann-Kendall test has been applied to data series to evaluate the presence of a monotonic upward or downward trend of the variable of interest over time (i.e. number of inversion days and number of inversion events), considering also non-linear trends (Gilbert, 1987); the null hypothesis (H_0) and the alternative one (H_1) are listed here below:

$$H_0: no\ monotonic\ trend$$

$$H_1: monotonic\ trend\ is\ present\ (upward\ or\ downward)$$

In this test, the *S* variable is based on the signum function (*sgn*) between two consecutive data in time:

$$S = \sum_{k-1}^{n-1} \sum_{j-k+1}^{n} sgn(x_j - x_k)$$

where:

- *sgn* (x_j - x_k) can assume three values (-1; 0; 1), according to the difference between the (*j*, *k*)-values;

- n = number of data;
- there are $n*(n - 1)/2$ possible differences with $j > k$.

So, if S is a positive number, observations obtained later in time tend to be larger than observations made earlier. Otherwise, if S is a negative number, then observations made later in time tend to be smaller than observations made earlier.

For $n > 10$, the variance of the S variable is determined as:

$$VAR\ (S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p-1}^{g} t_p(t_p - 1)(2t_p + 5)\right]$$

where g is the number of tied groups and t_p is the number of data points in the g^{th} group.

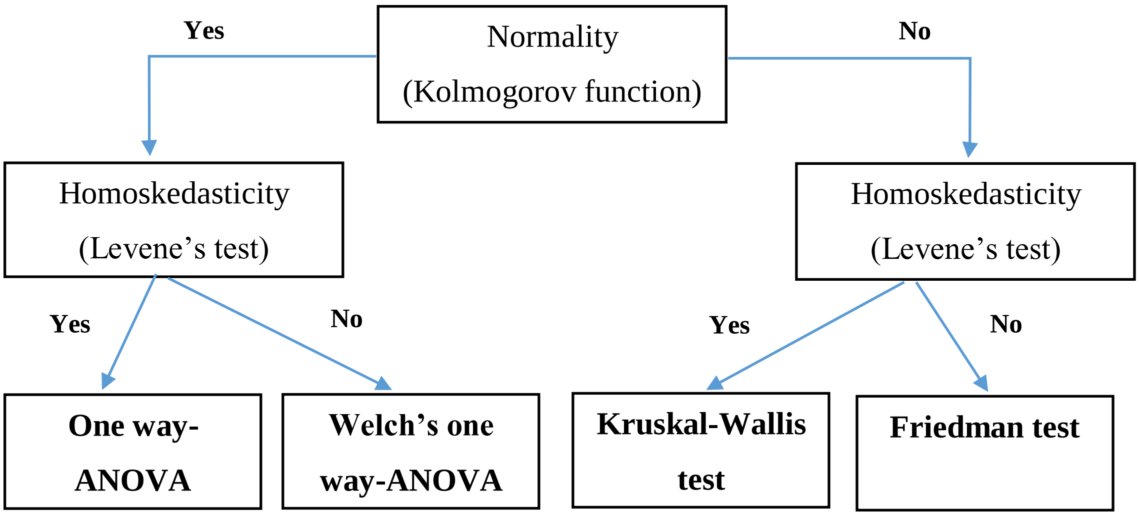
At this point, the Z_{MK} test statistic is defined as follows:

$$Z_{MK} = \begin{cases} \dfrac{S-1}{\sqrt{VAR\ (S)}}, if\ S > 0 \\ 0\ , if\ S = 0 \\ \dfrac{S+1}{\sqrt{VAR\ (S)}}, if\ S < 0 \end{cases}$$

This Z_{MK} statistic is compared with the values from the standard normal distribution Z; $|Z_{MK}|$ has to be greater than $Z_{(1-\alpha/2)}$ value to reject the null hypothesis at the type I error rate α. These evaluations about the number of inversion days and events have been carried on both on annual and seasonal basis.

In addition, a slightly modified version of the Mann-Kendall test, known as Seasonal Kendall test (Hirsch et al., 1982; Gilbert, 1987; Helsel, 1995) has been applied only on a three-month basis, as it was reported before. However, this test can be misleading if some seasons have an upward trend and it is downward in other ones. It consists in a Mann-Kendall test that is carried on separately for each season: this lead to four different values for S and VAR (S), respectively; then, these values are added in order to have a Z_{SK} statistic that it has been calculated in the same way of the Z_{MK} statistic.

In the regional analysis' chapter, the calculated means and standard deviations have been assessed in order to know if there have been significant differences between stations considered. For this purpose, two assumptions have been verified: the normality of the distribution, by using a slight modification of the Kolmogorov-Smirnov test (Abdi and Molin, 2007), and the homogeneity of the variance, by using the Levene's test. These two assessments have been performed for all the data series involved; after each evaluation, it has been decided to carry on a specific statistical test (and a related post-hoc test when three stations have been considered), by considering the accomplishment of the various assumptions. It has to be highlighted the fact that data series have been selected with a required minimum 75% data coverage for each year. These considerations have been summarized in this diagram below:



Many types of post-hoc tests are available for different applications, with the aim to know which group of measurement is statistically different from the others, and in this study it has been decided to apply the Tukey-Kramer test after the one-way ANOVA and the Games-Howell test after the Welch's one-way ANOVA. There have not been found cases where Friedman and Kruskal-Wallis' tests could be applied.

4 RESULTS AND DISCUSSION

In this chapter, results obtained for each meteorological station are presented separately: for each station, despite the different data consistency, the same evaluations about the main characteristics of the thermal inversion phenomenon have been developed. In particular, the following aspects have been investigated:

- Number of days with thermal inversion at 12Z*;*
- Number of thermal inversion events*;*
- Duration of events*;*
- Characteristics of thermal inversions.

Statistical tests for trends of the number of days and events, mentioned in the previous chapter, are applied only on the data coming from Milano Linate station (LIML) because of the good completeness in time of the data series. At the end of the characterization, possible common features between the four stations have been studied.

4.1 Cuneo Levaldigi Airport (LIMZ) station

4.1.1 Data availability

The station is located at 384 m above sea level, in a rural area in Southern Piedmont region. Soundings are managed by ARPA Piedmont and by the Italian Air Force Weather Service. Data availability is limited to the last 17 years, starting from 2000. However, during this 17-year period data were not continuously collected, with a significant drop of data coverage between 2010 and 2013 (as shown in Figure 4.1.1).

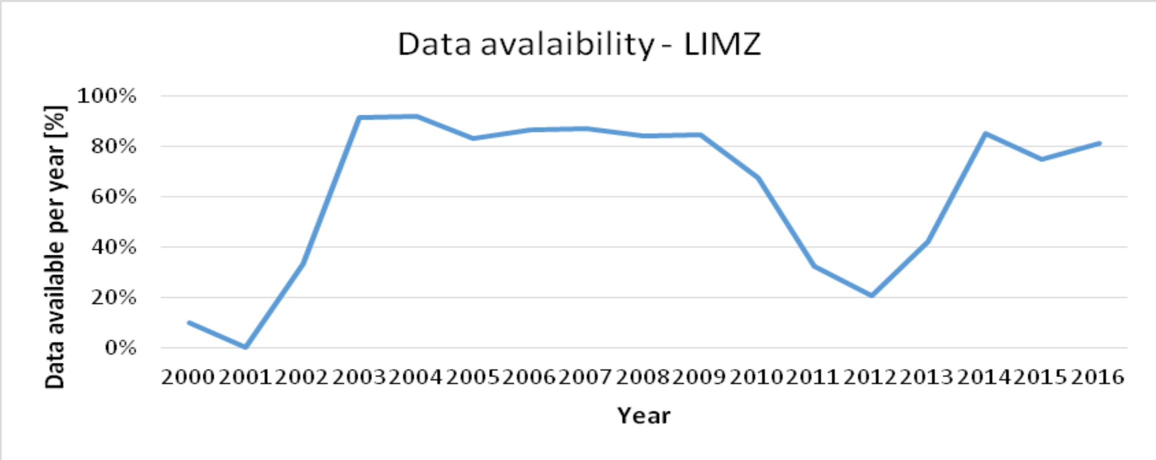


Figure 4.1.1: Data availability of Cuneo Levaldigi station

For this reason, some assessments about time trends could not be performed.

An overall evaluation of the presence of thermal inversions in the lower part of the atmosphere has been taken on by annual and seasonal basis. In Table 4.1.1, the number of days with observed thermal inversion at "12Z" is reported. Relative frequencies have been calculated with respect to the total number of data available for the considered period.

Cuneo Levaldigi (LIMZ)	**Thermal Inversions**			
Total	1448 (37,6%)			
Six-month	**Autumn - Winter**		**Spring - Summer**	
	992 (48,3%)		456 (25,3%)	
Seasonal	**SON**	**DJF**	**MAM**	**JJA**
	368 (36%)	624 (60,4%)	241 (26,9%)	215 (23,8%)

Table 4.1.1: Number of thermal inversions' days and relative frequency on data available – period 2000-2016

It is possible to notice that the thermal inversion days are relevant in the "cold" seasons (Autumn-Winter) and, in particular, in the winter period (DJF); however, thermal inversions have been observed also in the relatively warmer seasons. Those situations are related to different mechanisms, but the effect on air quality is basically the same. It has to be highlighted that the absolute number of inversion days depends clearly on the data availability, that is quite good in some years but it is not so good in others: for this reason, it may be also useful an evaluation of the relative frequency of inversion days occurrence for each period.

4.1.2 Days of thermal inversion

The first analysis that has been carried on is based on the evaluation of thermal inversion trends during the 2000-2016 period, using an annual reference time and a seasonal one.

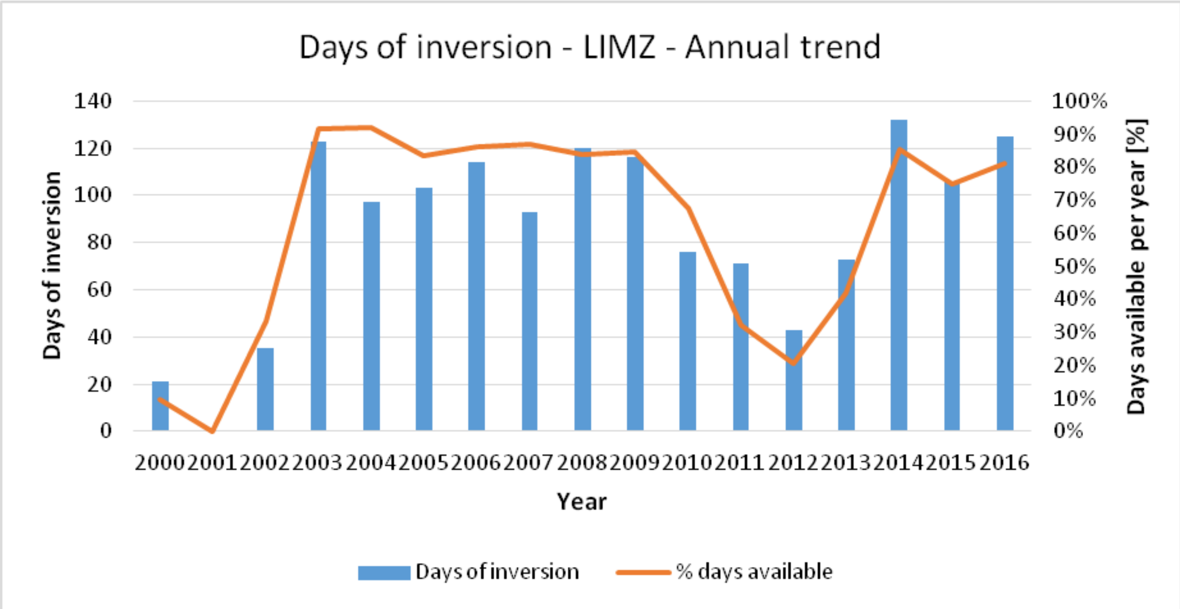


Figure 4.1.2: Days of inversion trend in Cuneo Levaldigi – Number of days

Figure 4.1.2 shows that there is not a specific evidence of a linear trend over the entire 2000-2017 period, but this fact can be caused by the lack of data between 2010 and 2013. A future evaluation on a seven-year period (2003-2009) and -maybe- from 2014 to 2020 can be useful to try to understand more the situation in this station, by comparing mean values.

Trends in the four seasons considered are reported below, in terms of the number of days when an inversion has occurred and data available:

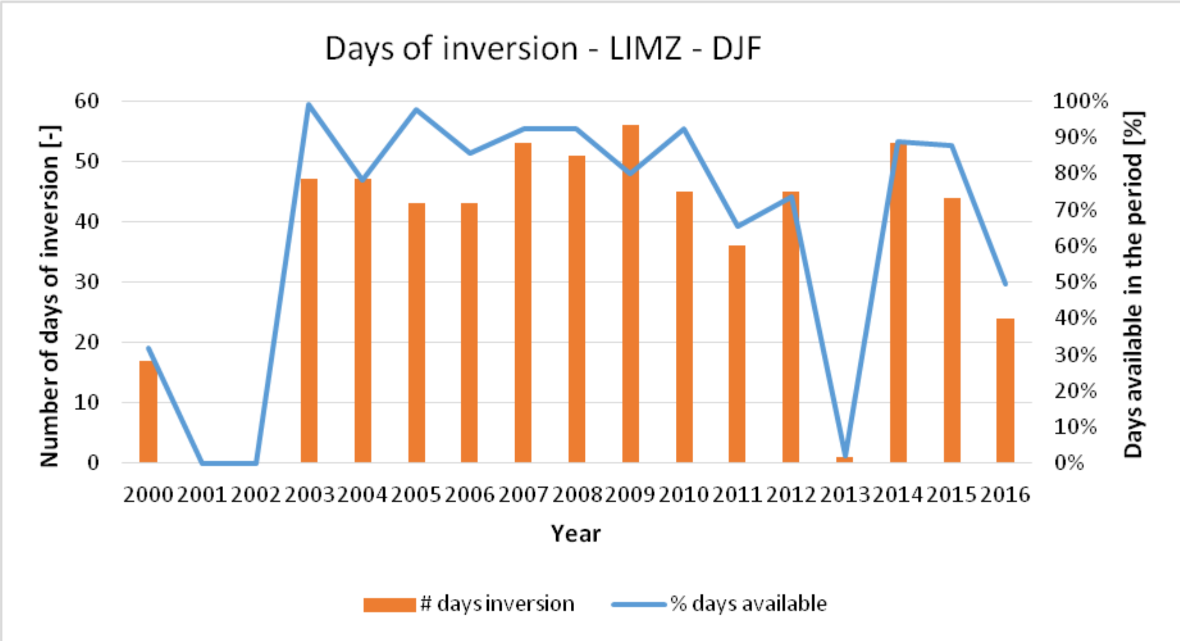


Figure 4.1.3: Days of inversion in Cuneo Levaldigi - Winter trend – Number of days

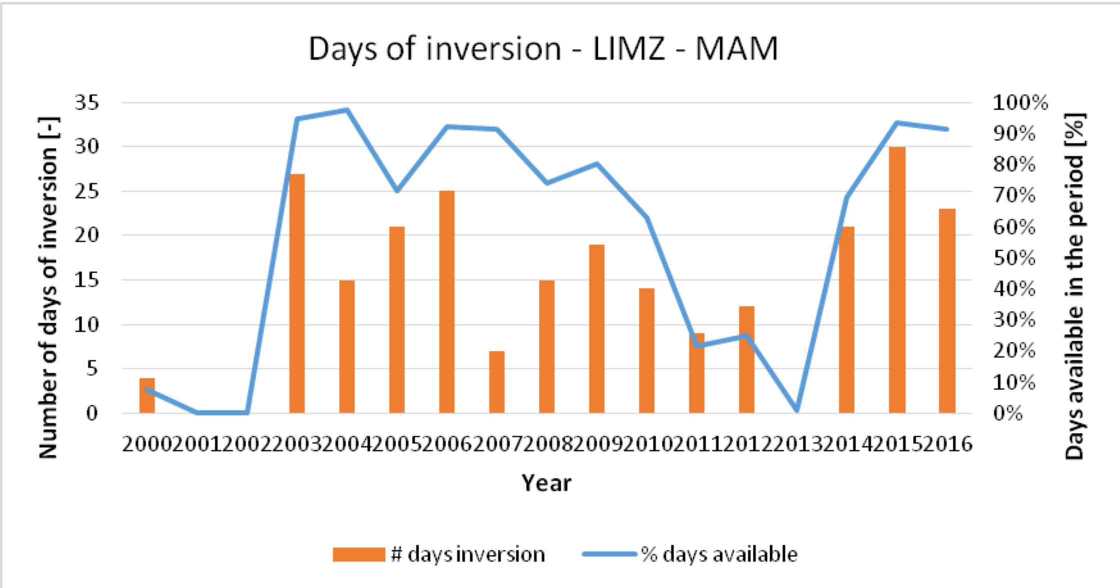


Figure 4.1.4: Days of inversion in Cuneo Levaldigi - Spring trend - Number of days

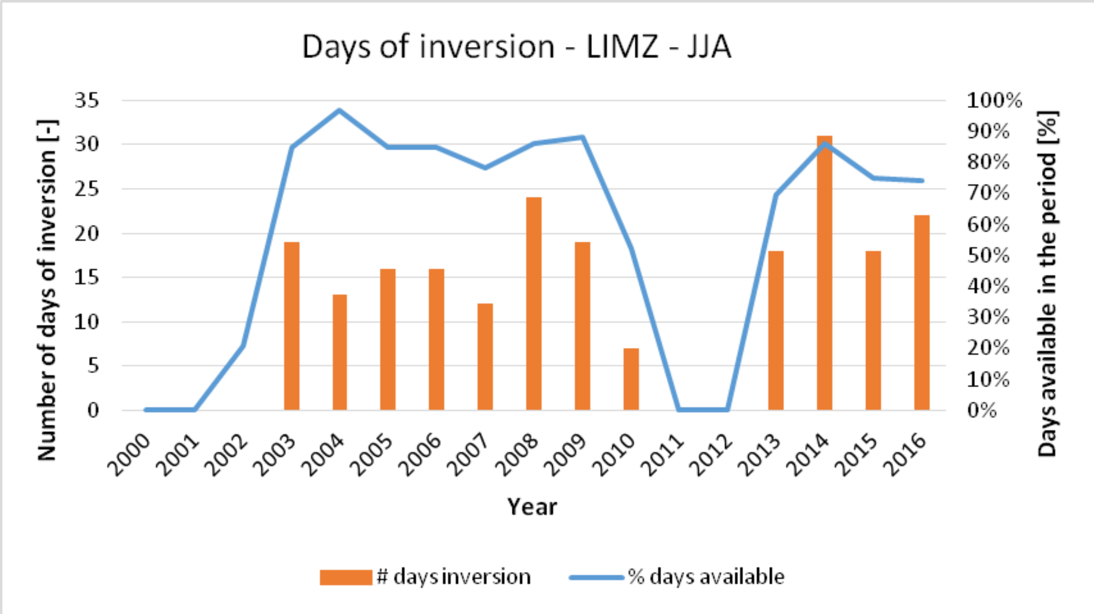


Figure 4.1.5: Days of inversion in Cuneo Levaldigi - Summer trend - Number of days

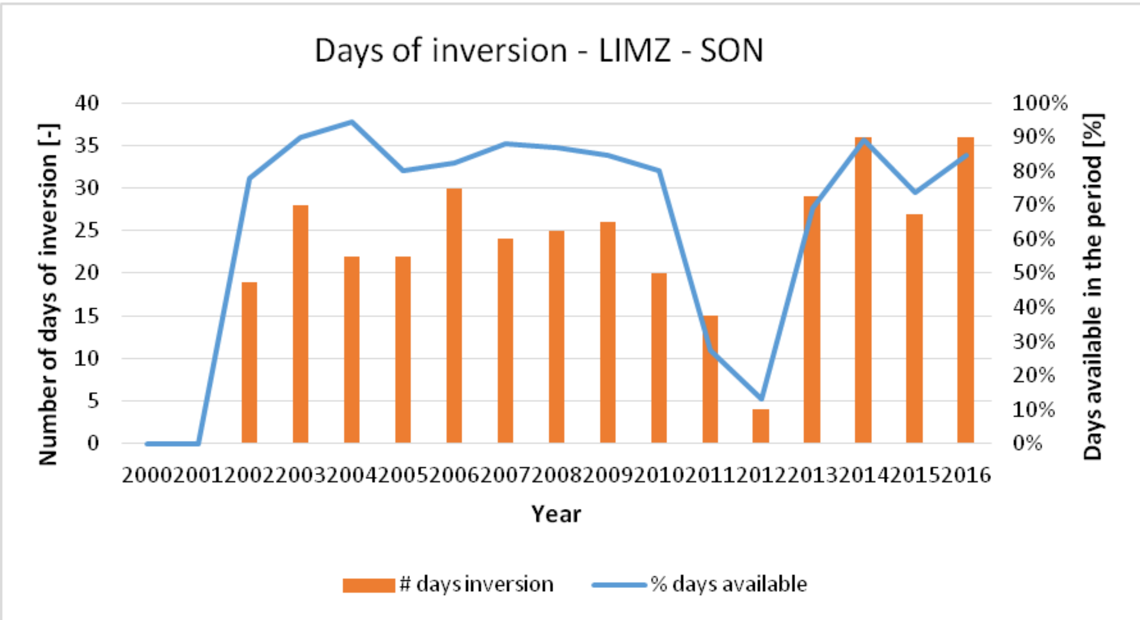


Figure 4.1.6: Days of inversion in Cuneo Levaldigi - Autumn trend - Number of days

It can be noticed that in winter there is a great amount of inversion days (about 45 days on average), while in the other three seasons the number of inversion days was much lower (in spring and summer a maximum 30 days of inversion has been reached and slightly higher values are a feature of autumn). In these cases listed above, an evaluation of a statistically significant trend is not possible due to the lack of data especially in the 2011-2013 period, but maybe it will be useful to make a comparison between mean values of inversion days in 7/8-year periods if the data will be taken continuously throughout the next few years.

4.1.3 Thermal inversion events

The annual trend of inversion events of is shown in Figure XXX:

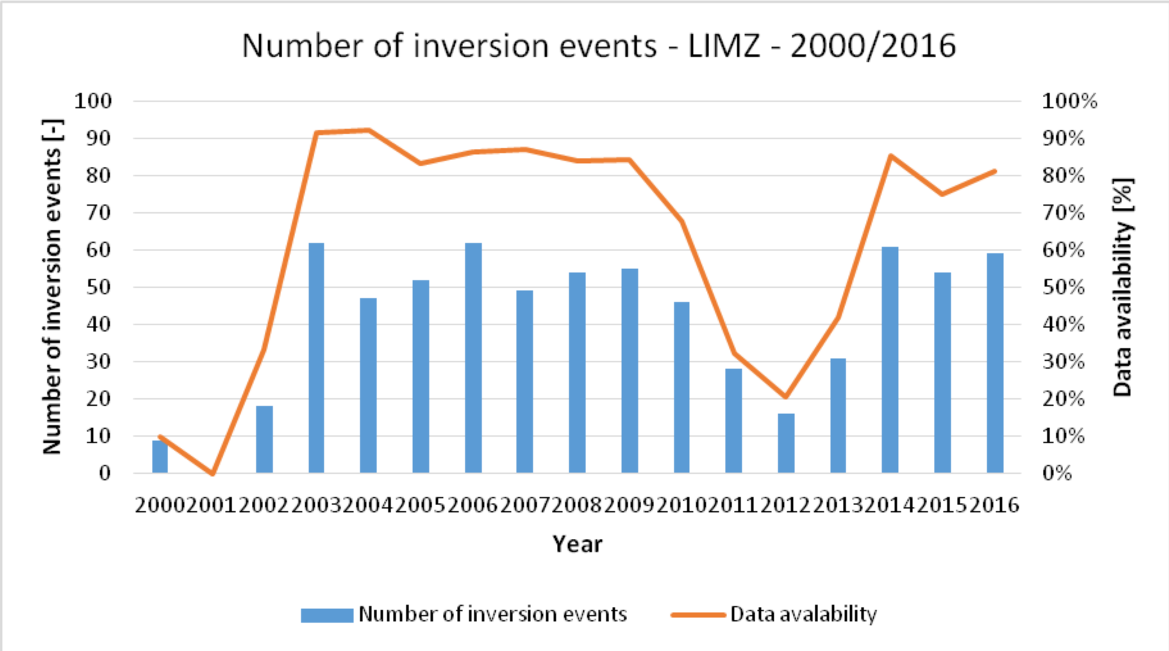


Figure 4.1.7: Number of inversion events in Cuneo Levaldigi station per year

In this case, there were at maximum 62 events per year (in 2002, 2006 and 2014); it appears there is no a specific trend in this situation but it is quite clear that the number of events depends on the availability of data; a better evaluation can be obtained with a complete series of data in the next few years. An assessment has been taken also considering the seasons mentioned in Chapter 2:

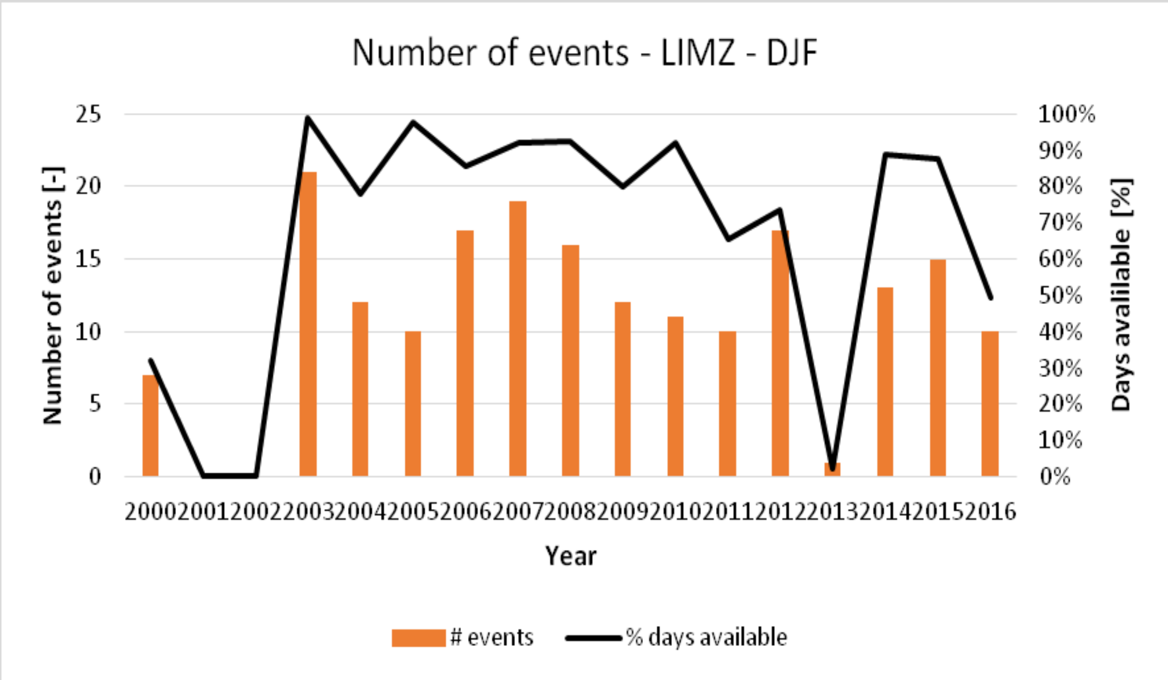


Figure 4.1.8: Trend of number of events in Cuneo Levaldigi - Winter

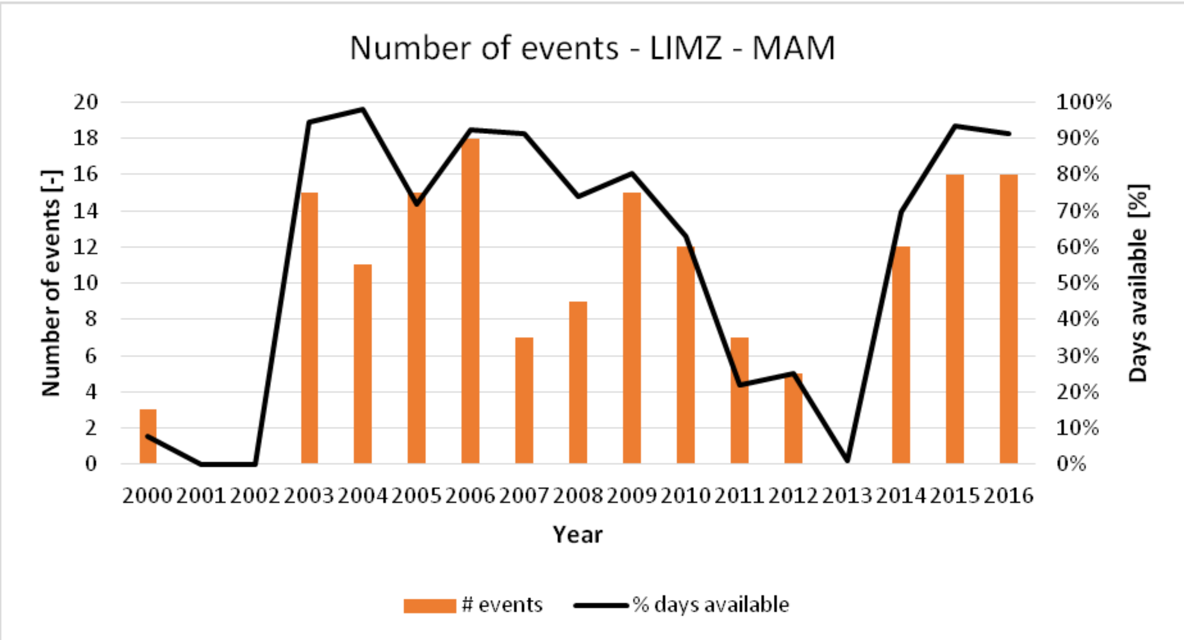


Figure 4.1.9: Trend of number of events in Cuneo Levaldigi – Spring

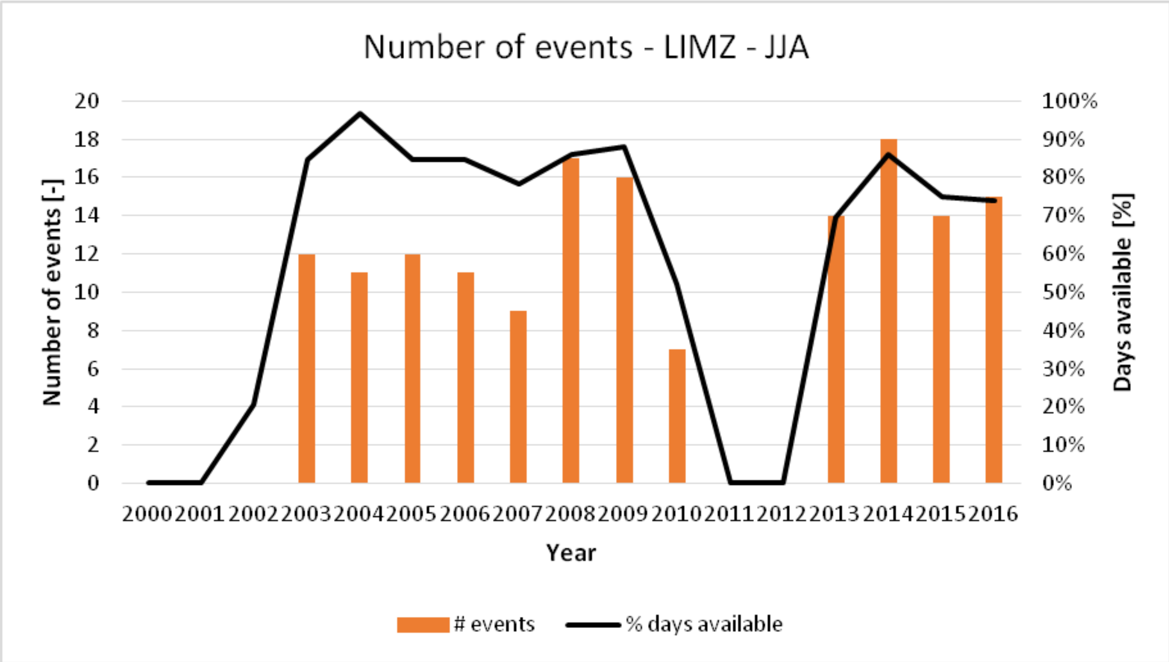


Figure 4.1.10: Trend of number of events in Cuneo Levaldigi – Summer

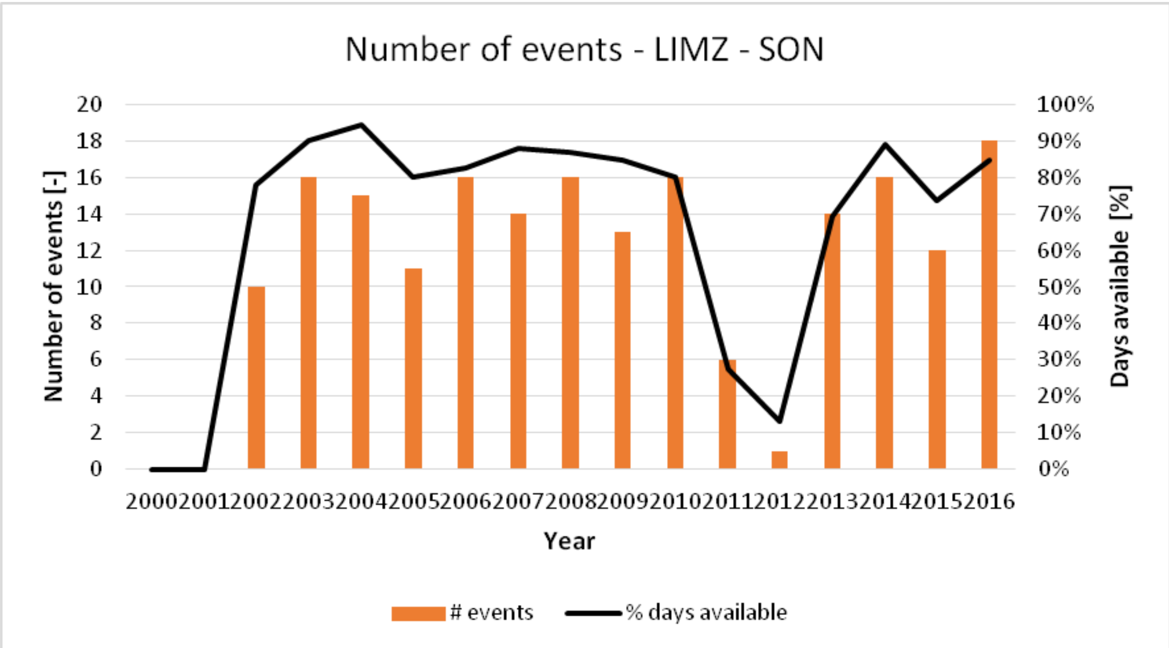


Figure 4.1.11: Trend of number of events in Cuneo Levaldigi – Autumn

The number of events is quite similar in the four seasons considered, but there is no evidence of a significant trend throughout these years. In the last autumn, a peak of 18 events has been reached for the first time since 2002, but winter events seem to have not the same trend. It is not possible to introduce further analysis about trends because of the missing data, but generally it seems that the number of events is comparable between the four seasons, even if there are relevant differences due to the type of inversion and its duration.

4.1.4 Duration of events

Events of thermal inversion were analysed by their duration considering the whole 2000-2016 period:

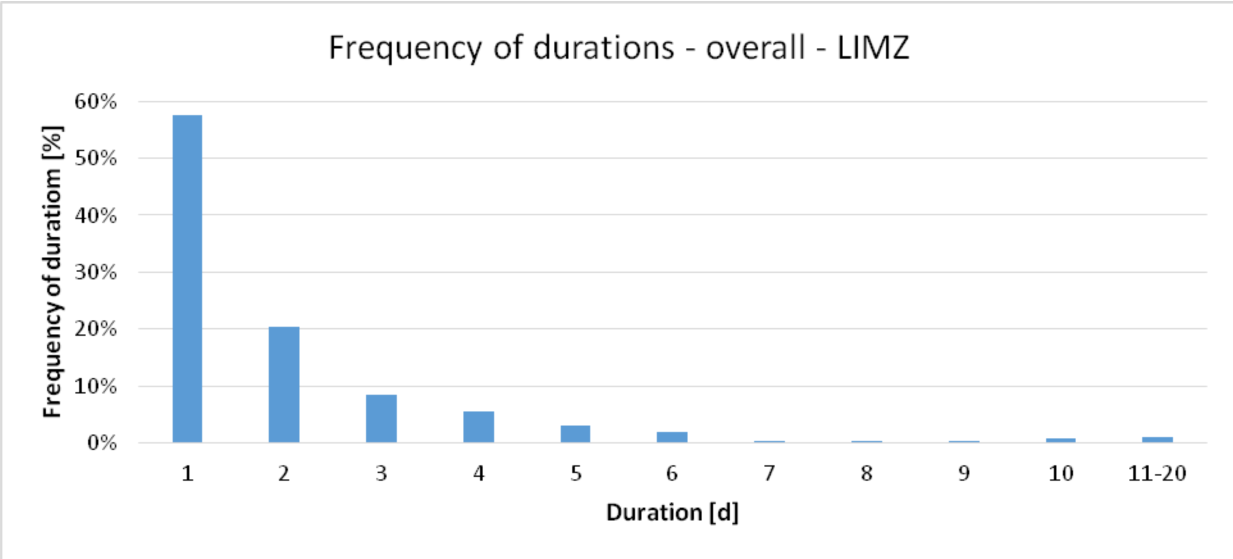


Figure 4.1.12: Overall durations in Cuneo Levaldigi

It can be noticed that approximately 90% of events lasted at maximum for three days, but some events lasted for more than 10 days, and a maximum 20-day event occurred in 2013. At this point, an evaluation of the number of events classified by duration has been done considering an annual time reference. In this case, “short” events (1, 2 or 3 consecutive inversion days) have been divided from “longer” ones (4, 5, 6, 7 or more than 7 consecutive inversion days), in order to have a better understanding of the phenomenon.

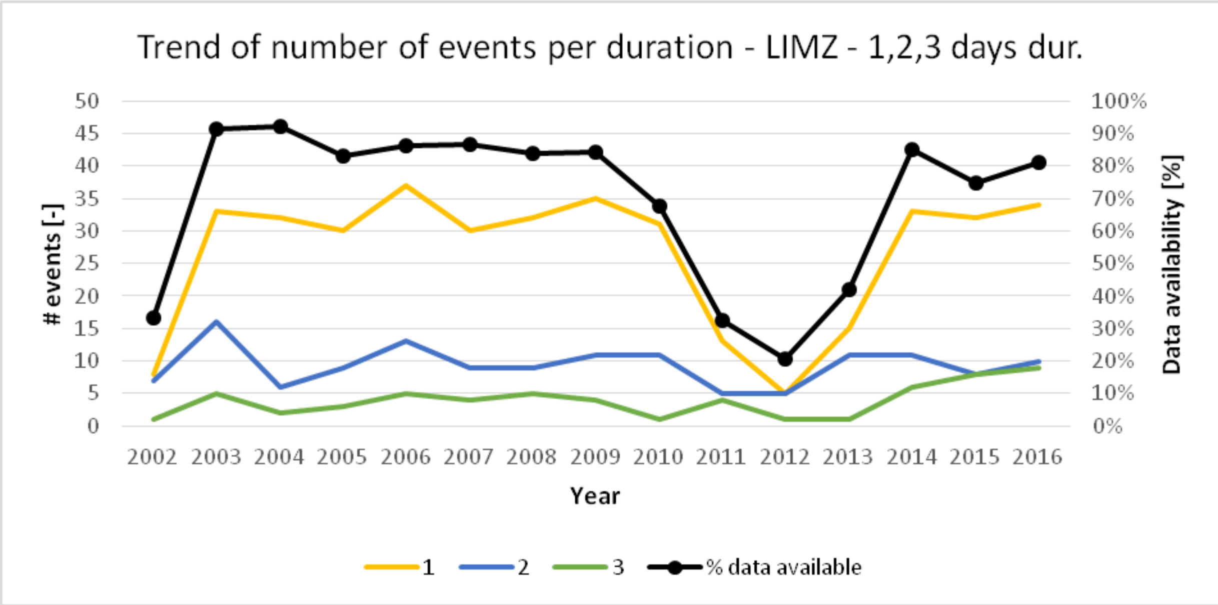


Figure 4.1.13: Trend in number of events per duration in Cuneo Levaldigi - annual basis - 2002/2016 period - <4 days events

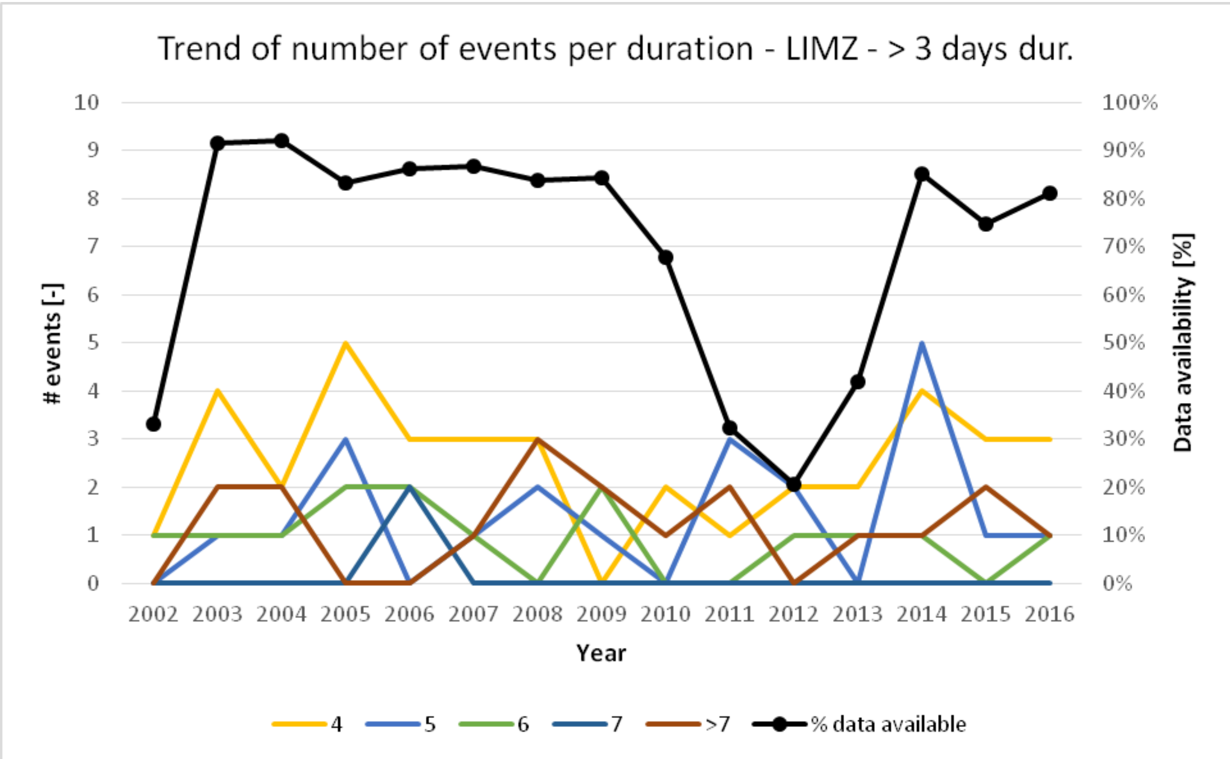


Figure 4.1.14: Trend in number of events per duration in Cuneo Levaldigi - annual basis - 2002/2016 period - >3 days events

The number of events with short durations (from 1 to 3 days) is quite steady over this period (Figure 4.1.13): for 3-day events a rise from one to nine event between 2013 and 2016, but the lack of data in 2012 and 2013 can affect this apparent increase, as in 2011 we had 4 events. On the contrary, there are not significant trends in 3-or-more day events. An assessment on the variation of the number of thermal inversion events by duration has been carried on also on a seasonal basis as shown in Figure 4.1.15-4.1.18.

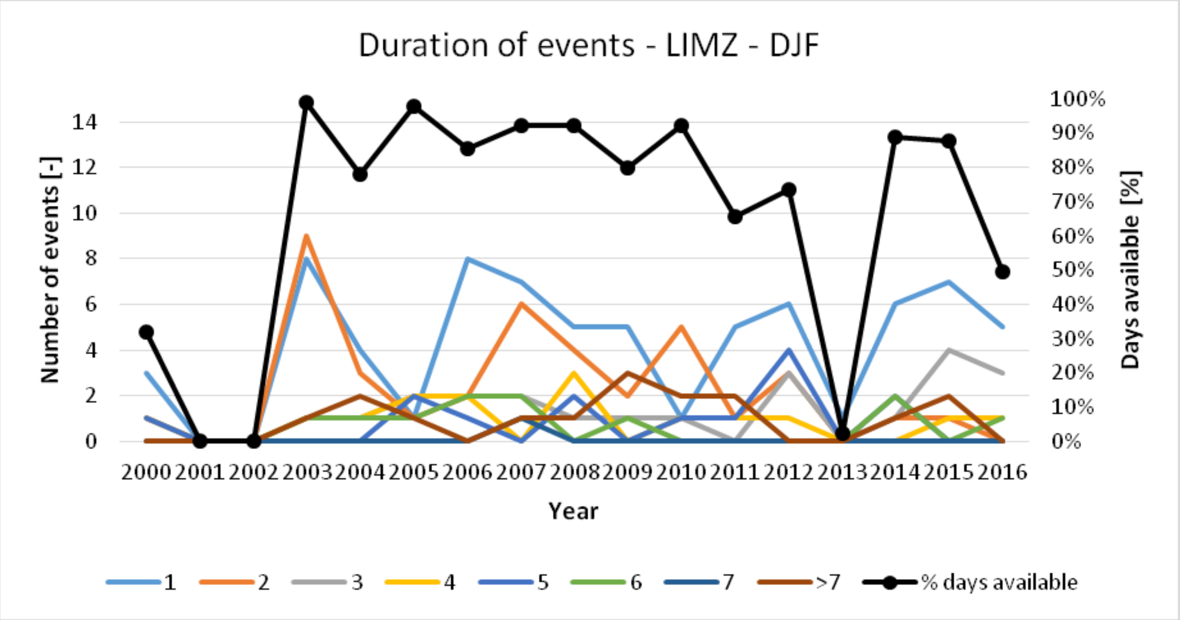


Figure 4.1.15: Duration of events in Cuneo Levaldigi – Winter

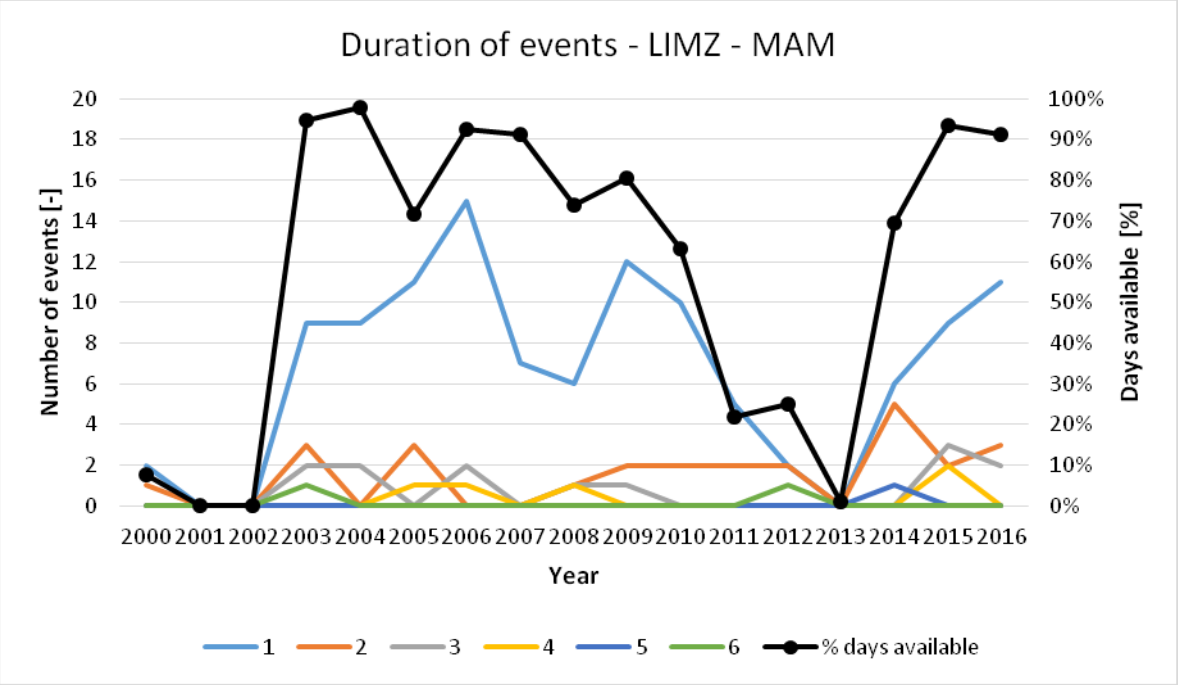


Figure 4.1.16: Duration of events in Cuneo Levaldigi – Spring

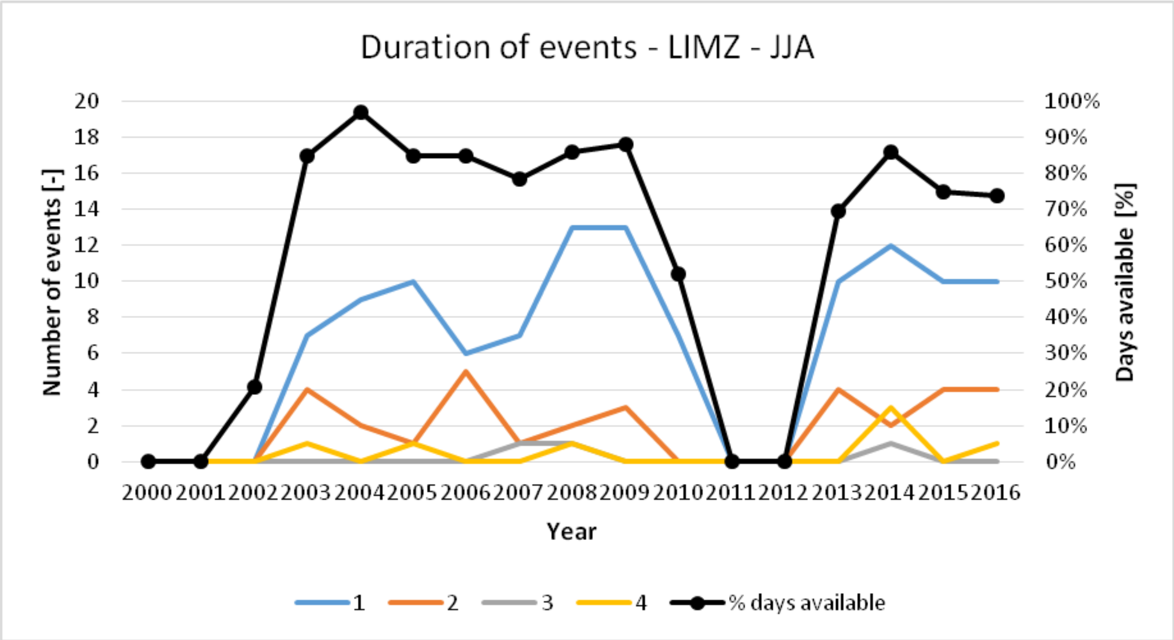


Figure 4.1.17: Duration of events in Cuneo Levaldigi – Summer

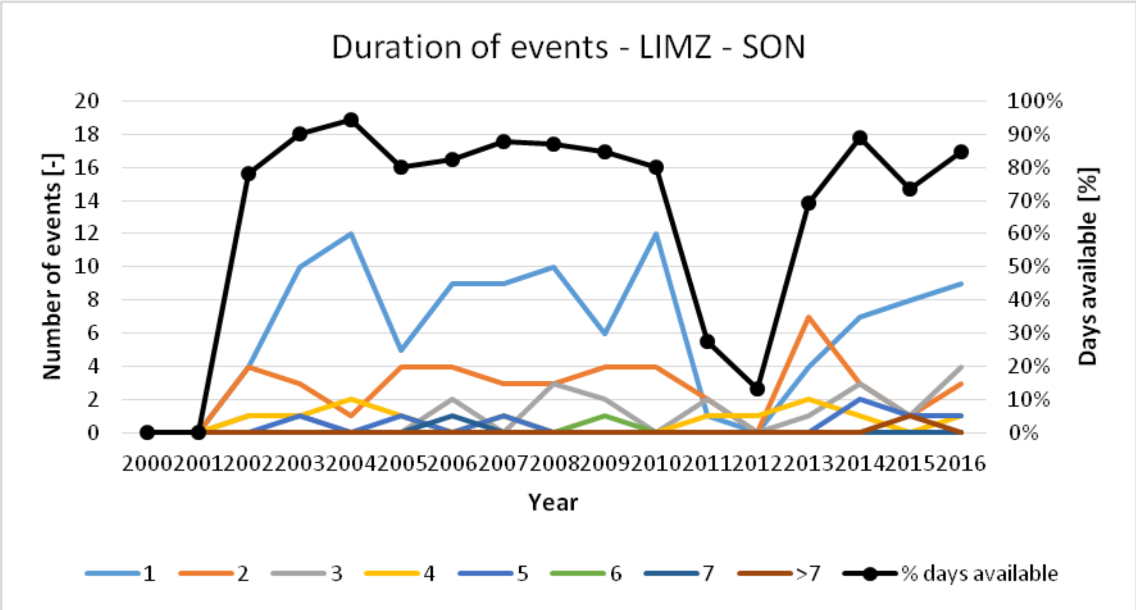


Figure 4.1.18: Duration of events in Cuneo Levaldigi – Autumn

As it is shown by graphs above, very short events are typical of spring and summer (at maximum 4-day events have occurred since 2003 in JJA) and much longer events are more frequent during autumn and winter. In particular, the number of events are comparable between different durations during wintertime, but this feature changes significantly during other seasons.

4.1.5 Characteristics of thermal inversions

Inversions have been characterized by their type (radiation/subsidence), thickness (depth between top and base) and height (considering the base of the inversion). This evaluation has been developed considering the pressure level data (in hPa) because of some missing data in altitude (in metres) in the "weather balloons" soundings. The assessment on the characteristics of thermal inversion has been performed also splitting ground-based (radiation) inversions and subsidence inversions (Figure 4.1.19-4.1.21).

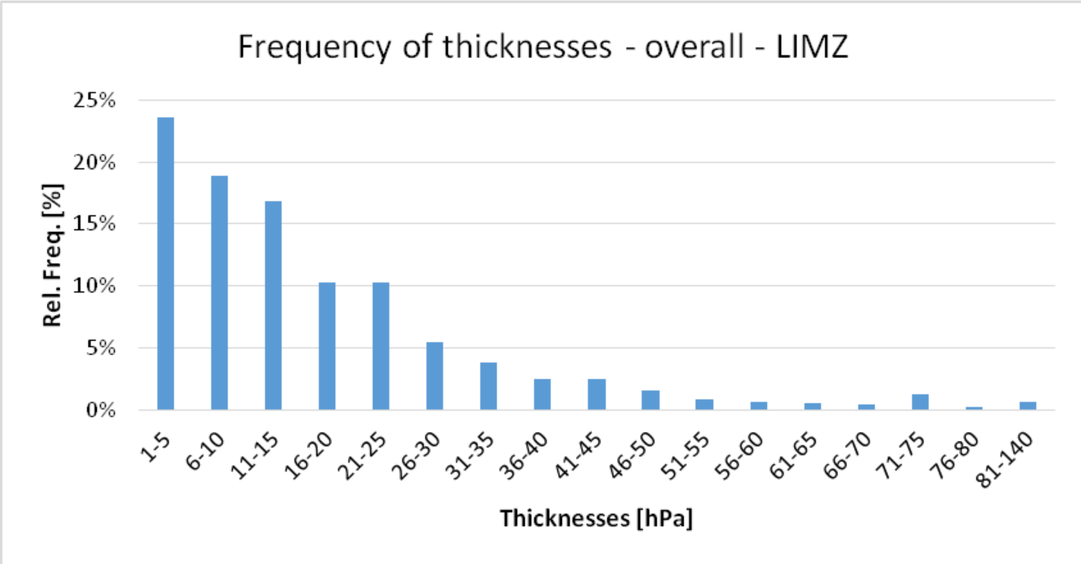


Figure 4.1.19: Thicknesses of all kind of inversions in Cuneo Levaldigi

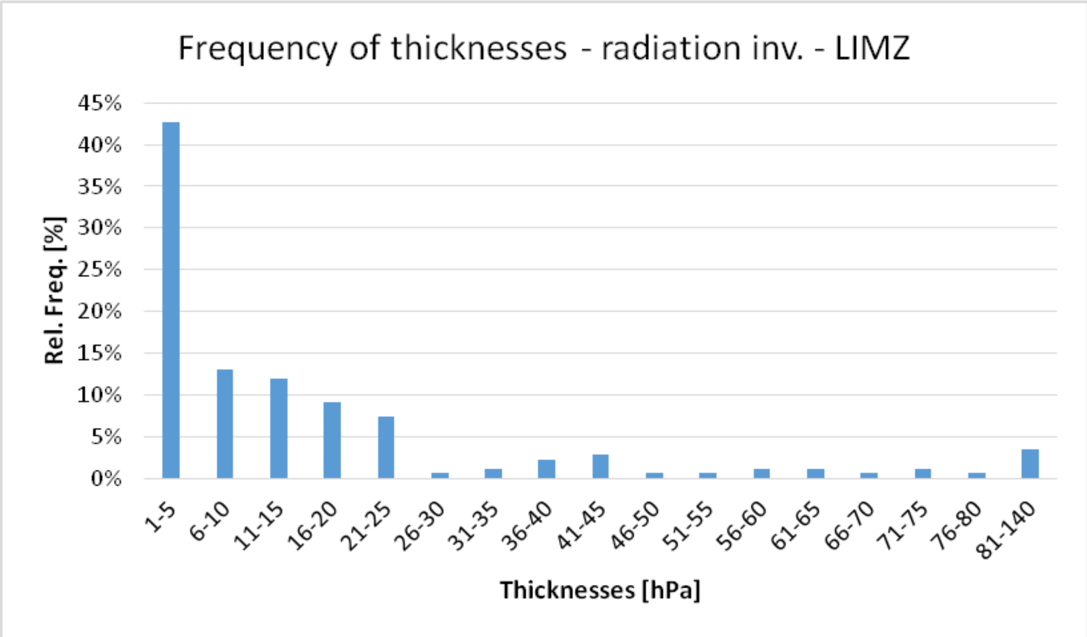


Figure 4.1.20: Thicknesses of ground-level inversions in Cuneo Levaldigi

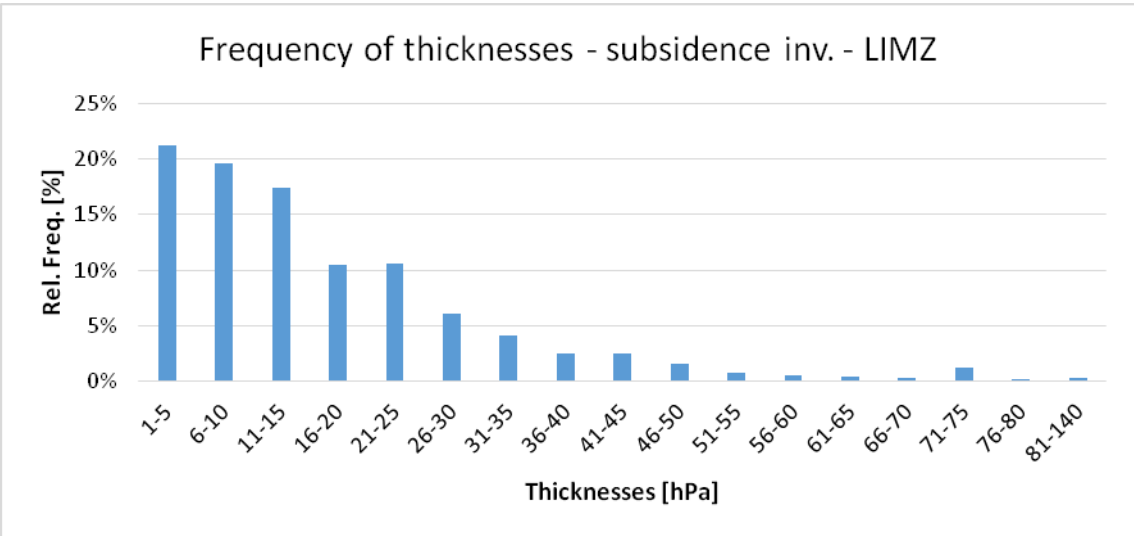


Figure 4.1.21: Thicknesses of subsidence inversions in Cuneo Levaldigi

Approximately 70% of all the inversions has a thickness lower than 20 hPa (that corresponds to about 180 m). In case of radiation inversions, a maximum 140 hPa thickness was reached, but the major contribution is given by very thin layers (less than 50 m from ground level), with about 80% of layers thinner than 25 hPa. Subsidence inversions have a slightly more spread distribution, but also in this case about 85% of events have a thickness lower than 30 hPa (under 300 m). This last kind of inversion occur at different heights, influencing the thickness of the mixing layer below and affecting the air quality. Therefore, an evaluation of the free mixed height has been carried on, investigating the pressure levels where the base of the inversion is located.

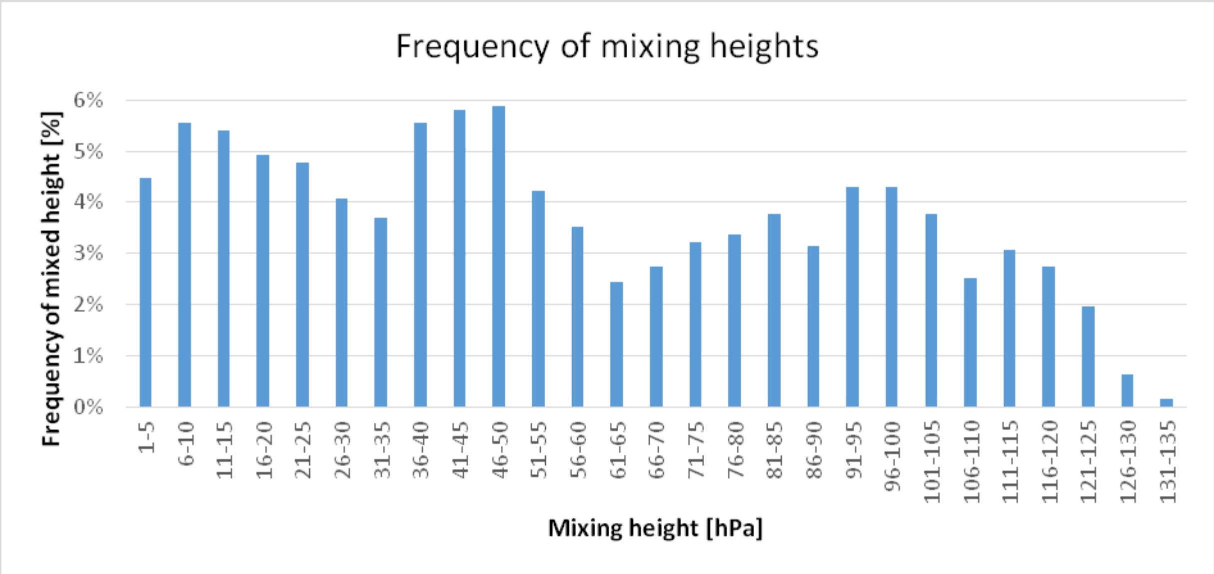


Figure 4.1.22: Mixing height distribution in Cuneo Levaldigi

Figure 4.1.22 shows that the depth of the mixing height, that is the layer of the lower atmosphere where pollutants can be dispersed, is quite variable. Most frequently the base of the inversion is at 46-50 hPa, which corresponds to about 400 m from the ground level.

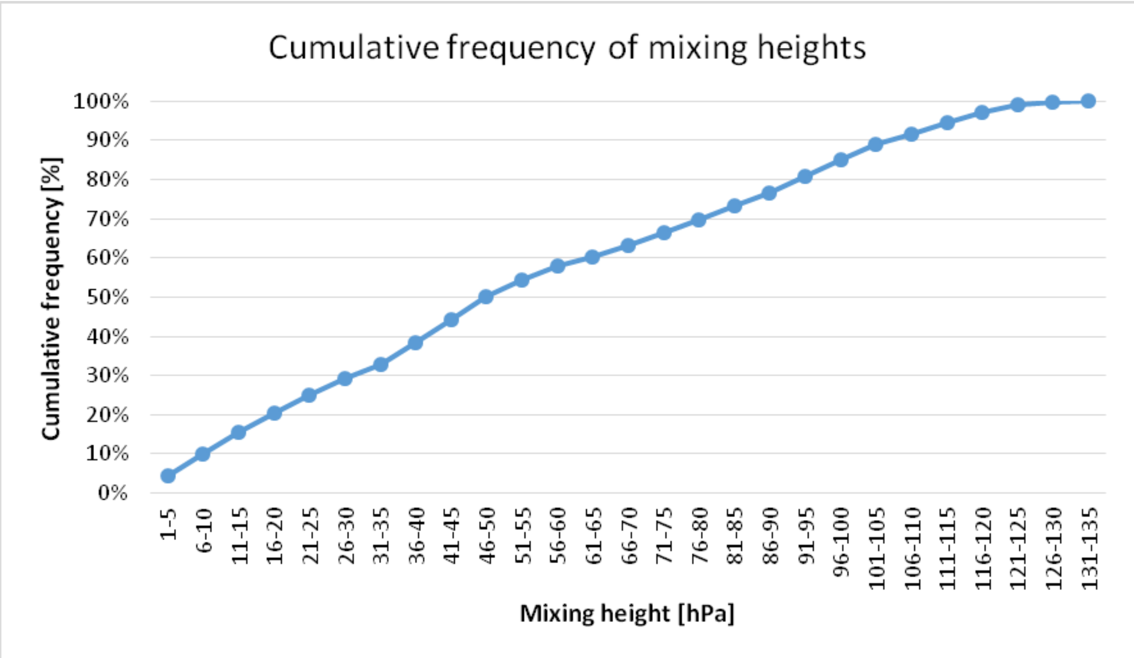


Figure 4.1.23: Cumulative distribution of mixing heights divided per classes in Cuneo Levaldigi

As 60% of mixing heights does not reach 65 hPa (600 m above ground level), there is a significant tendency to have an occurrence of small mixing heights in this Western part of the Po valley: Seasonality analyses (Figure 4.1.24) show that the most critical situation occur during wintertime, when the occurrence of shallower mixing height is more frequent than in the other seasons.

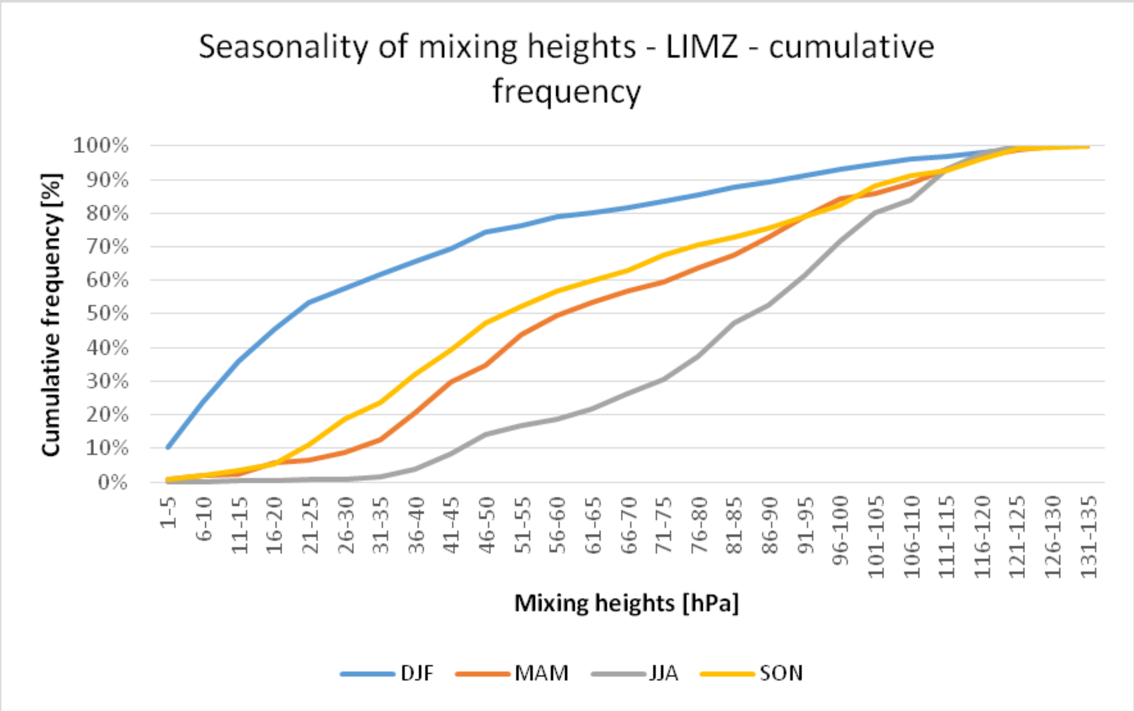


Figure 4.1.24: Cumulative frequency of mixing heights classified by season - LIMZ

It was not possible to do more assessments on the seasonality of inversion types and related trends because of the poor data availability in some years.

An additional investigation was intended to analyse more in detail the structure of inversion profiles, namely considering the number of temperature inversion along the vertical profile considered. Actually, the temperature profile can display a single or a multiple series of inversions. This analysis showed that multiple-layer events are not so common in Cuneo Levaldigi (Table 4.1.2):

LIMZ	1 layer	2 layers	3 layers
# days	1269	175	4
Rel. Freq. [%]	87,6%	12,1%	0,3%

Table 4.1.2: Number of days with simultaneous inversions – Cuneo Levaldigi

4.2 Milano Linate Airport (LIML) station

4.2.1 Data availability

This station is located in the central part of the Po Valley (Lombardy region), nearby the city of Milan, at 103 m a.s.l., in a suburban context. Soundings are managed by ENAV and by the Italian Air Force Weather Service.

First, a scheduling of the data has been done to have a better comprehension of data coverage: from this point of view, Milano Linate is the best station in the Po Valley area among these that have been considered in the period from 1985 to 2016, as it is observable from Figure 4.2.1:

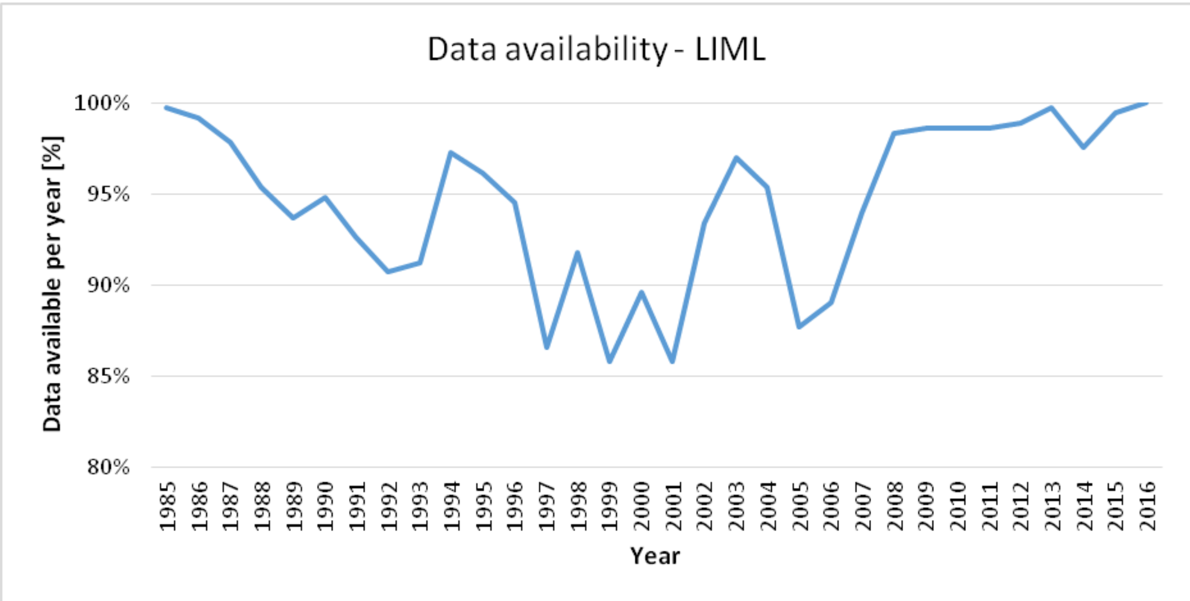


Figure 4.2.1: Data availability of Milano Linate station

Table 4.2.1 summarizes the total and seasonal number of inversion days observed between 1985 and 2016, clearly pointing out that thermal inversions are a typical feature of the colder part of the year.

Milano Linate (LIML)	**Thermal Inversions**			
Total	5141 (46,5%)			
Six-month	**Autumn - Winter**		**Spring - Summer**	
	3401 (62,0%)		1740 (31,2%)	
Seasonal	**SON**	**DJF**	**MAM**	**JJA**
	1374 (50,3%)	2027 (73,7%)	932 (33,5%)	808 (28,9%)

Table 4.2.1: Number of thermal inversions' days and relative frequency on data available – period 1985-2016

4.2.2 Days of thermal inversion

In this case, it has been evaluated a possible linear trend of days of inversion on annual basis; it has been found that the trend line suggests an increase of inversion occurrence at a +6 days per decade. It can be also added that it seems to occur a slight decrease of events between 1985 and 1995 (that corresponds to a lower coverage-of-data period) so the trend seems a little bit unstable. For this reason, statistical tests mentioned in Chapter 2 have been applied on the number of days' and events' trend; here a statement has to be done: only for seasonal basis data, tests have been performed on two different data series: one directly coming from the original database and another from an adjusted series, where the number of days and events have been corrected as it is show here below:

$$Data\ adjusted_{i,j} = \frac{Data\ from\ database_{i,j}}{\%\ of\ data\ available_{i,j}}$$

where:

- i = year considered;
- j = season considered (DJF, MAM, JJA, SON)

The main assumption is that measurements have been taken independently one from another; for this reason, the frequency of occurrence in one period with a certain data coverage can be rescaled to the total period. This has not be done on an annual basis because it might lead to some inaccuracies, due to different frequencies of occurrence between different seasons.

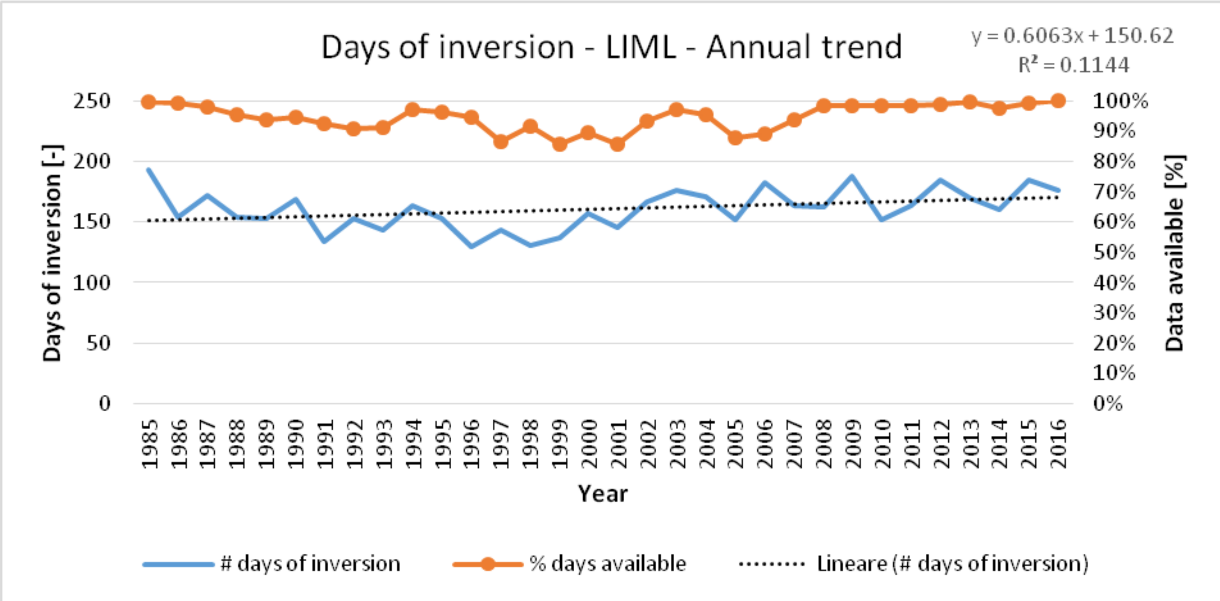


Figure 4.2.2: Days of inversion trend in Milano Linate

On annual basis, the F test reveals that the statistic calculated is located into the acceptance region of the null hypothesis, so there is not a statistical significance on the linear trend supposed (α= 0.05), with a p value equal to 0.06. The same result has been obtained by the Mann-Kendall test, where the Z_{MK} statistic has a p value equal to 0.126, so there is no evidence of a monotonic trend.

On a seasonal basis, tests has been applied as indicated in Chapter 2.

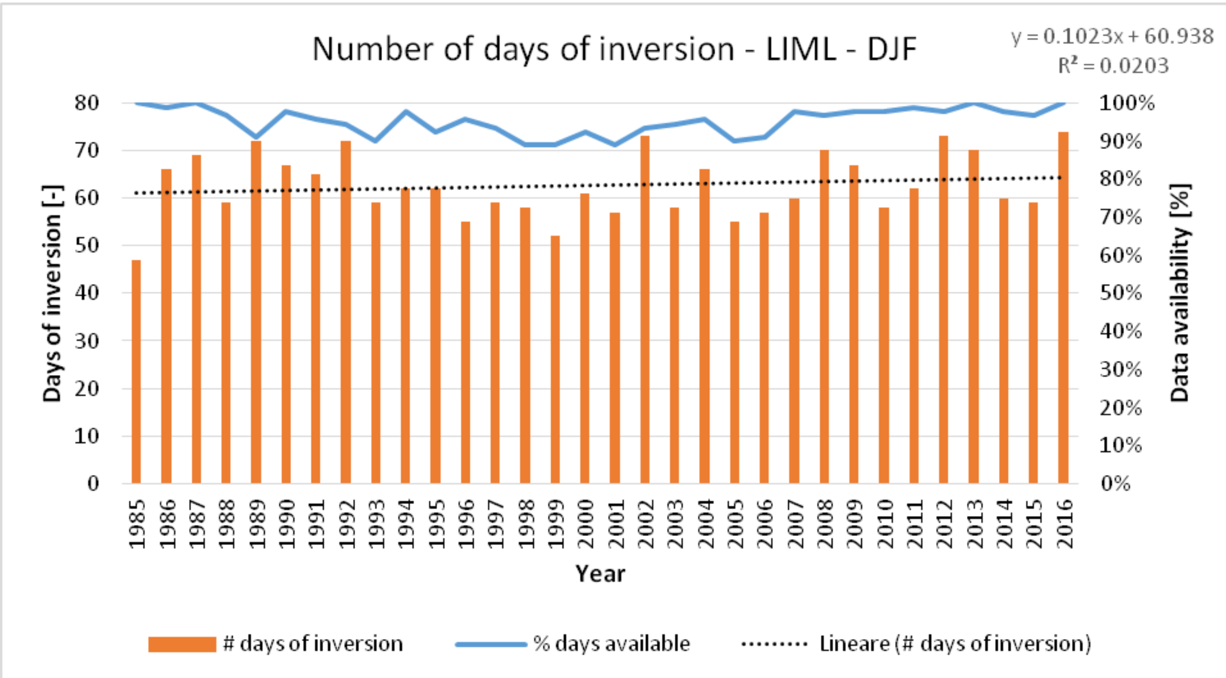


Figure 4.2.3: Days of inversion in Milano Linate - Winter trend – Number of days

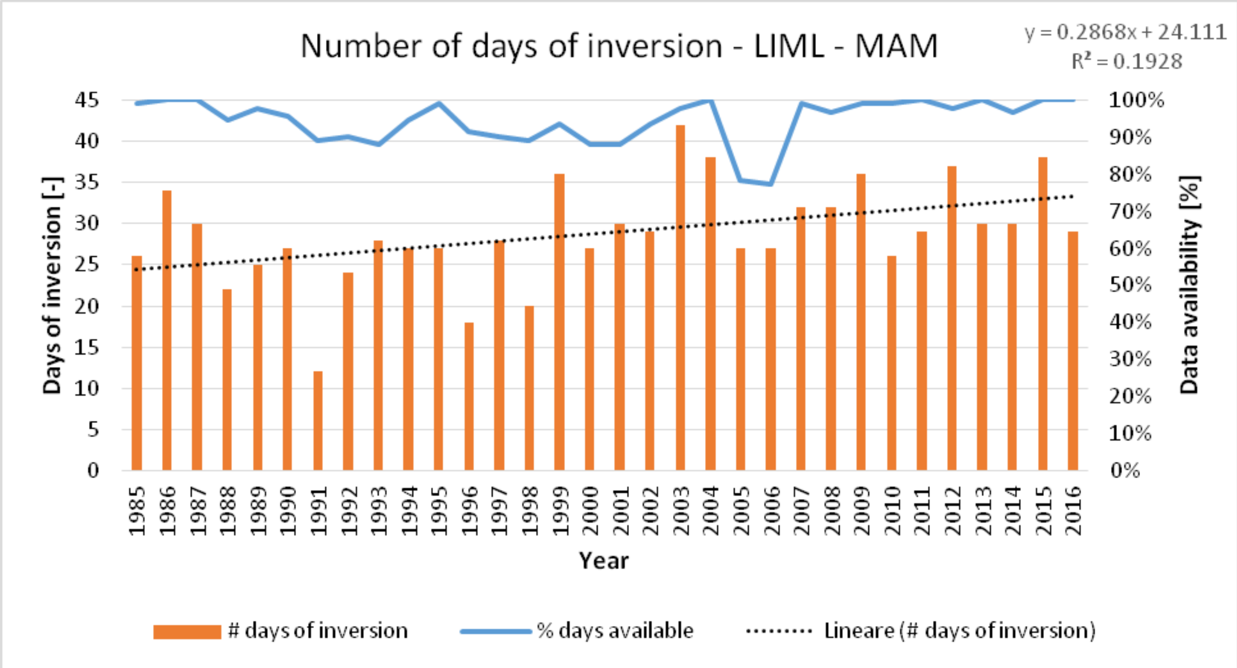


Figure 4.2.4: Days of inversion in Milano Linate - Spring trend – Number of days

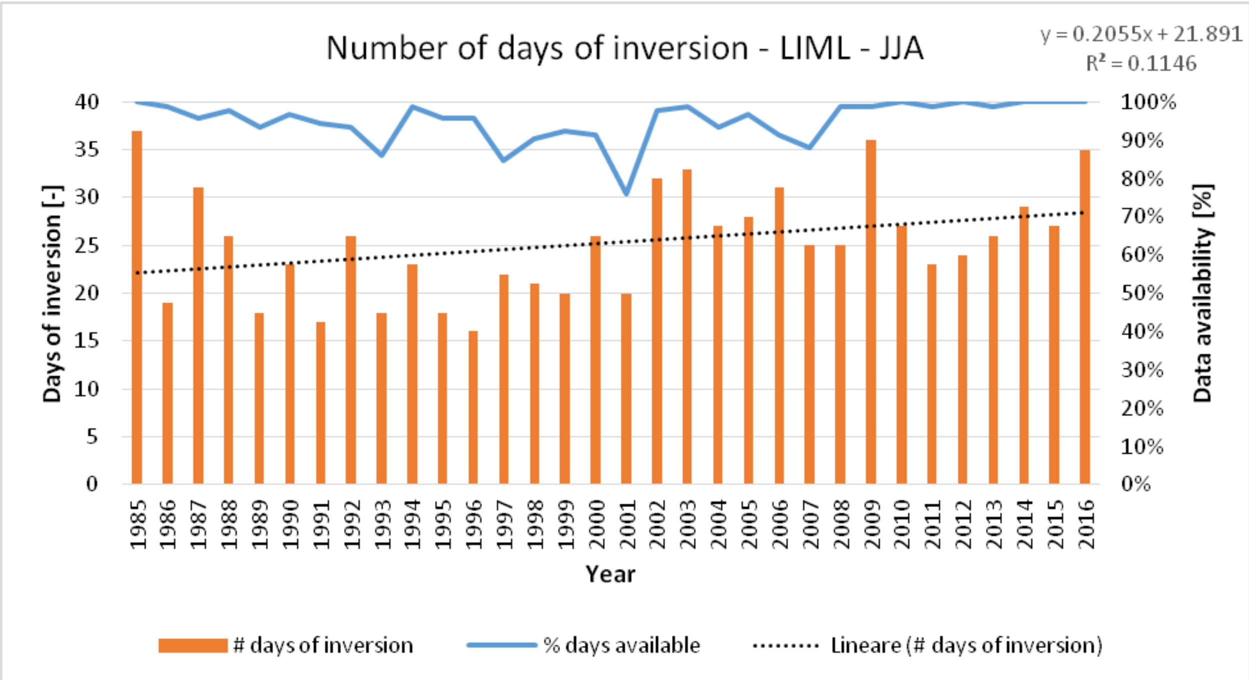


Figure 4.2.5: Days of inversion in Milano Linate - Summer trend – Number of days

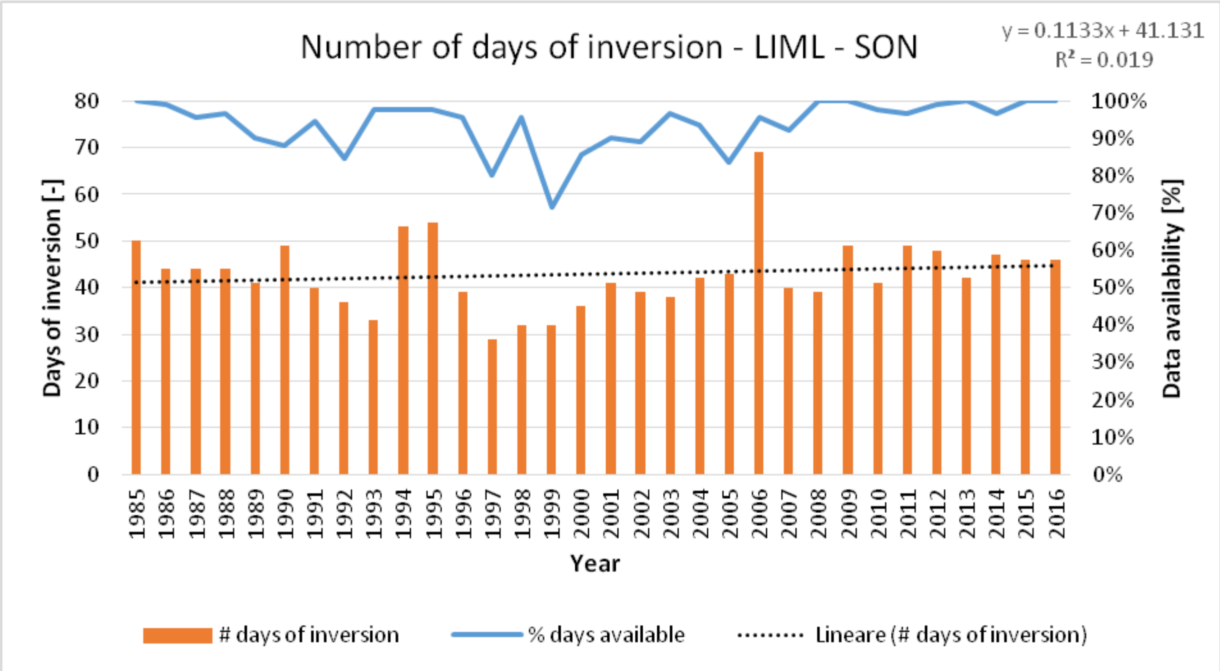


Figure 4.2.6: Days of inversion in Milano Linate - Autumn trend – Number of days

From the linear trend lines plotted in Figure 4.2.3-4.2.6, it seems that there is a general increase of the number of days with thermal inversion, with more pronounced slopes in spring (+3 days per decade) and summer (+2 days per decade) than in colder seasons (about +1 day per decade). However, even when the slope is more pronounced there is a large variability in the seasonal number of inversion days, thus leading to low levels of the coefficient of determination calculated ($R^2 < 0{,}2$). Obviously, the number of inversion days remains lower in the relatively warmer seasons. The F test applied for each season to test the presence of a time trend for the number of inversion days suggests that the trend is statistically significant only in the MAM season (Table 4.2.2):

#days	**DJF**	**MAM**	**JJA**	**SON**
F calc.	0,62	7,17	3,88	0,58
$F_{(1,30),\alpha=0.05}$	4,17	4,17	4,17	4,17
Linear trend	No	Yes	No	No
P value	0,437	0,012	0,058	0,452

Table 4.2.2: Results of F test on seasonal basis (alpha = 5%)

Similar results have been obtained through the Mann-Kendall test as summarized in Table 4.2.3; according to this test, however, also the trend for the JJA period is significant.

#days	DJF	MAM	JJA	SON
Z_{MK} calc.	0,44	2,71	2,13	0,70
$Z_{\alpha=0.05}$	1,96	1,96	1,96	1,96
Monotonic trend	No	Yes	Yes	No
P value	0,660	0,007	0,033	0,484

Table 4.2.3: Results of Mann-Kendall test on seasonal basis (alpha = 5%)

The application of the Seasonal Kendall give us a misleading information, because there is not an absolute monotonic upward trend in all season (Table 4.2.3), so the result has not been reported here. In conclusion, it is possible to state that there is a general positive trend in warmer seasons (with a rate of +3 days per decade in spring -linear monotonic trend-, +2 days per decade in summer, non-linear monotonic trend) but there is not a statistically significant linear/monotonic trend in cooler seasons, when inversion days are quite common nowadays. As similar results have been obtained for the adjusted series of data, the actual data availability does not influence the statistical meaning of the outlined trends.

4.2.3 Thermal inversion events

The evaluation about possible trends has been carried on also for the thermal inversion events, on both annual and seasonal basis, through a series of statistical tests.

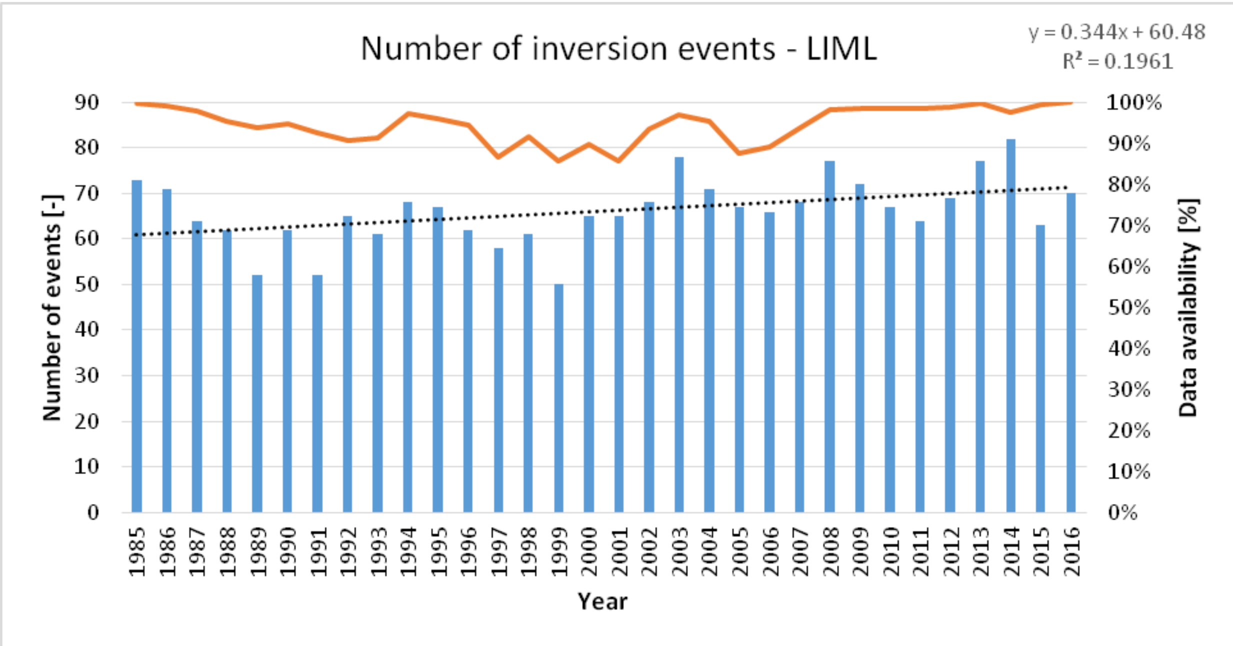


Figure 4.2.7: Number of inversion events in Milano Linate station per year

On annual basis, it seems that there is an increase of number of events through these years, with a rate greater than +3 events per decade, with the highest amount of events (82 per year) reached in 2014. Results obtained by F and Mann-Kendall tests, applied following the methodology, described in Chapter 2, are reported in Table 4.2.4:

Test	Stat. calc.	Refer. Stat.	Trend	P value
F	7,32	4,17	Yes	0,011
Mann-Kendall	2,28	1,96	Yes	0,023

Table 4.2.4: Results of tests for a possible trend in number of events on annual basis

Both tests show that that there is a monotonic (linear) upward trend in this data series, with the rate that has been reported earlier. The same analysis has been carried on a seasonal basis, where the variability seems much higher, as shown in Figure 4.2.8-4.2.11, also by using the adjusted data series:

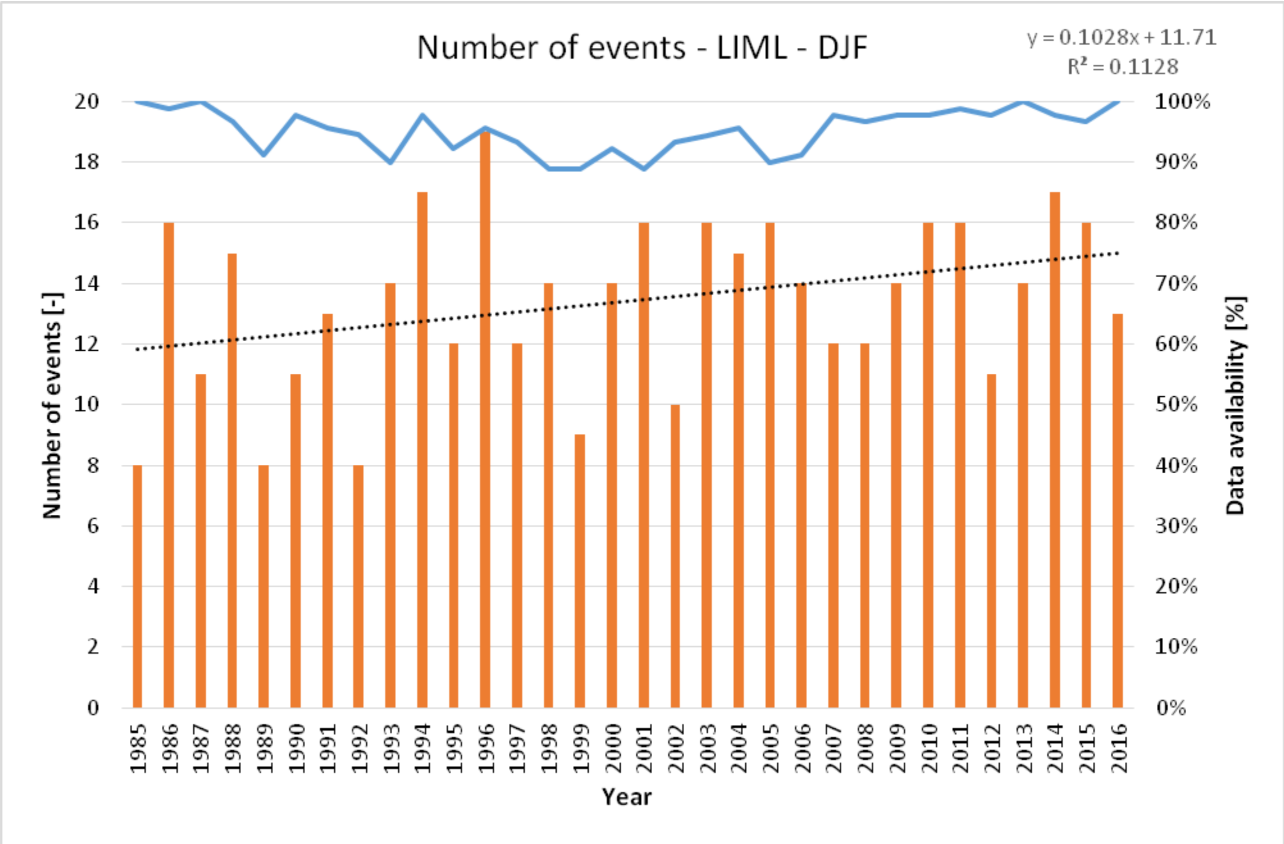


Figure 4.2.8: Trend of number of events in Milano Linate – Winter

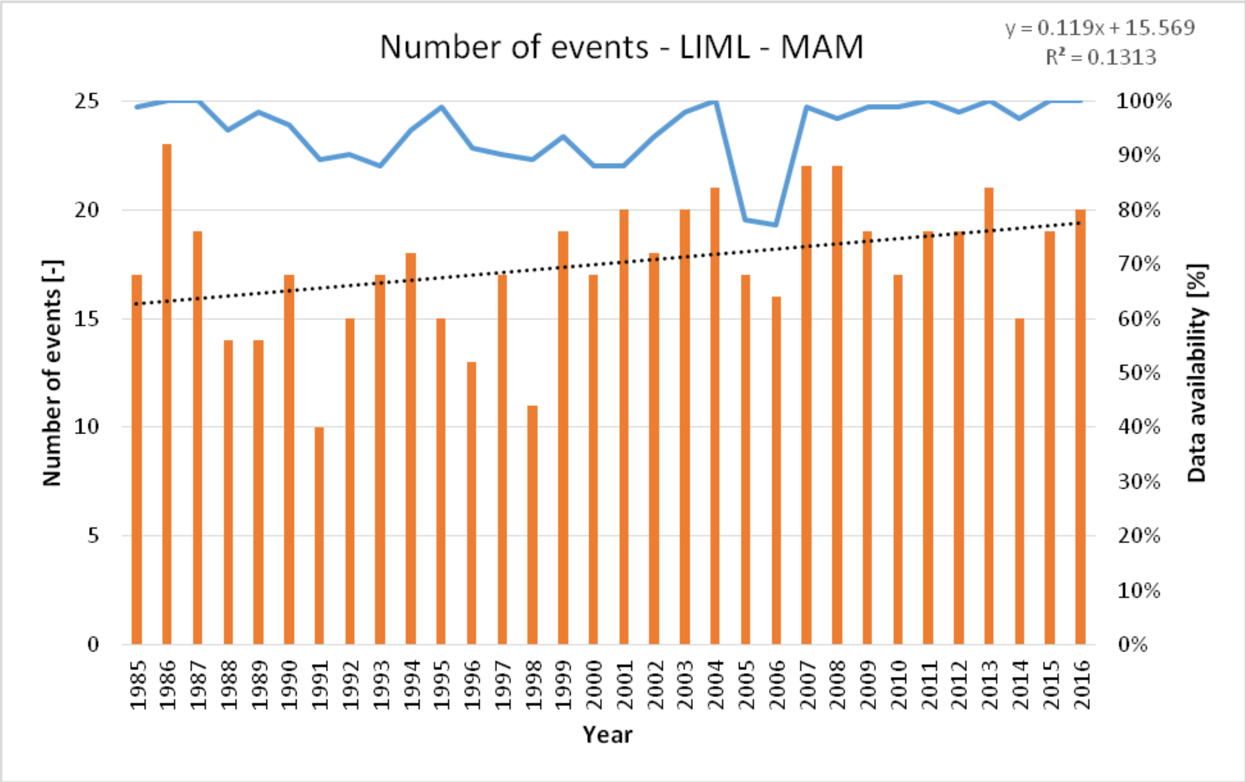


Figure 4.2.9: Trend of number of events in Milano Linate – Spring

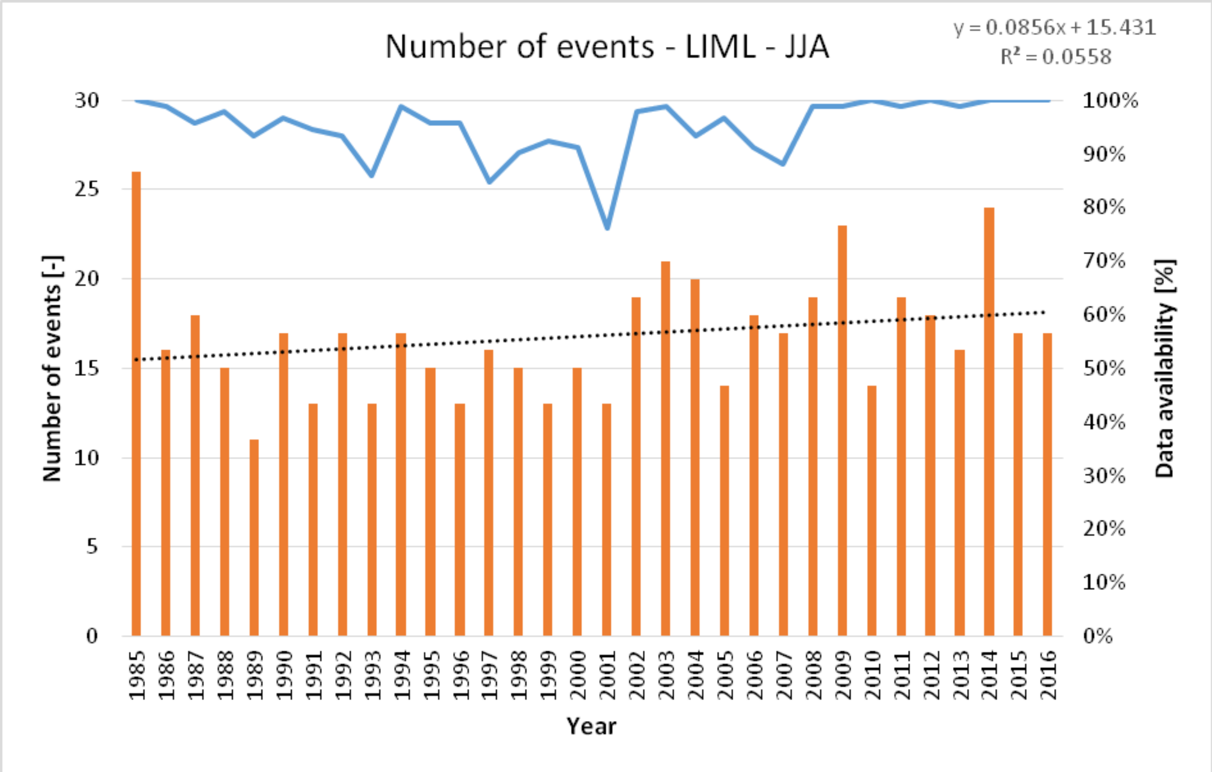


Figure 4.2.10: Trend of number of events in Milano Linate – Summer

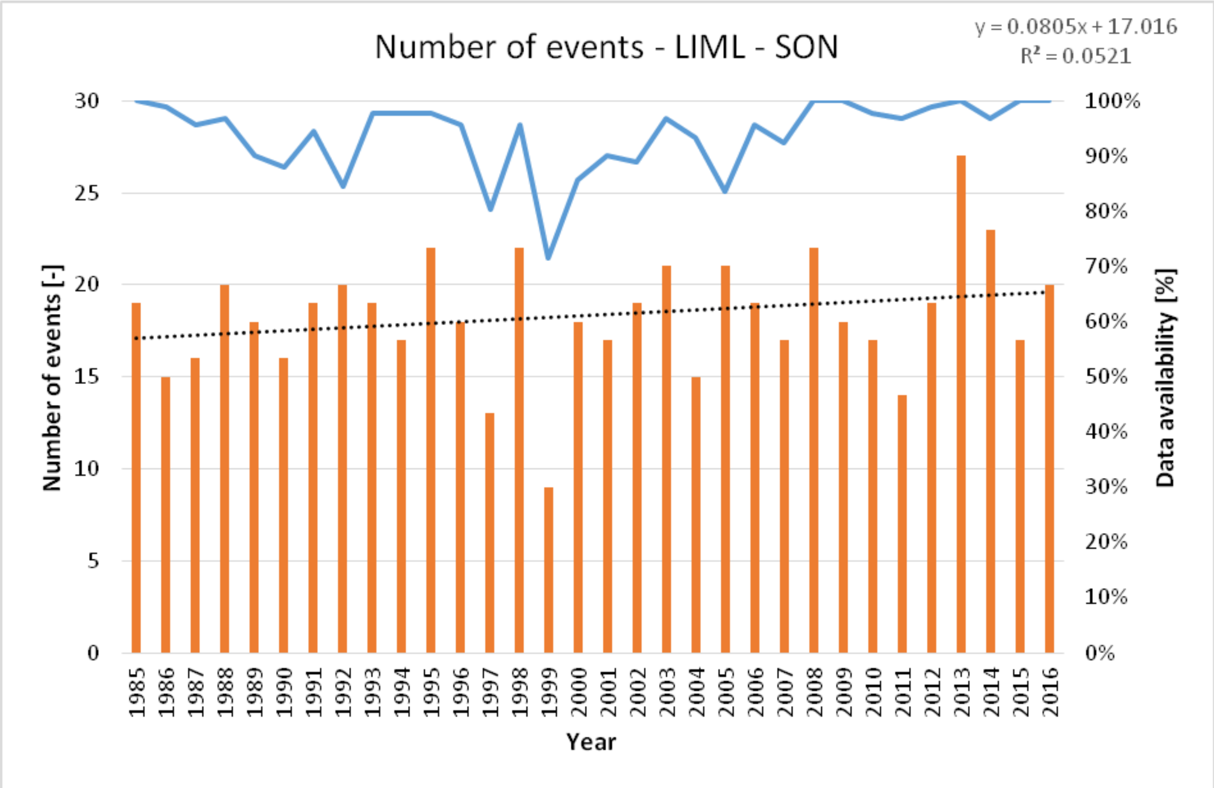


Figure 4.2.11: Trend of number of events in Milano Linate – Autumn

In all seasons it seems that there is a very slight increase of thermal inversion events (about +1 event per season per decade) and that there is not a particular period where the trend is more substantial. Statistical tests have been applied, giving these results (Table 4.2.5-4.2.6):

# events	**DJF**	**MAM**	**JJA**	**SON**
F calc.	3,81	4,53	1,77	1,65
$F_{(1,30),\alpha=0.05}$	4,17	4,17	4,17	4,17
Linear trend	No	Yes	No	No
P value	0,06	0,042	0,193	0,209

Table 4.2.5: Results of F test on seasonal basis (alpha = 5%)

# events	**DJF**	**MAM**	**JJA**	**SON**
Z_{MK} calc.	1,77	2,25	1,60	1,06
$Z_{\alpha=0.05}$	1,96	1,96	1,96	1,96
Monotonic trend	No	Yes	No	No
P value	0,077	0,024	0,11	0,289

Table 4.2.6: Results of Mann-Kendall test on seasonal basis (alpha = 5%)

Both tests resulted in a significant linear monotonic trend only during spring (about +1 day per decade). Even in this case, the Seasonal Kendall test give us a misleading interpretation: for this test, there is basically a significant trend in all seasons, with a Z_{SK} statistic equal to 3,37. However, same results have been obtained with the adjusted series of data in all seasons considered.

4.2.4 Duration of events

The analysis of the duration of events in Milano Linate firstly considered the whole 32-year period, and then focused both on annual and seasonal data.

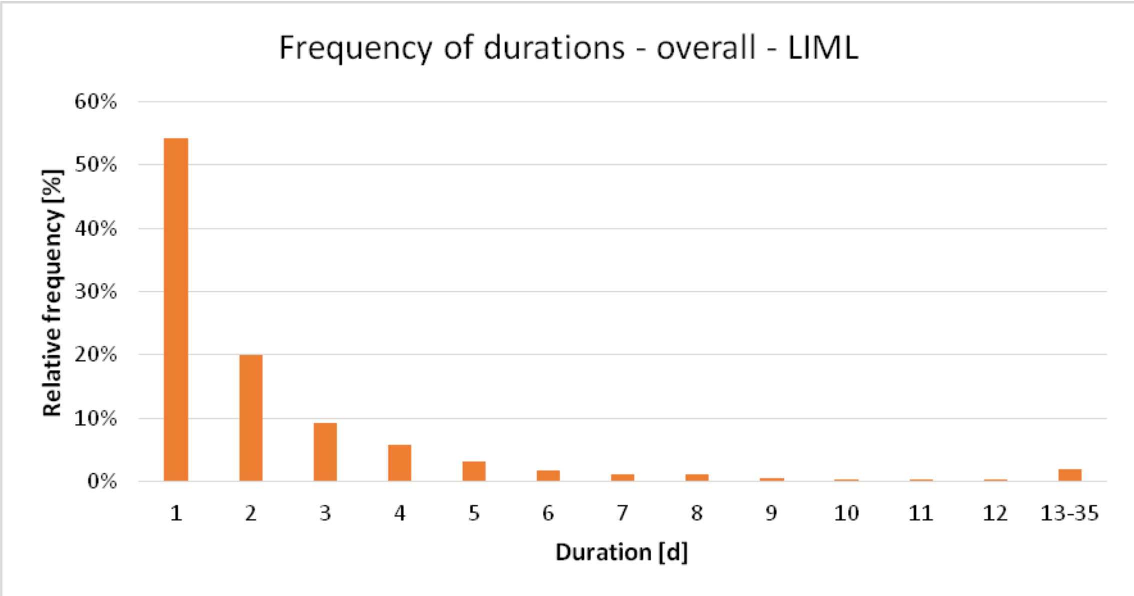


Figure 4.2.12: Overall durations in Milano Linate

As it is shown in Figure 4.2.12, about 83% of events last at maximum for 3 days, but it has been found that some events can reach very high durations, like the one that occurred between 25/11/2015 and 29/12/2015 (35-days event).

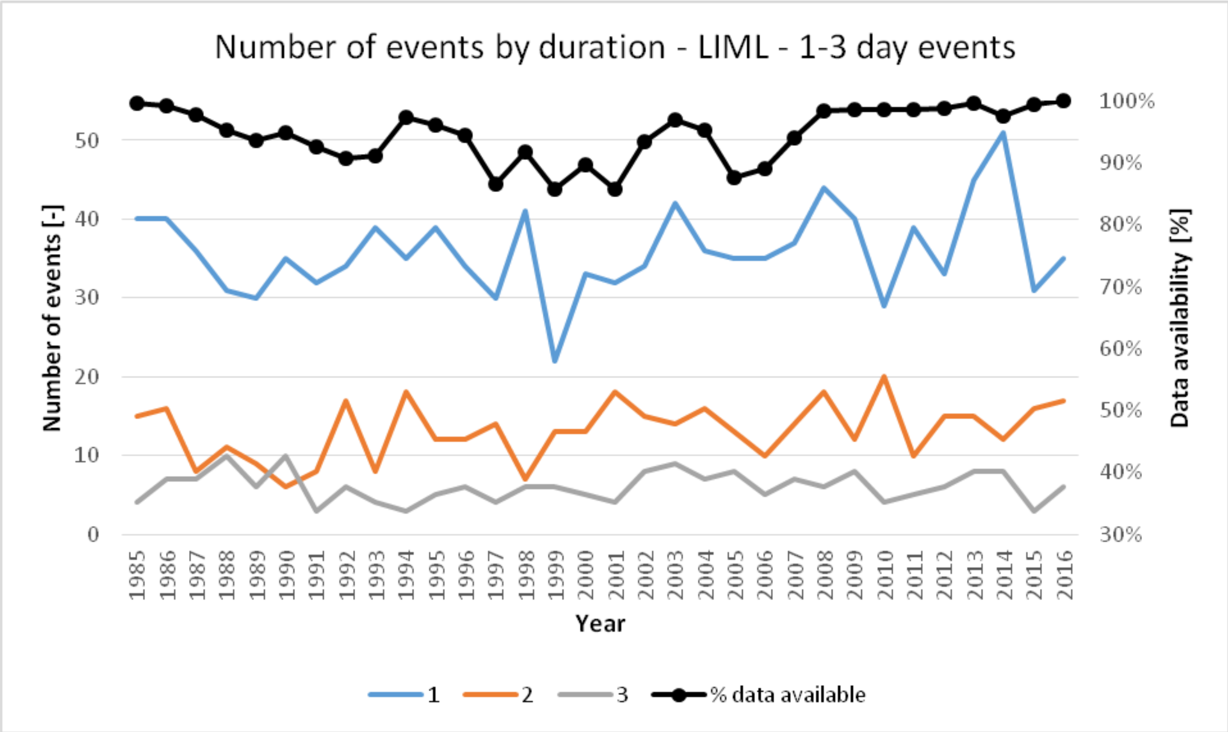


Figure 4.2.13: Trend in number of events per duration in Milano Linate - annual basis - 1985/2016 period - <4 days events

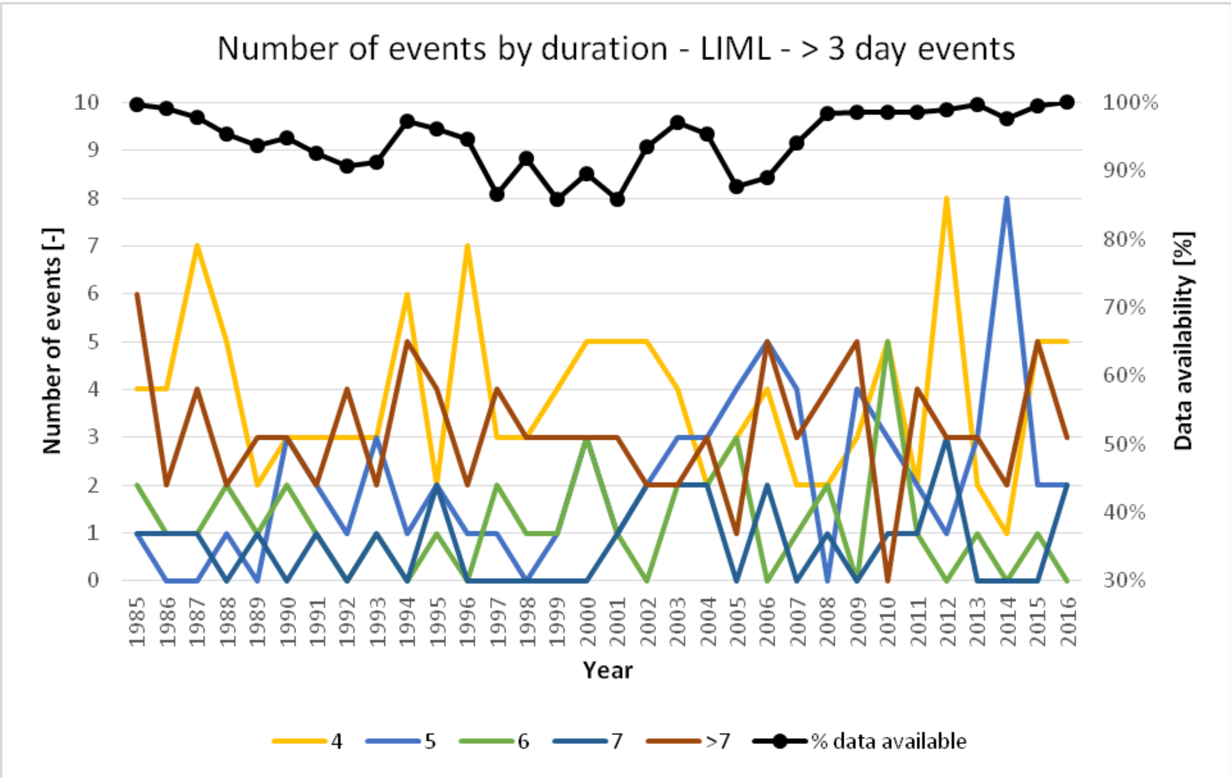


Figure 4.2.14: Trend in number of events per duration in Milano Linate - annual basis - 1985/2016 period - >3 days events

From this kind of data shown in Figure 4.2.13-4.2.14, it appears that very long events (more than 7 days) occur almost every year (the exception is 2010), so they cannot be considered as extraordinary ones, even if their occurrence is quite low (maximum 6 time per year) if compared to shorter events. A seasonal evaluation has been carried on to have a better overview of this feature:

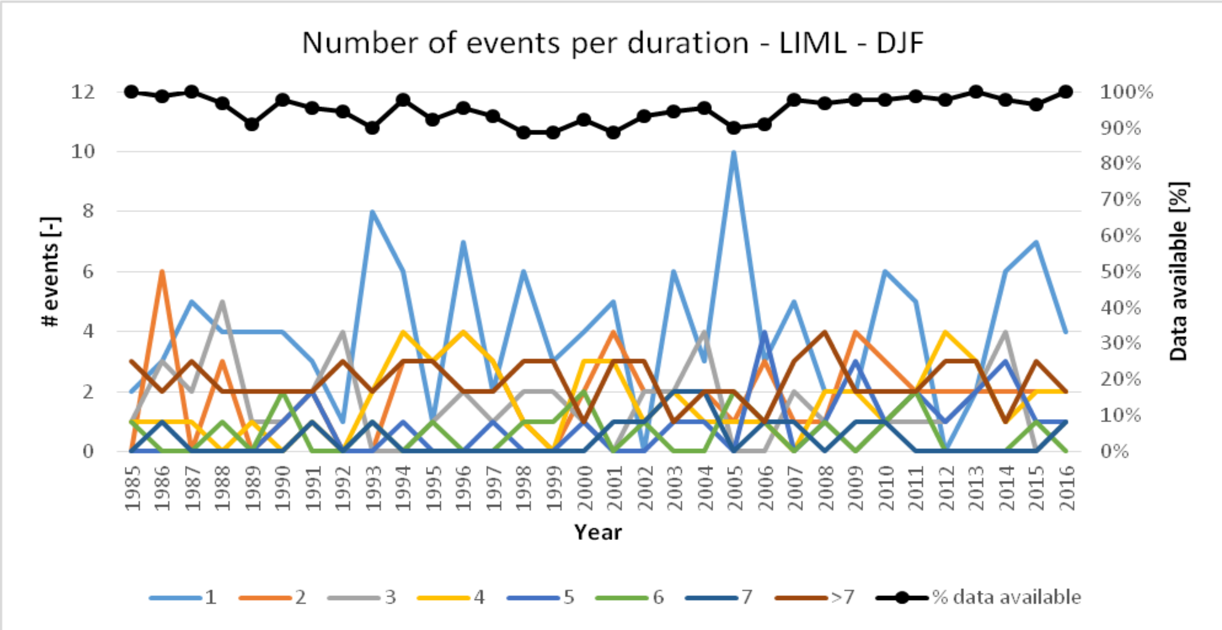


Figure 4.2.15: Duration of events in Milano Linate – Winter

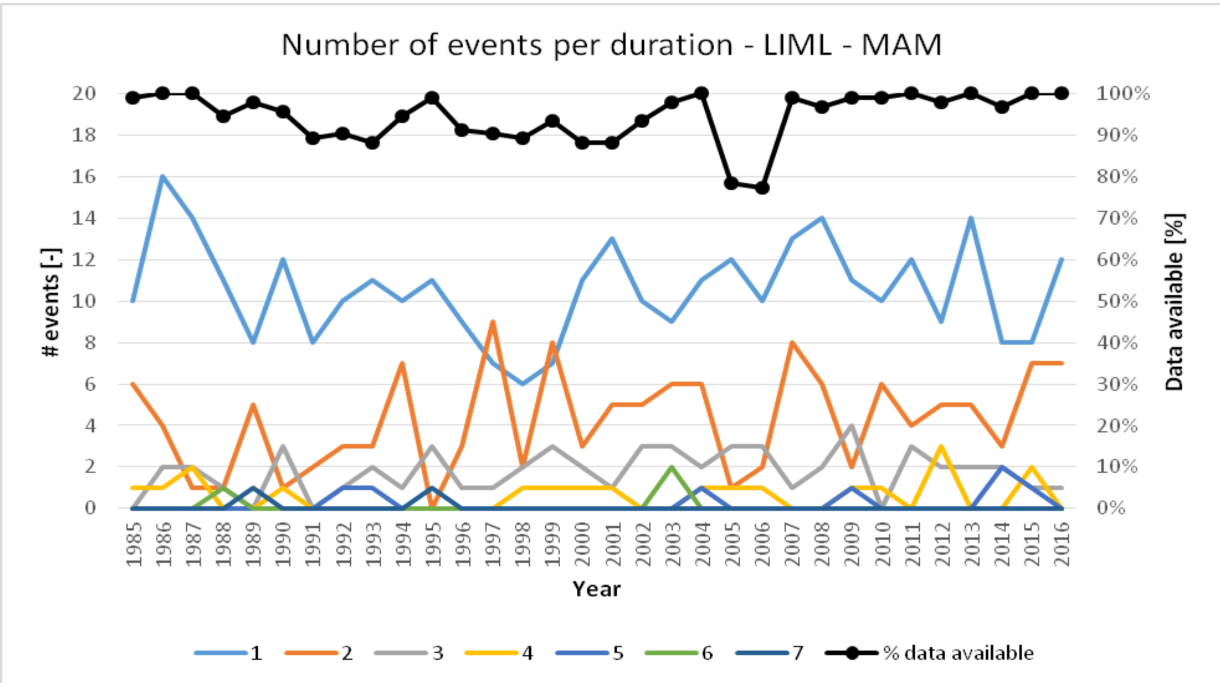


Figure 4.2.16: Duration of events in Milano Linate – Spring

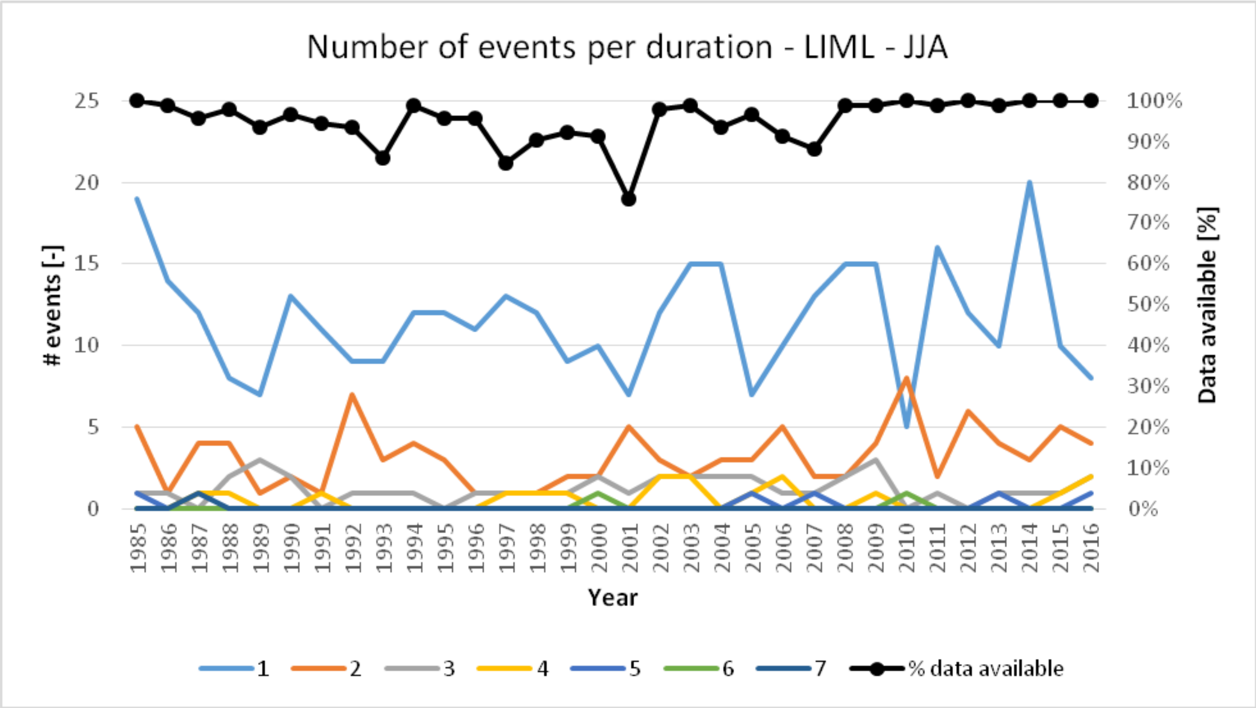


Figure 4.2.17: Duration of events in Milano Linate – Summer

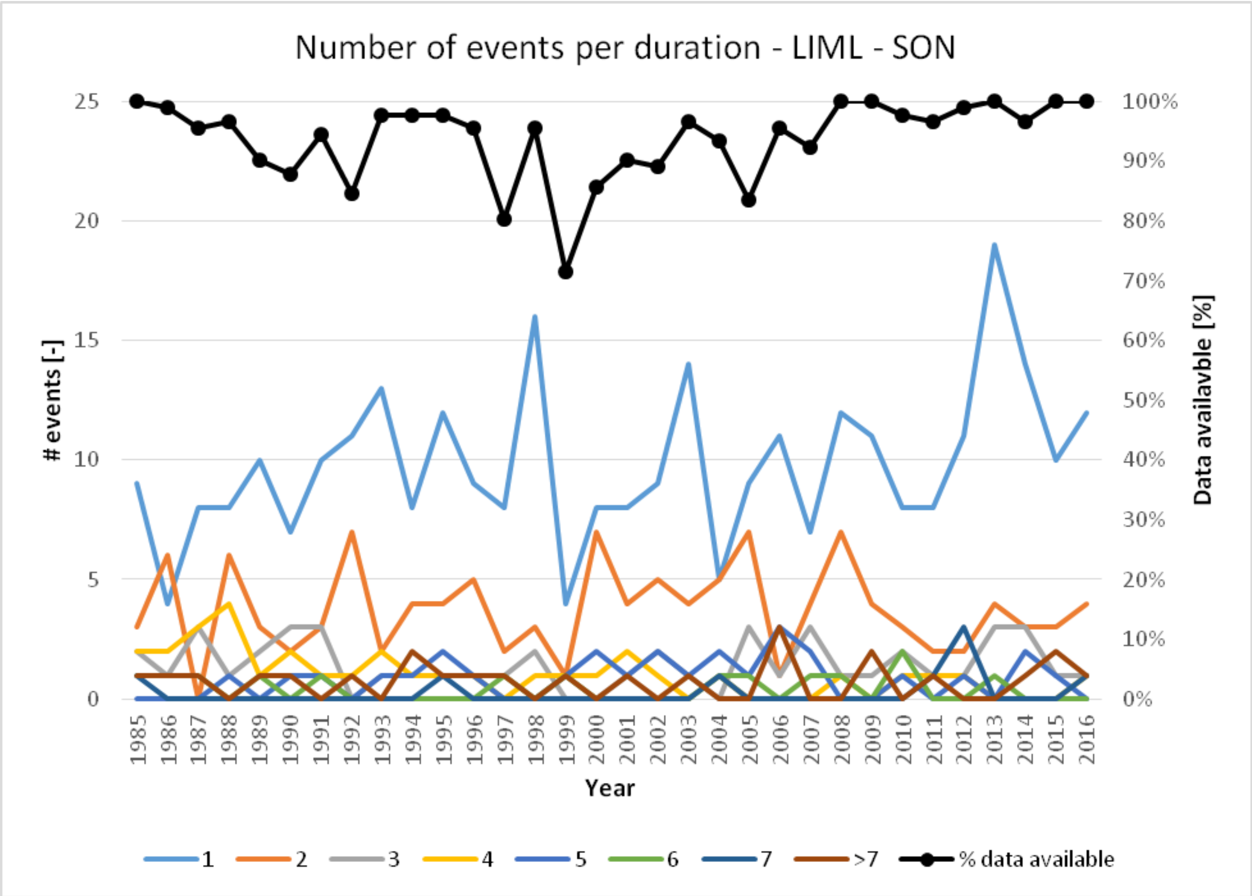


Figure 4.2.18: Duration of events in Milano Linate – Autumn

From these graphs above (Figure 4.2.15-4.2.18), it is possible to see that in relatively warmer seasons 3-or-more days events are very rare; on the contrary, there is a similar occurrence between different duration events in the relatively colder seasons. Therefore, the important occurrence of “long” events is an expression of the great stability of the atmosphere in this area during wintertime.

4.2.5 Characteristics of thermal inversions

Inversions have been characterized by their type, thickness and height. In this case, the data has a good quality in terms of coverage and completeness. The assessment on the characteristics of thermal inversion has been done considering also a splitting between ground-based (radiation) inversions and subsidence one.

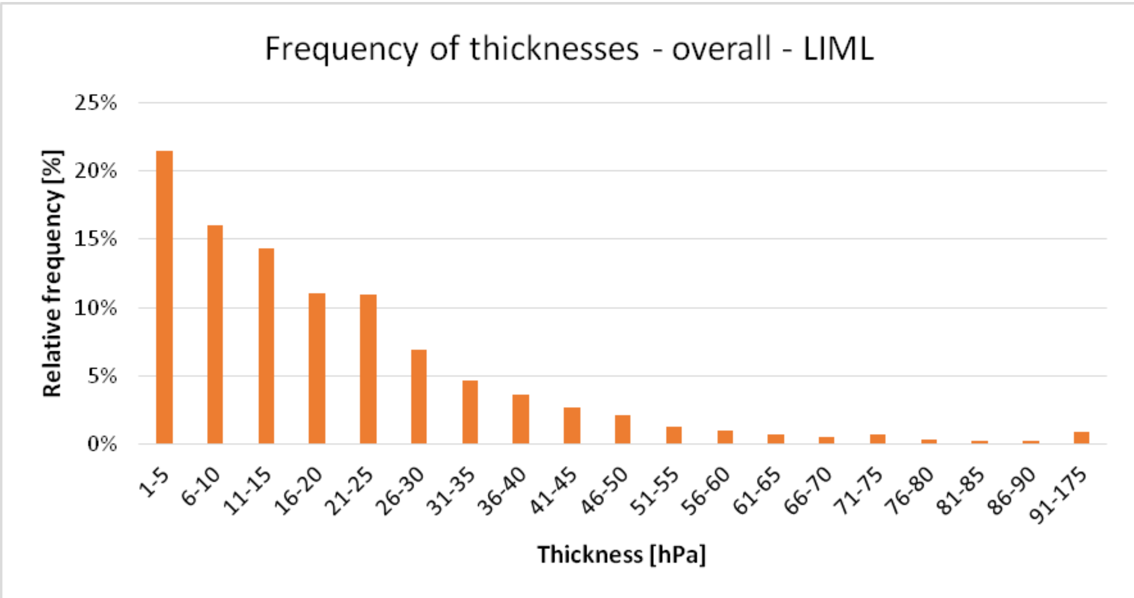


Figure 4.2.19: Thicknesses of all kind of inversions in Milano Linate

In LIML station, more than 80% of all inversion layers have a thickness lower than 30 hPa (about 270 m from ground level), but it has been reached a 175 hPa thick layer (over 1500 m from ground level), so the entire lower-atmosphere layer could be considered as an inversion layer (Figure 4.2.19).

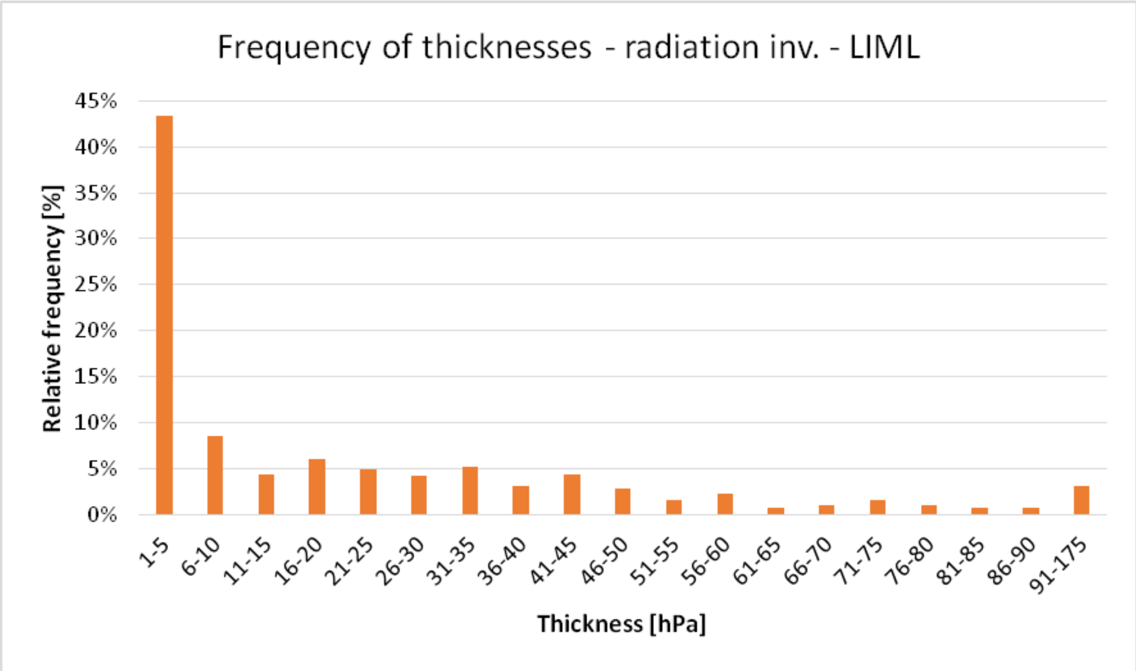


Figure 4.2.20: Thicknesses of ground-level inversions in Milano Linate

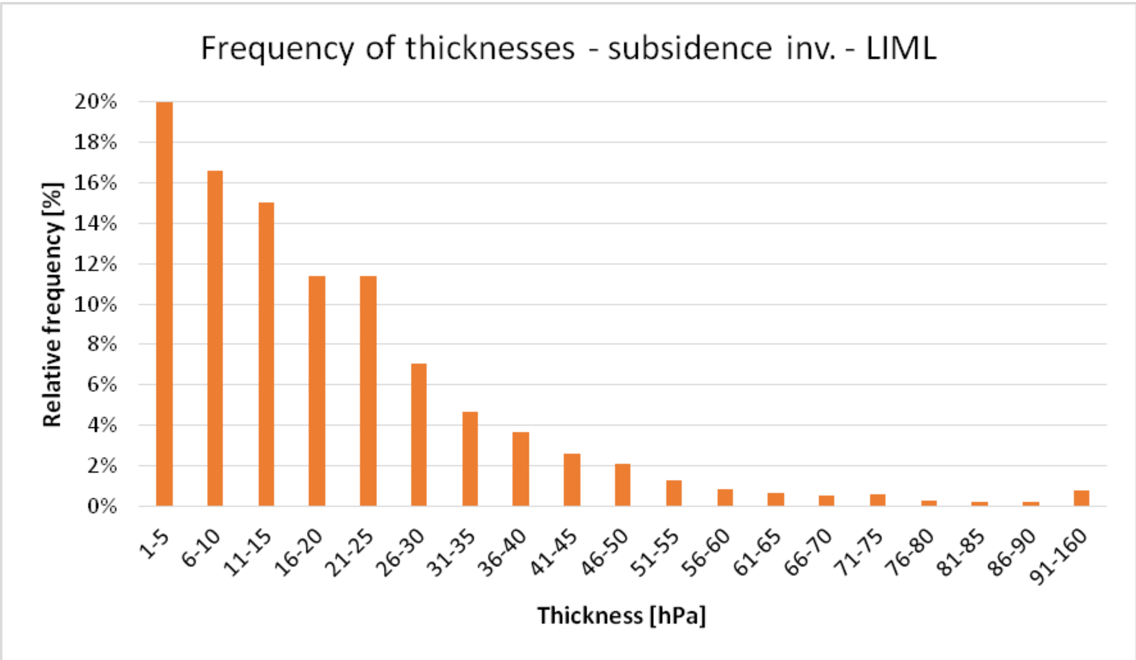


Figure 4.2.21: Thicknesses of subsidence inversions in Milano Linate

Looking at the relative frequency of the inversion thickness during radiation and subsidence episodes (Figure 4.2.20-4.2.21), a quite clear dominance of very small radiation layers (nearly 60% with a thickness lower than about 100 m from ground level) can be observed. Thus, the contribution of ground-based inversion is very important for thinner layers; on the other side, there is a higher variability in subsidence inversions.

Trend in time of the number of inversion divided per type (radiation or inversion) on a seasonal basis are reported here in Figure 4.2.22-4.2.25. It is important to notice that radiation inversions occur not so many times on all seasons at 12 UTC, even in the relative cooler ones; an anomaly can be found between SON 1986 and JJA 1987 when radiation inversion had a significant contribution to the overall amount, situation that has not repeated until 2016.

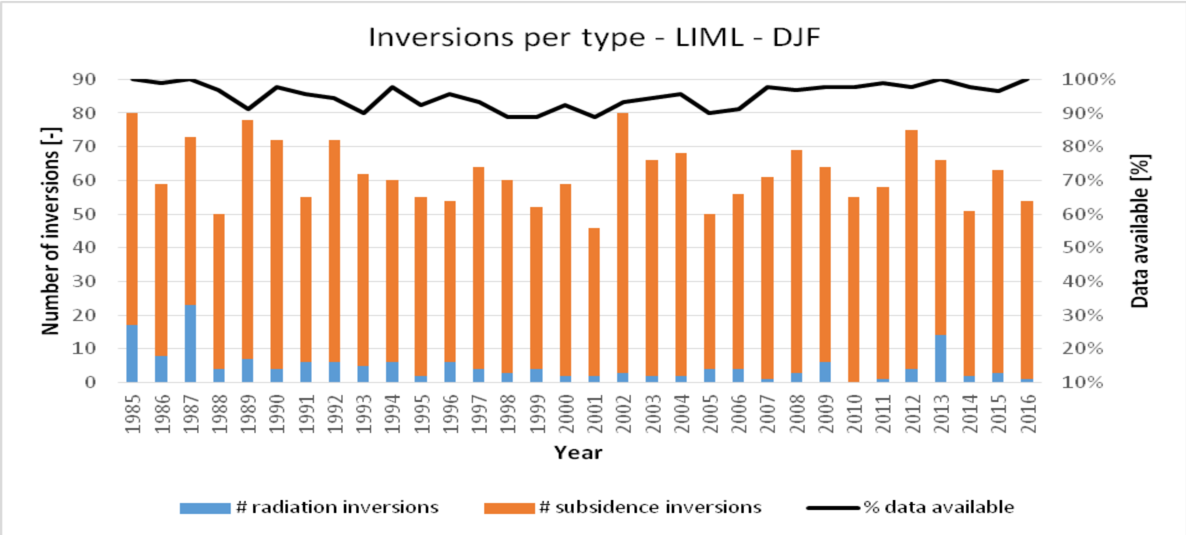


Figure 4.2.22: Number of inversions per type from 1985 to 2016 - Milano Linate - Winter

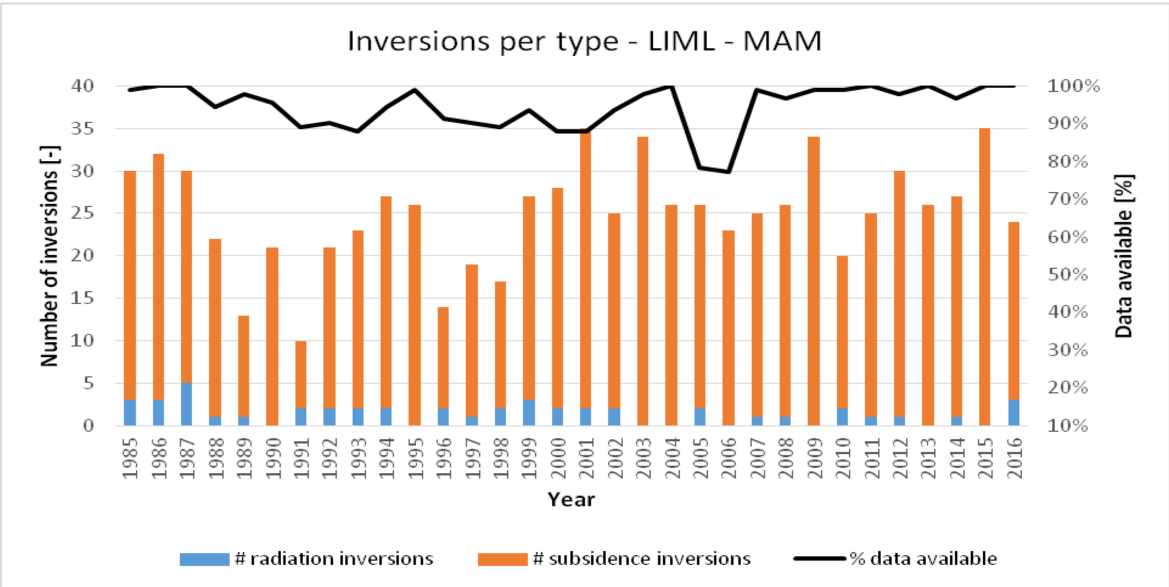


Figure 4.2.23: Number of inversions per type from 1985 to 2016 - Milano Linate - Spring

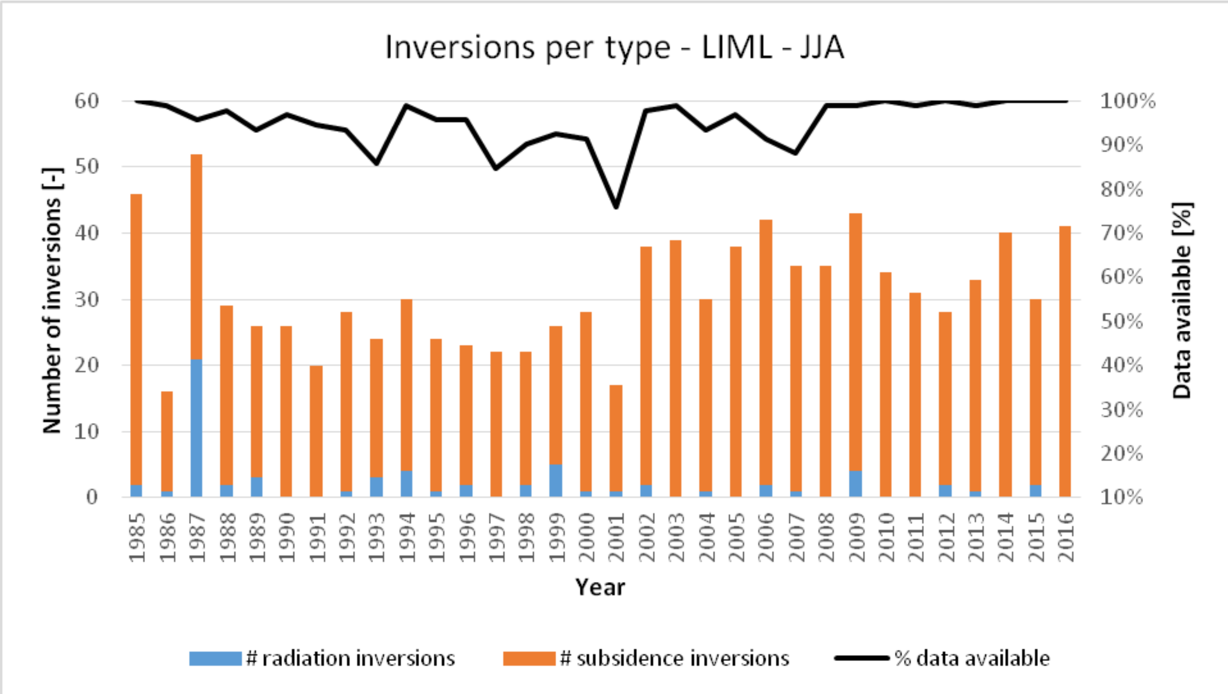


Figure 4.2.24: Number of inversions per type from 1985 to 2016 - Milano Linate - Summer

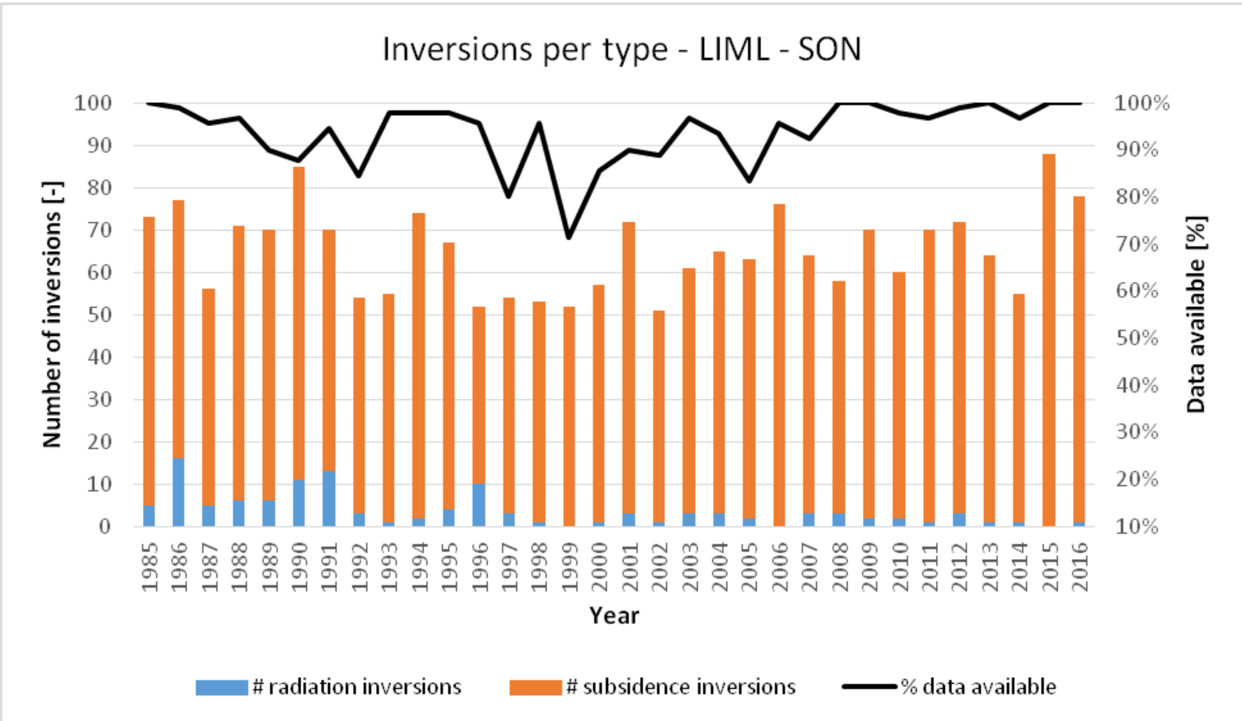


Figure 4.2.25: Number of inversions per type from 1985 to 2016 - Milano Linate - Autumn

In Figure 4.2.26 the distribution of the depth of mixing height under subsidence inversion condition, is reported.

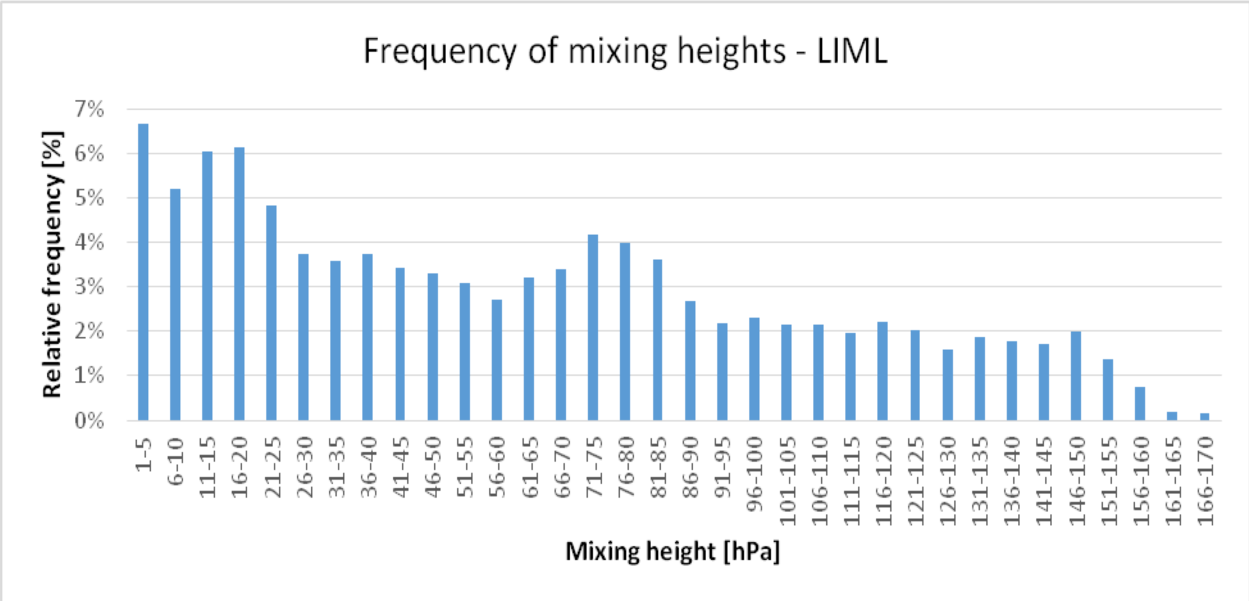


Figure 4.2.26: Mixing height distribution in Milano Linate

The modal class is located into the lowest range (1-5 hPa), even if the differences among relative frequencies are not so large, especially for depth range up to 25 hPa. This means that very thin mixing heights are quite frequent, as better shown by the cumulative frequency of mixing height classes reported in Figure 4.2.27.

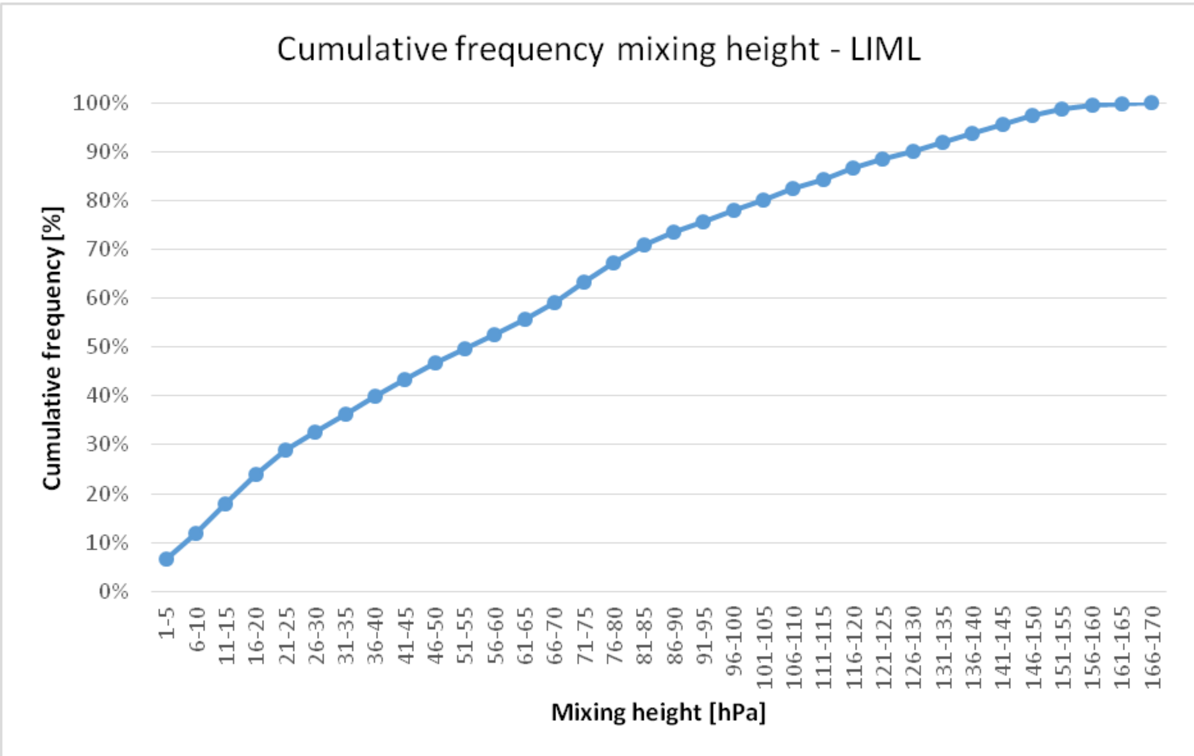


Figure 4.2.27: Cumulative distribution of mixing heights divided per classes in Milano Linate

About 30% of mixing heights is lower than 25 hPa (which is about 230 m from ground level), and more than 70% is lower than 85 hPa (about 760 m from ground level). Seasonal analyses (Figure 4.2.28) show that there is an important tendency to have shallow free mixing heights, especially during wintertime, which is the most critical period for air pollution.

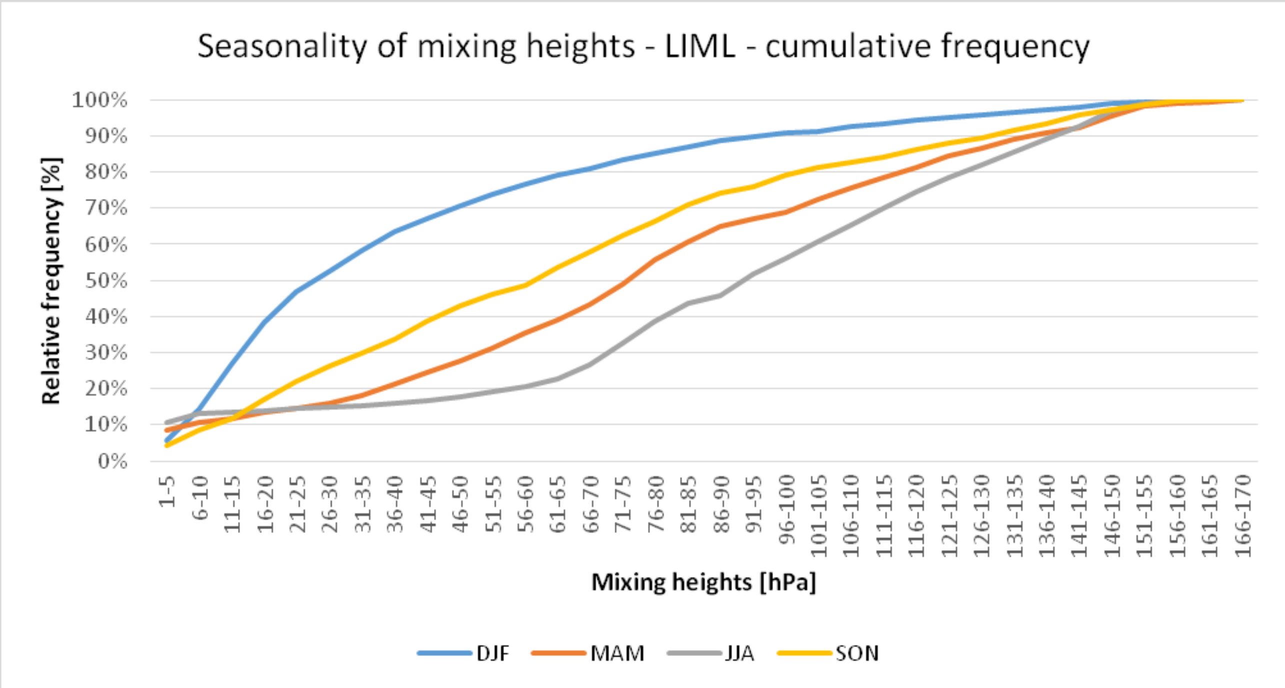


Figure 4.2.28: Cumulative frequency of mixing heights classified by season – LIML

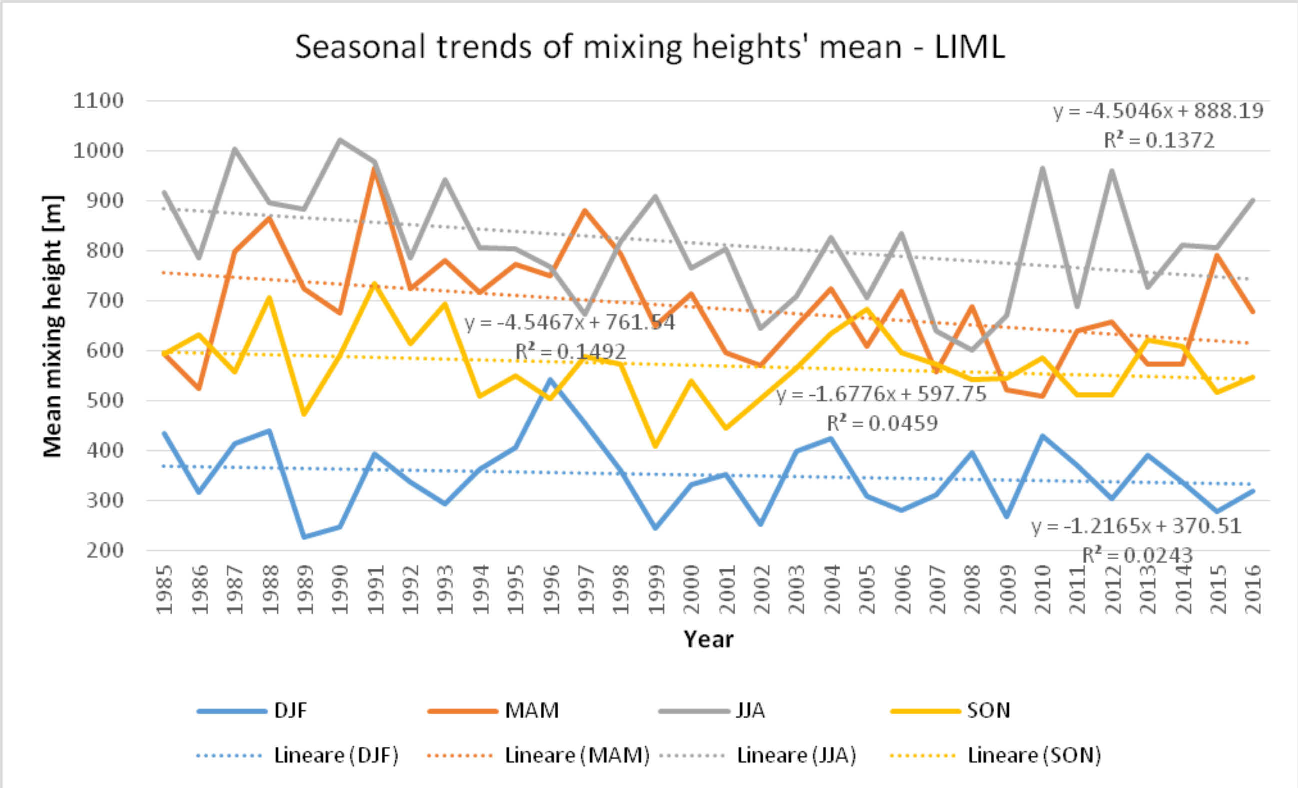


Figure 4.2.29: Seasonal trend in free mixing height mean (per year) – LIML

In Figure 4.2.29, for each year, the mean between all the mixing height have been calculated, considering only subsidence inversions, leading to four different trends in various seasons. The application of a F test revealed that there are significant trends in the average mixing height in spring and summer (with a downward rate of about 45 m per decade) and there are not significant trends in relatively cooler seasons; however, the mean mixing height of spring and summer is at an higher level than the other two seasons.

As it has been done for LIMZ station, it has been studied that multiple layers are not so common in Milano Linate soundings (less than 14% of the total), as it is shown in Table 4.2.7:

LIML	1 layer	2 layers	3 layers
# days	4430	683	25
Rel. Freq. [%]	86,2%	13,3%	0,5%

Table 4.2.7: Number of days with simultaneous inversions – Milano Linate

So, it can be stand that in LIML station, especially in the spring period, there are worsening trends for the features of the lower atmosphere (an increasing trend of both inversion days and events and a reduction of the free mixing height's thickness); however, the most critical season remains winter when inversions have a rather high frequency of occurrence and tend to be persistent, thus determining unfavourable conditions for the dispersion of the atmospheric pollutants.

4.3 San Pietro Capofiume (SPC) station

4.3.1 Data availability

This station is located at 10 m a.s.l. in the South-Eastern part of the Po Valley area, in Emilia Romagna region, in a rural area between cities like Ferrara, Bologna and Ravenna. Soundings are managed by the Hydrometereological Service of the ARPA Emilia Romagna. These measurements have been taken with good time coverage from 1986 to 2006, but from that point on there have been a significant drop of measurements at "12Z" time as shown in Figure 4.3.1. Therefore, it has not been possible to carry out any study in order to evaluate trends in time in the last 10 years.

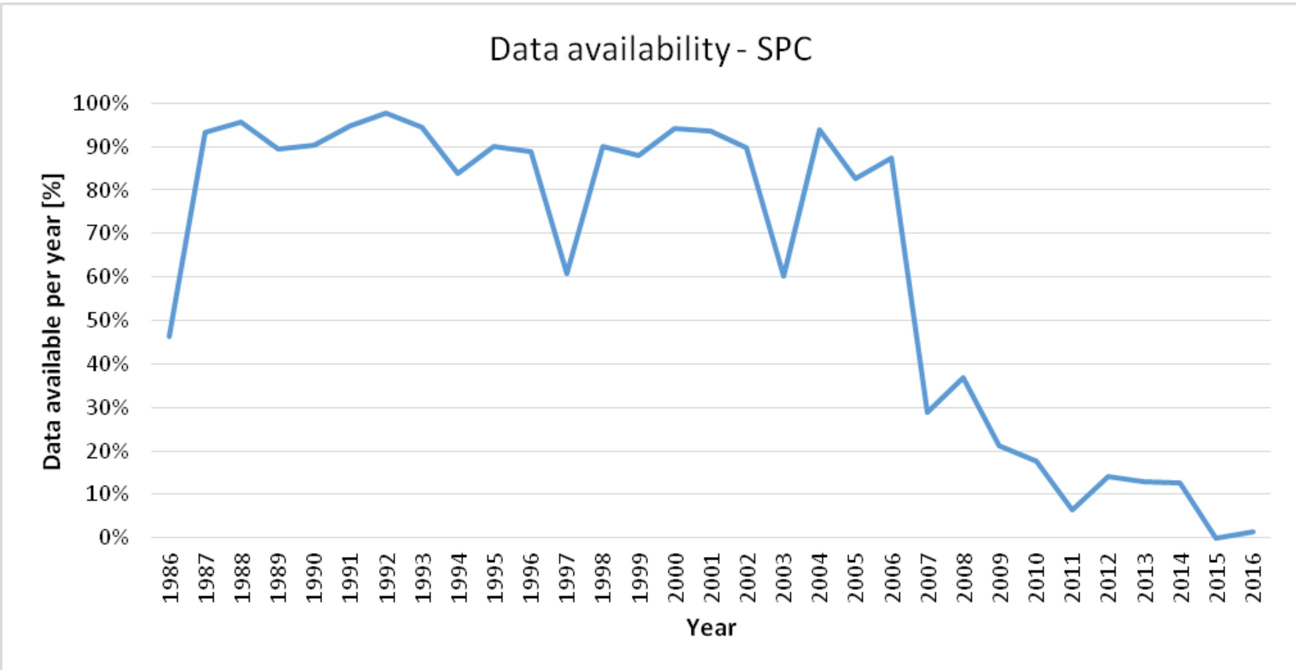


Figure 4.3.1: Data availability of San Pietro Capofiume station

From a global point of view, it is possible to observe that cooler months are particularly affected by thermal inversion events, especially in wintertime (Table 4.3.1):

S. Pietro Capofiume (SPC)	**Thermal Inversions**			
Total	3149 (44%)			
Six-month	**Autumn - Winter**		**Spring - Summer**	
	2249 (64,8%)		900 (24,5%)	
Seasonal	**SON**	**DJF**	**MAM**	**JJA**
	884 (51,4%)	1365 (77,9%)	491 (26,3%)	409 (22,6%)

Table 4.3.1: Number of thermal inversions' days and relative frequency on data available – period 1986-2016

4.3.2 Days of thermal inversion

In this case, data coming from SPC station have been analysed, paying attention to the fact that there is a huge lack of useful data in the last decade:

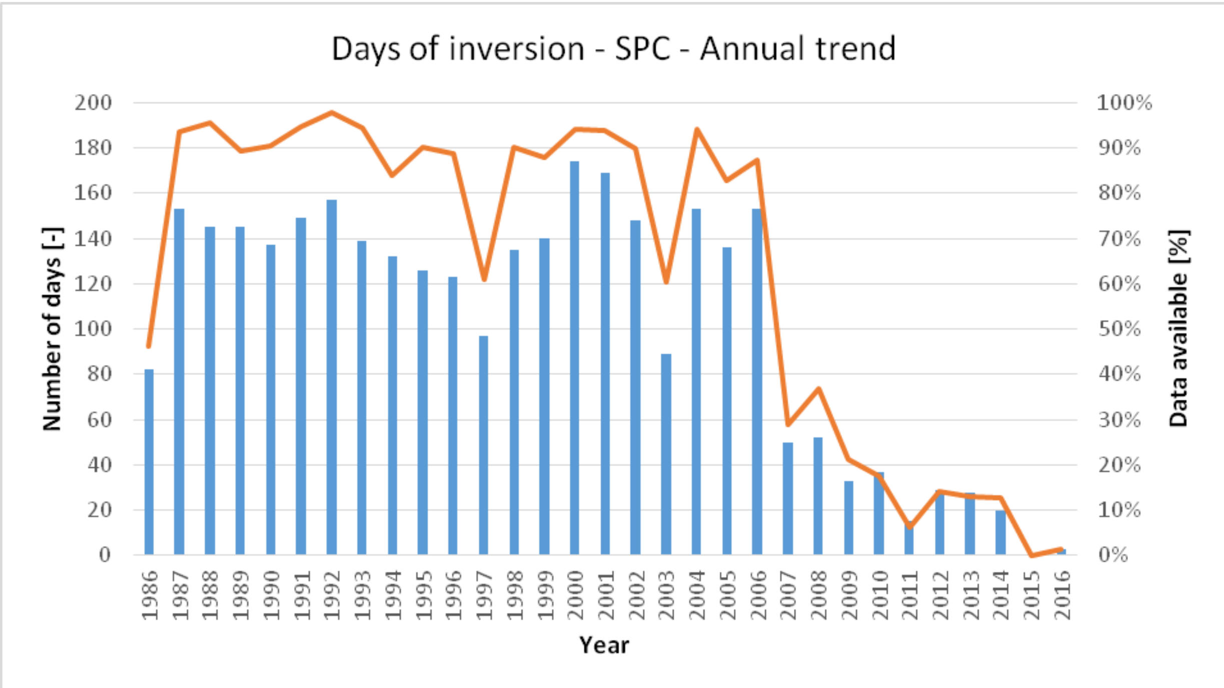


Figure 4.3.2: Days of inversion trend in San Pietro Capofiume

It is possible to notice (Figure 4.3.2) that there is a direct relationship between data coverage and the number of "inversion days", so it has not been feasible a deeper assessment about trends in time. However, a maximum 174 days of inversion has been reached in 2000.

Limiting the investigation to the 1986-2006 period, the seasonal trends for the number of inversion days are reported in Figure 4.3.3-4.3.6:

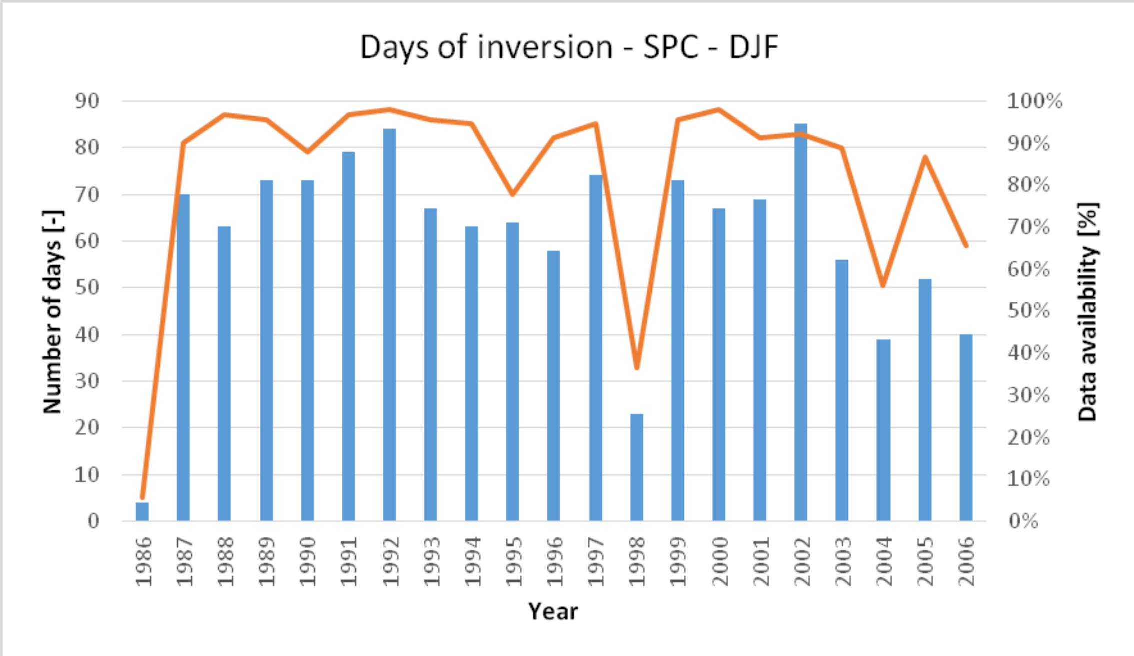


Figure 4.3.3: Days of inversion trend in San Pietro Capofiume - Winter

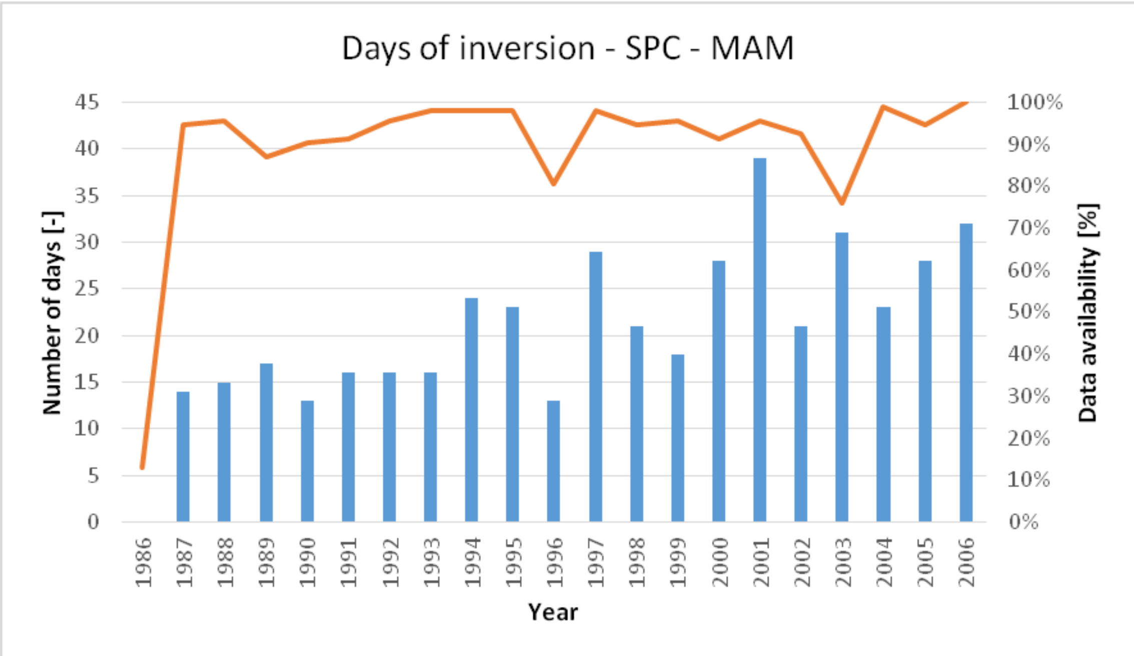


Figure 4.3.4: Days of inversion trend in San Pietro Capofiume - Spring

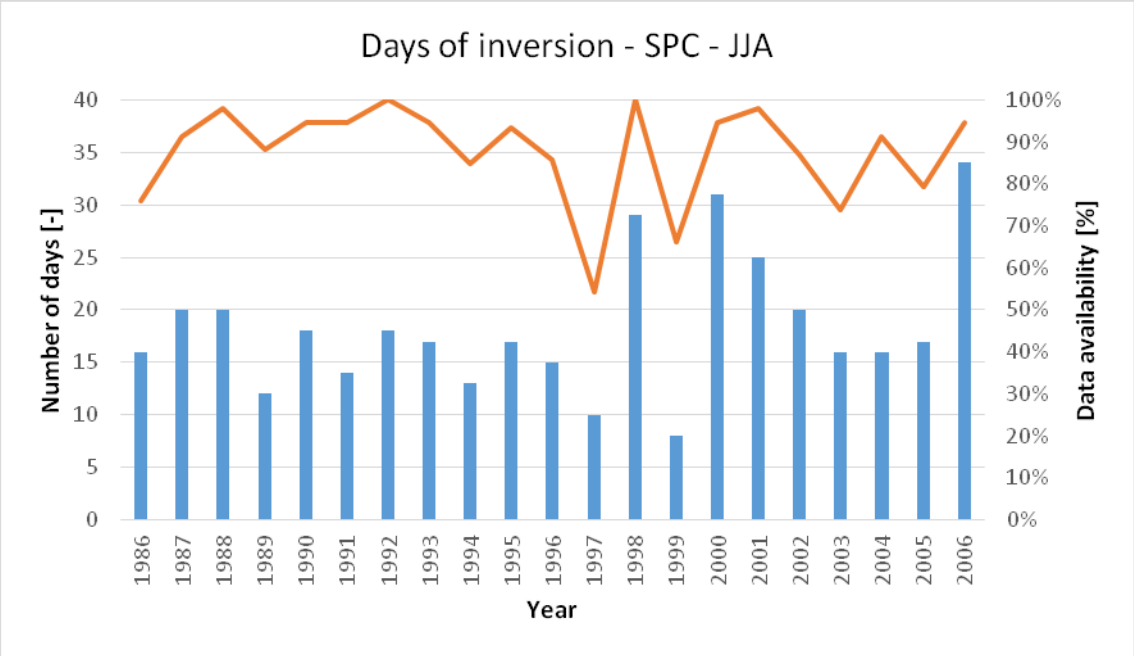


Figure 4.3.5: Days of inversion trend in San Pietro Capofiume - Summer

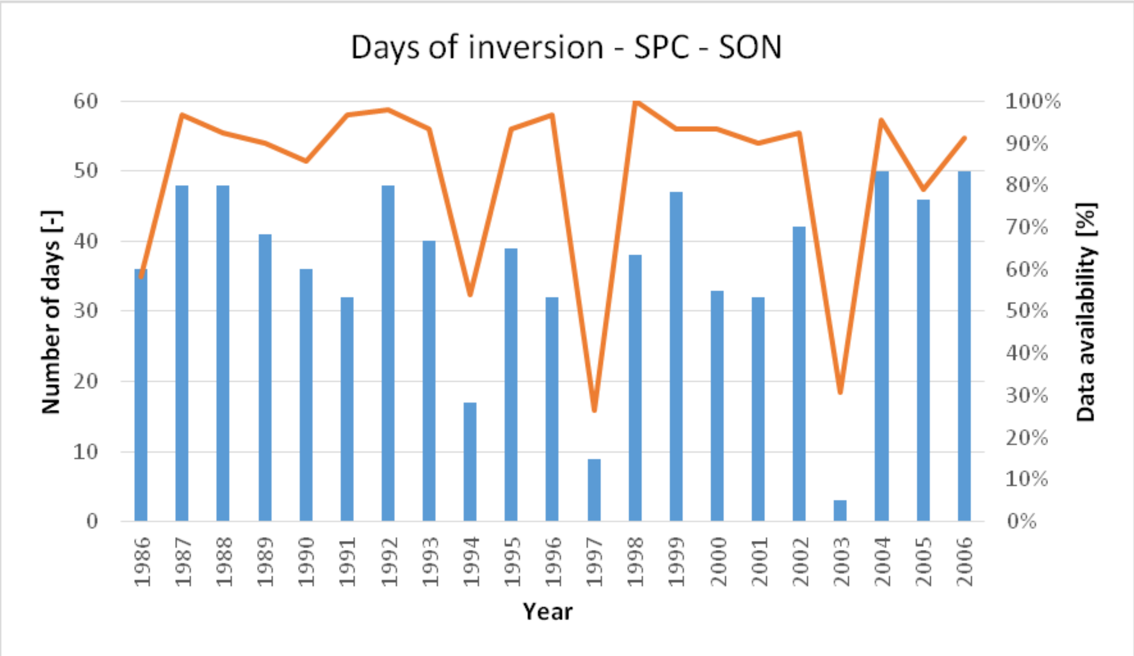


Figure 4.3.6: Days of inversion trend in San Pietro Capofiume – Autumn

For this period, it seems that there is an important trend in spring where inversion days raised from about 15 to 25 or more in 20 years, while in other seasons trends are not very clear; without considering DJF, the highest values of inversion days have been found in the early 2000s.

4.3.3 Thermal inversion events

The number of events from the last 32-years has been studied, according with the data available; after that, the focus has been done on the 1986-2006 period (Figure 4.3.7):

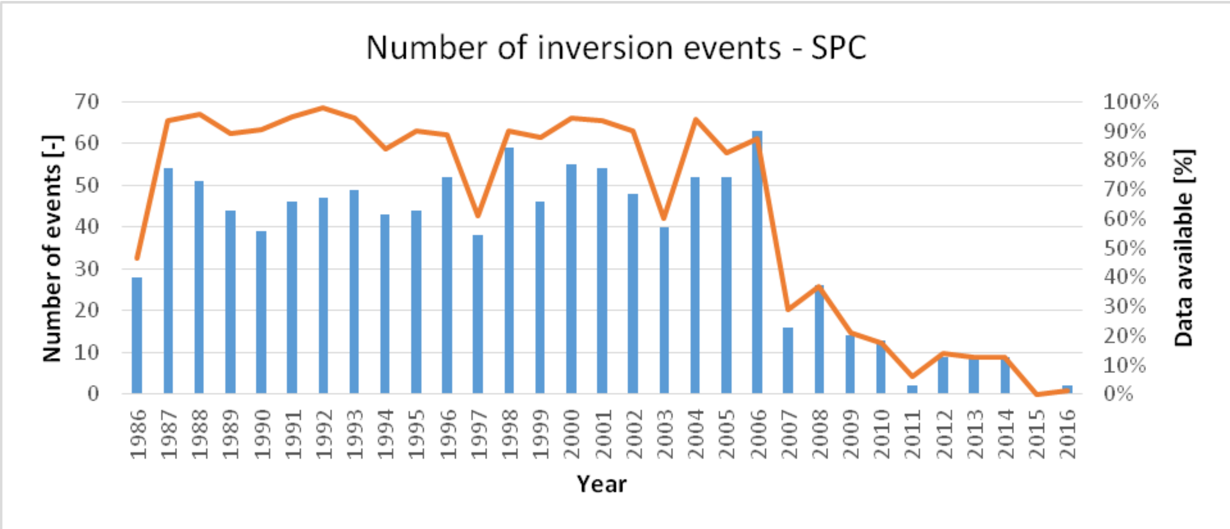


Figure 4.3.7: Number of inversion events in San Pietro Capofiume station per year

From this kind of data, it is possible to stand that there have been 45 events of thermal inversion per year on average from 1986 to 2006. On a seasonal basis, it seems that there is not a big difference among different seasons, in terms of number of events (Figure 4.3.8-4.3.11).

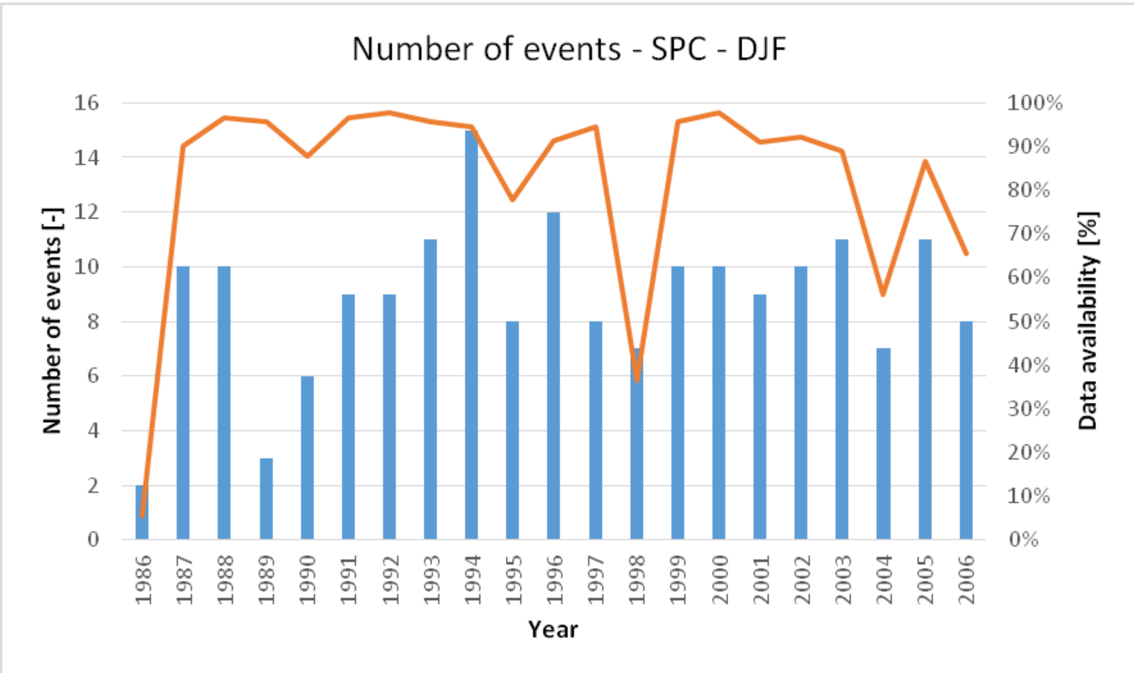


Figure 4.3.8: Trend of number of events in San Pietro Capofiume – Winter

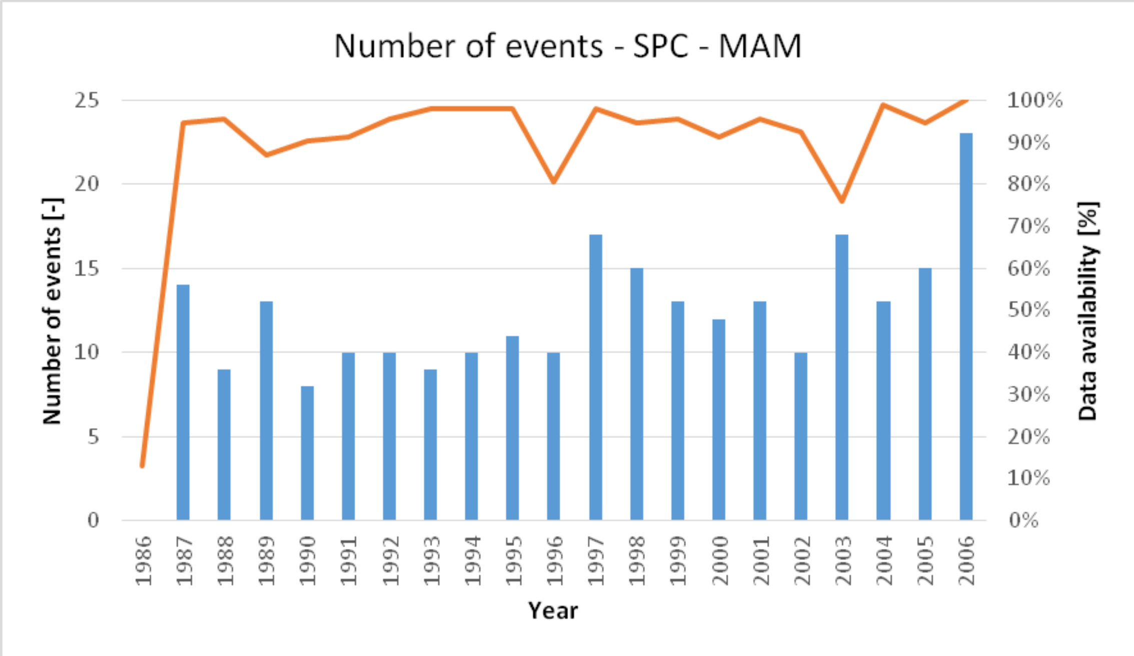


Figure 4.3.9: Trend of number of events in San Pietro Capofiume – Spring

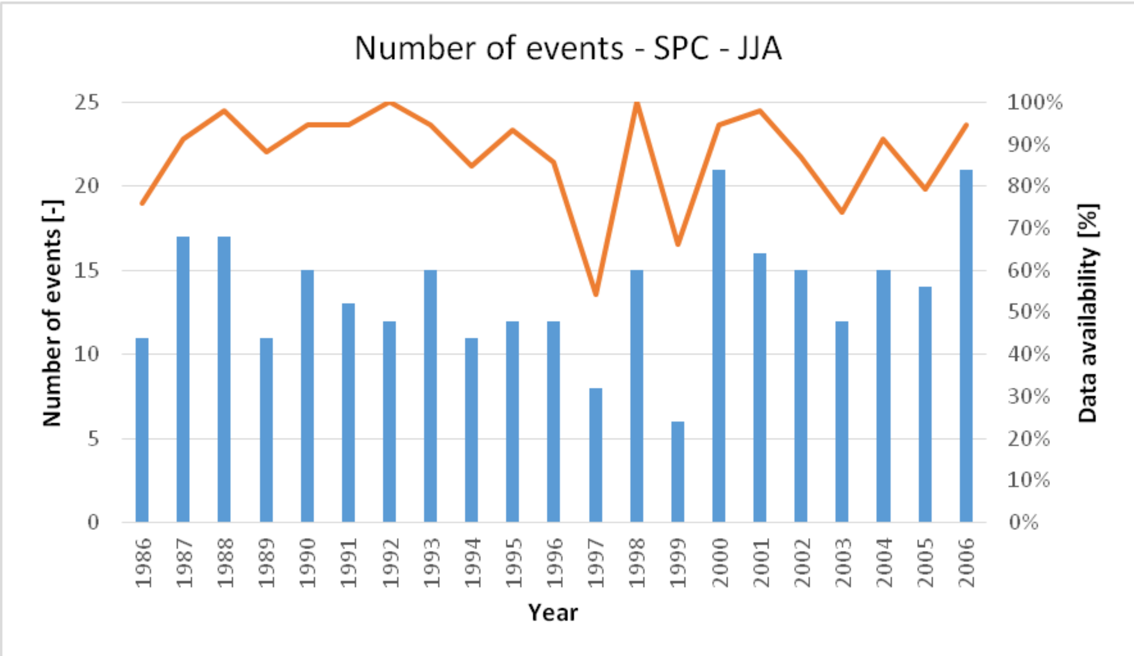


Figure 4.3.10: Trend of number of events in San Pietro Capofiume – Summer

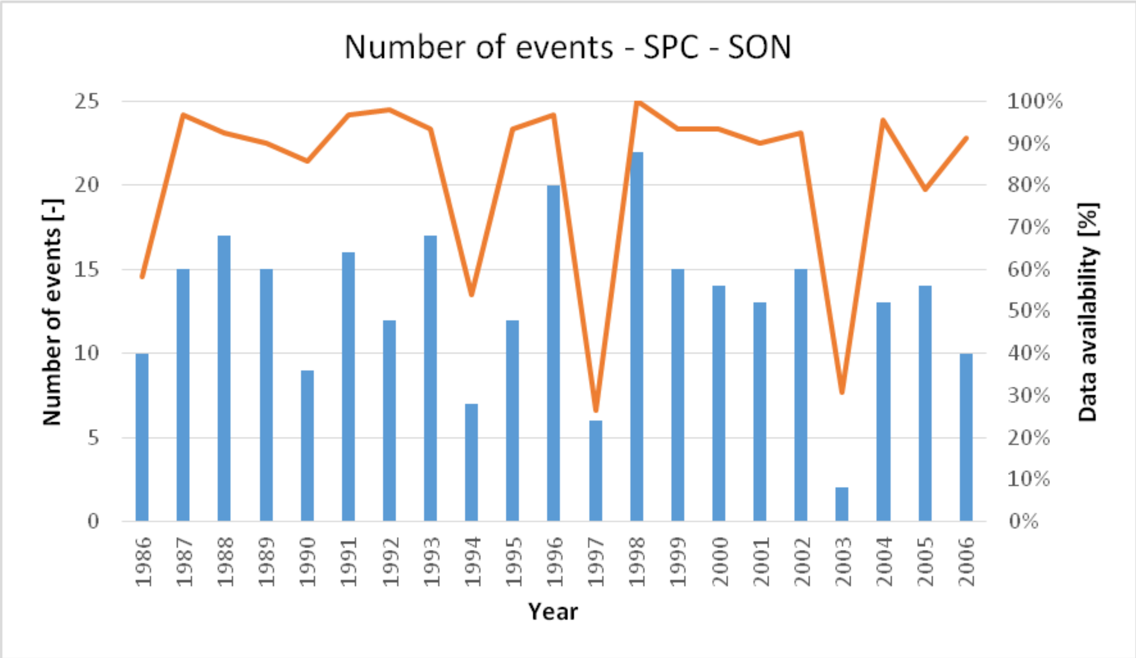


Figure 4.3.11: Trend of number of events in San Pietro Capofiume – Autumn

Even in this case spring has a particular characteristic: a peak of 23 inversion events in 2006 that has never been reached in other seasons in the period considered. However, the number of events seems to be quite comparable within different seasons.

4.3.4 Duration of events

Overall, durations in SPC measurements are predominantly short: in fact, three-or-less events are about 82% of total events at "12Z". The longest event occurred between December 1988 and January 1989 (55 consecutive days' event).

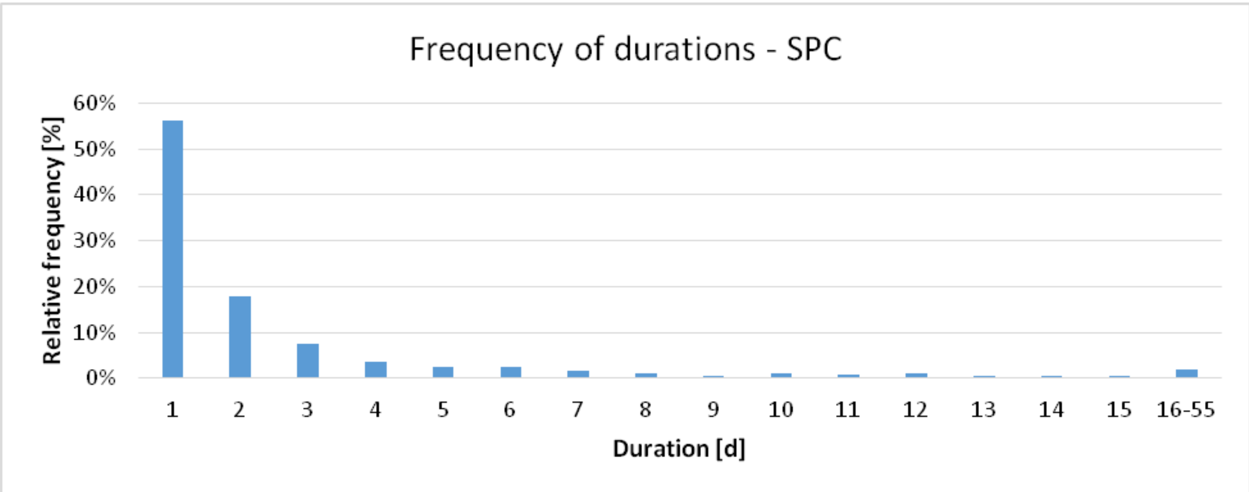


Figure 4.3.12: Overall durations in San Pietro Capofiume

The trends of number of events classified by duration, both on annual and seasonal basis are reported here below (Figure 4.3.13-4.3.14 on annual basis, Figure 4.3.15-4.3.18 on seasonal one):

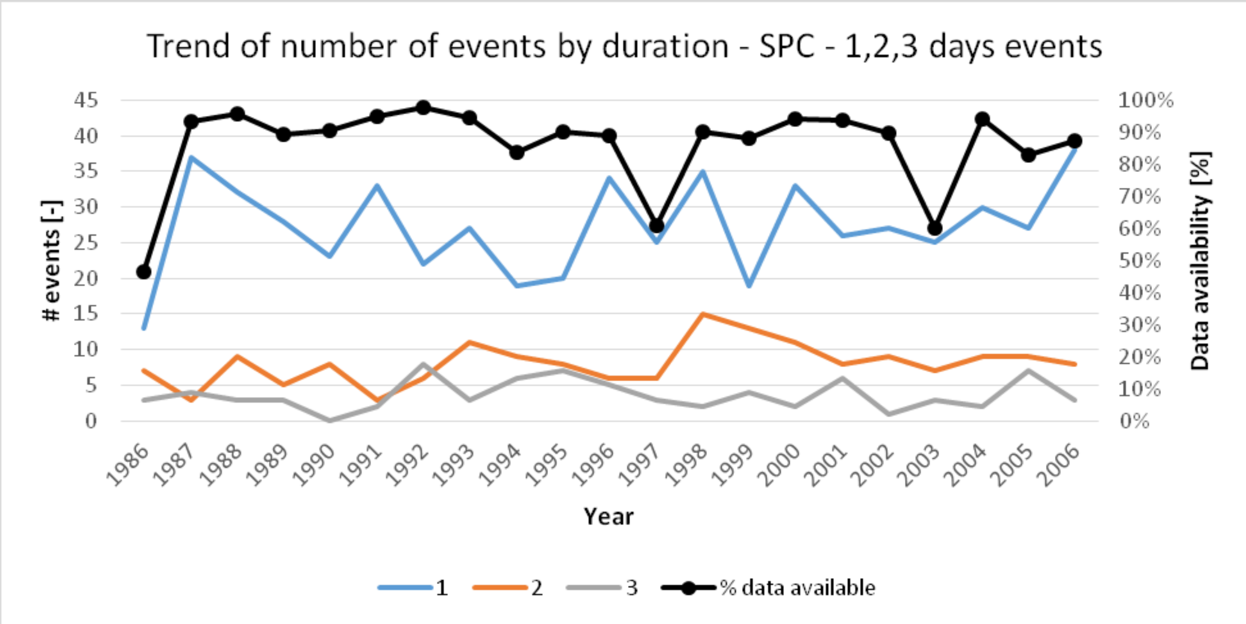


Figure 4.3.13: Trend in number of events per duration in San Pietro Capofiume - annual basis - 1986/2006 period - <4 days events

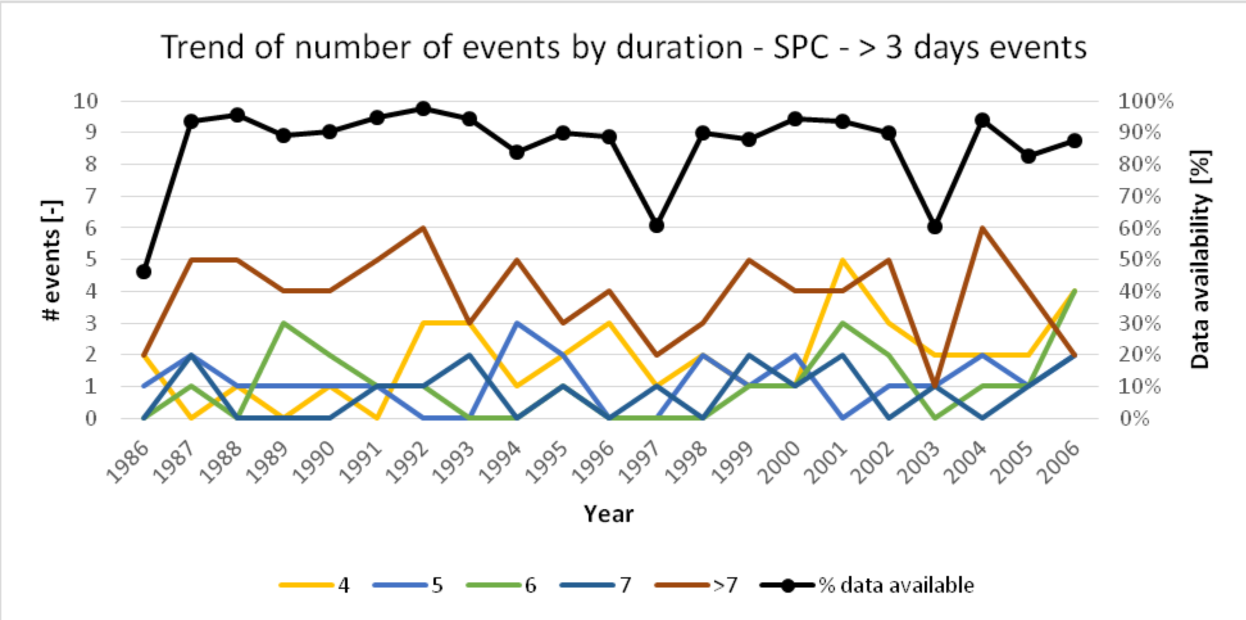


Figure 4.3.14: Trend in number of events per duration in San Pietro Capofiume - annual basis - 1986/2006 period - >3 days events

“Short” events occur quite regularly during the period 1986-2006 but also very “long” events do the same thing. A little increase of 4-days events has been noticed from the graph above (Figure 4.3.14).

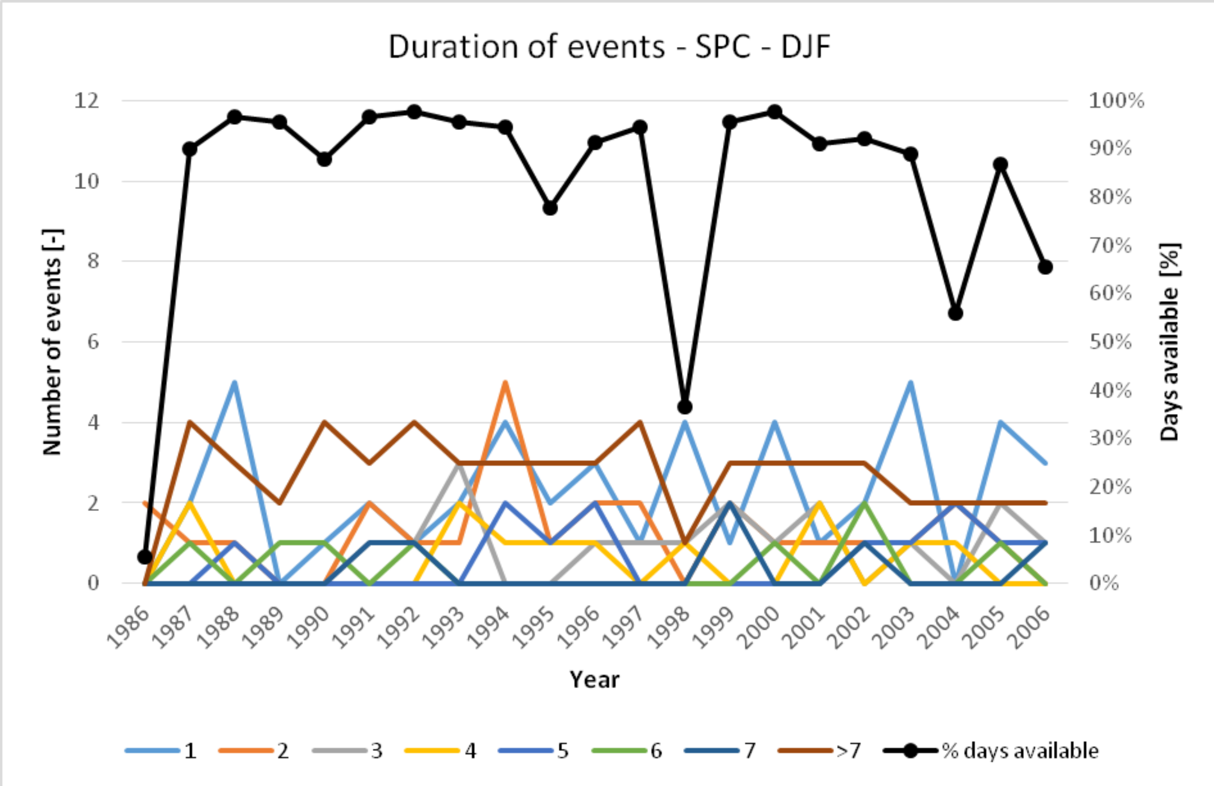


Figure 4.3.15: Duration of events in San Pietro Capofiume – Winter

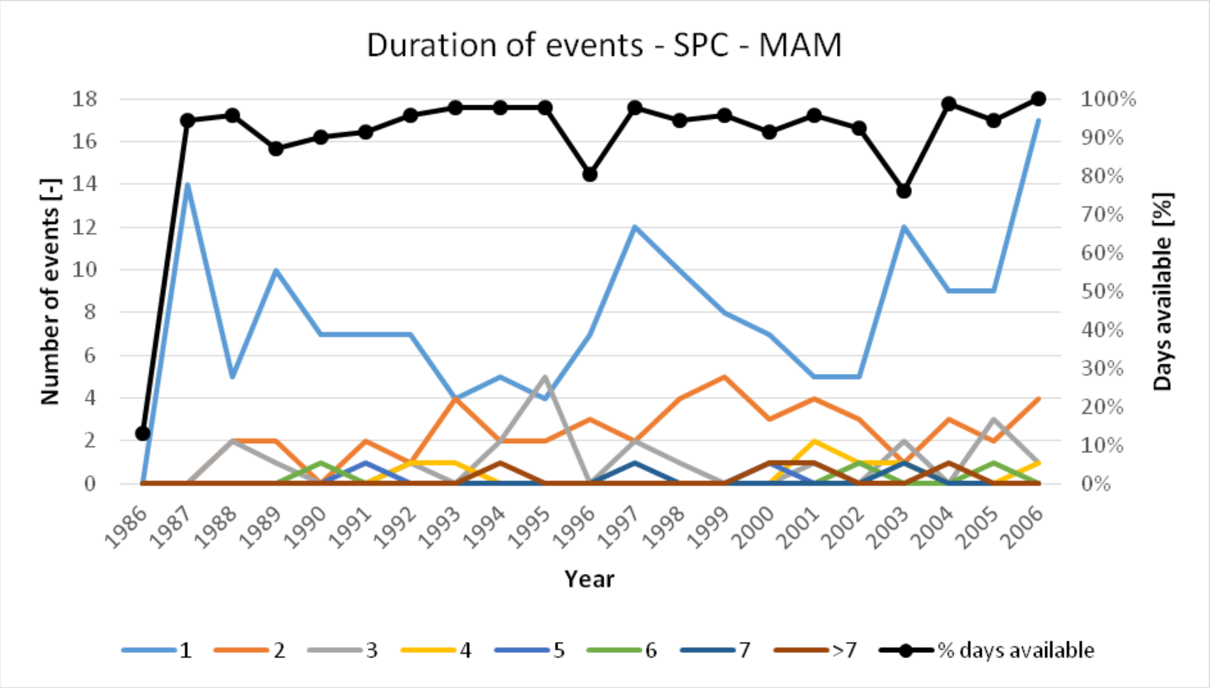


Figure 4.3.16: Duration of events in San Pietro Capofiume – Spring

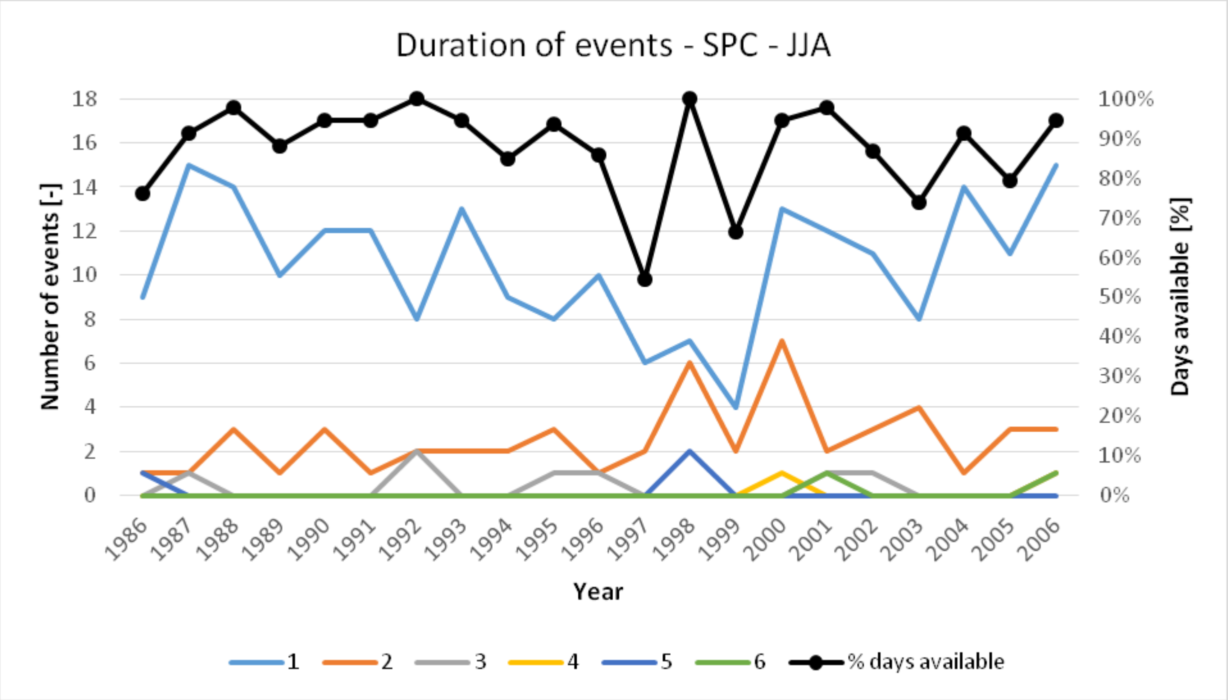


Figure 4.3.17: Duration of events in San Pietro Capofiume – Summer

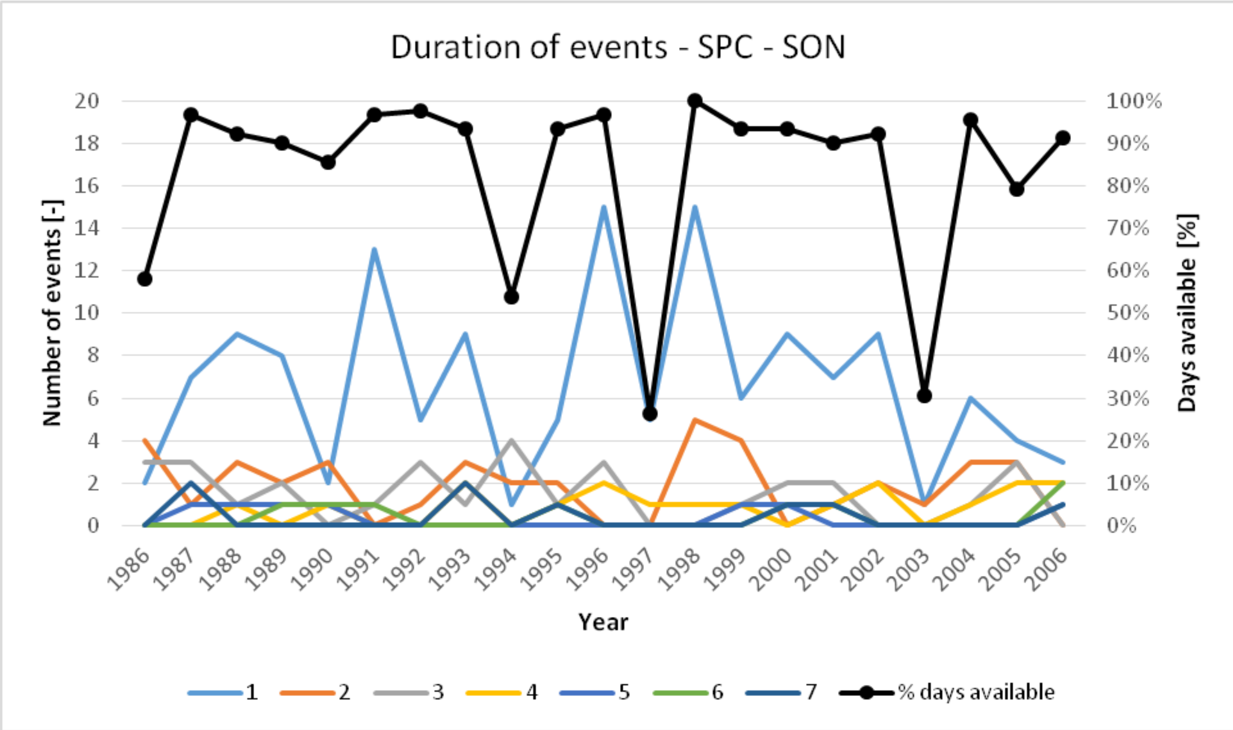


Figure 4.3.18: Duration of events in San Pietro Capofiume – Autumn

Short events (two-or-less day events) are a common feature of spring, summer and autumn; during winter, there is not a significant difference between occurrences of short or long events. From 1987, an eight-or-more day event has always occurred at least once during wintertime, but quite “long” events can happen occasionally even in relative warmer seasons.

4.3.5 Characteristics of thermal inversions

The analysis of the inversion thicknesses’ distribution in San Pietro Capofiume shows that thin layers are not so common: in fact, the modal class (16,3%) has an average thickness of about 110 m, but it happened that the whole vertical profile studied was affected by a thermal inversion (Figure 4.3.19):

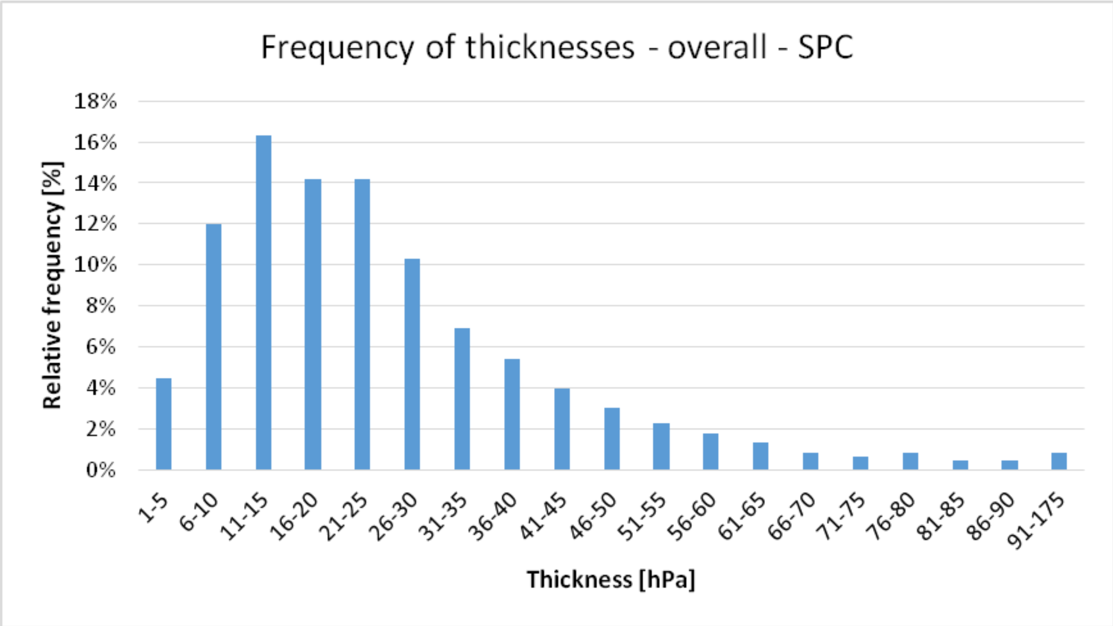


Figure 4.3.19: Thicknesses of all kind of inversions in San Pietro Capofiume

By focusing on the type of inversion, it is clear that radiation inversions (Figure 4.3.20) tend to be very thin (about 20% of layers have a thickness smaller than 5 hPa, less than 50 m from ground level). Subsidence inversions have a different distribution, very similar to the overall one showed above in Figure 4.3.21: for this reason, it is clear that subsidence inversions have been the most common in SPC station since 1986.

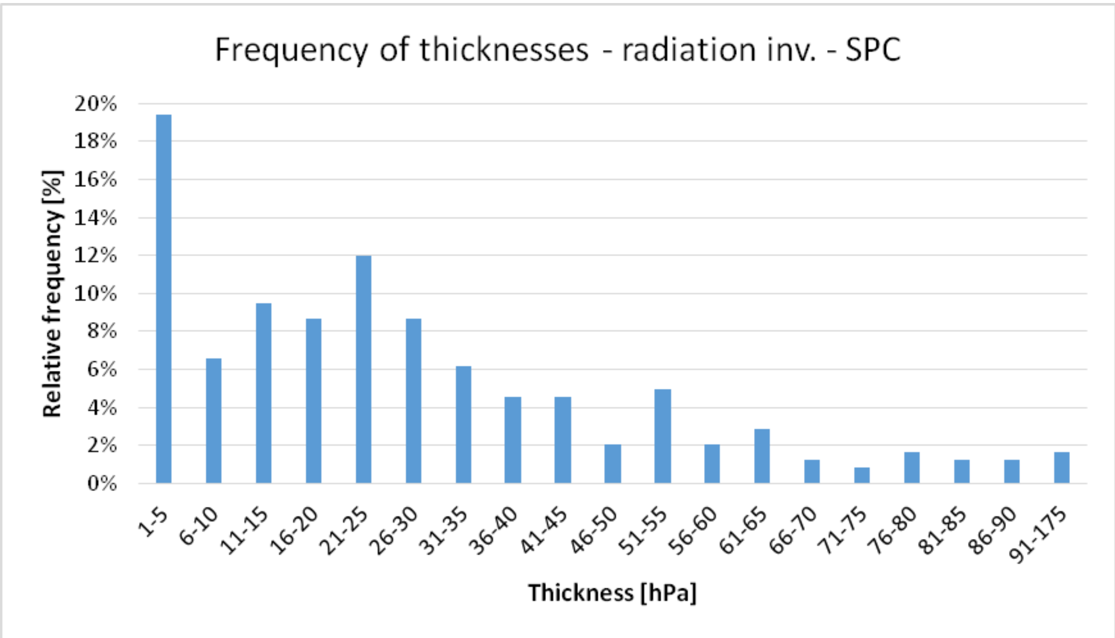


Figure 4.3.20: Thicknesses of ground-level inversions in San Pietro Capofiume

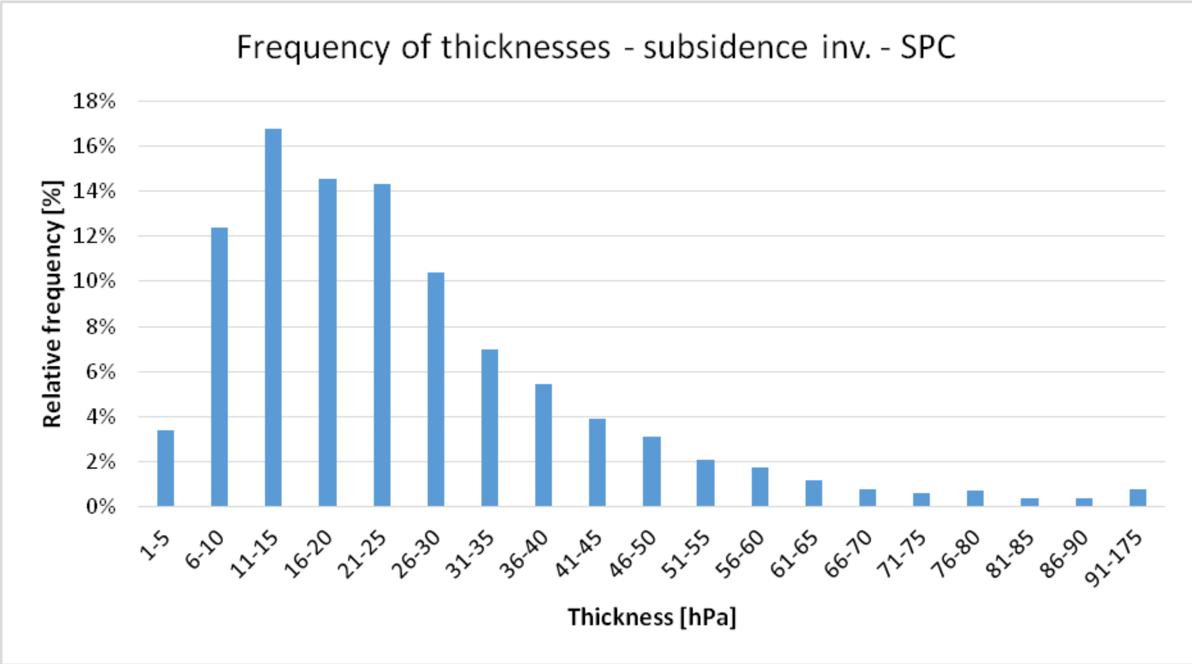


Figure 4.3.21: Thicknesses of subsidence inversions in San Pietro Capofiume

The free mixing height is influenced by the height of occurrence of a subsidence inversion; in San Pietro Capofiume, the distribution of these mixing heights has an interesting characteristic (Figure 4.3.22-4.3.23):

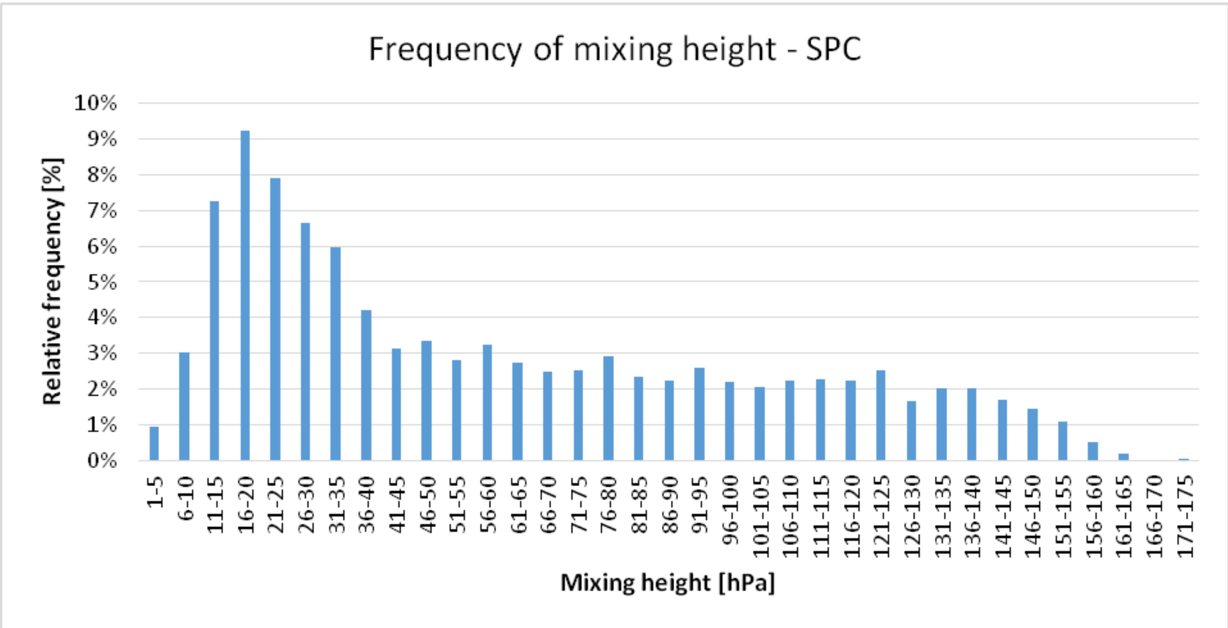


Figure 4.3.22: Mixing height distribution in San Pietro Capofiume

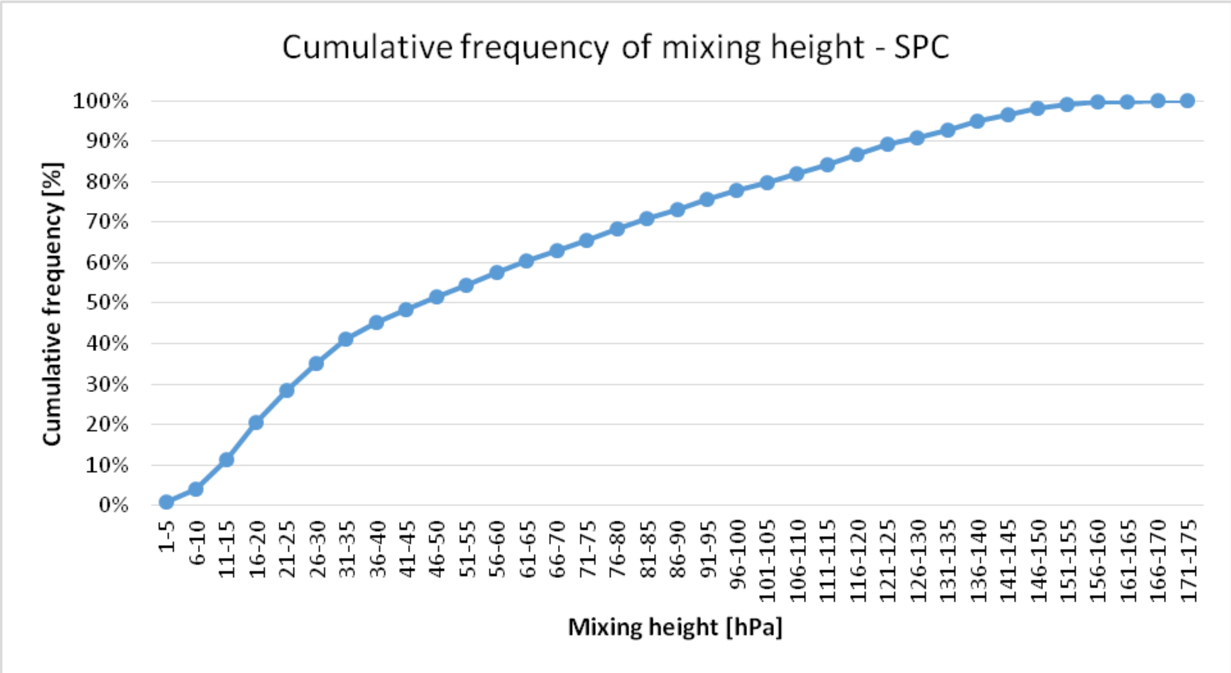


Figure 4.3.23: Cumulative distribution of mixing heights divided per classes in San Pietro Capofiume

There is a significant modal class (16-20 hPa, which corresponds to about 180 m); this fact is shown very well by the cumulative distribution that is quite linear for a wide range of values from medium classes, but it is not for very low ones. If this curve is analysed by season (Figure 4.3.24), it can be found that winter is the most critical season:

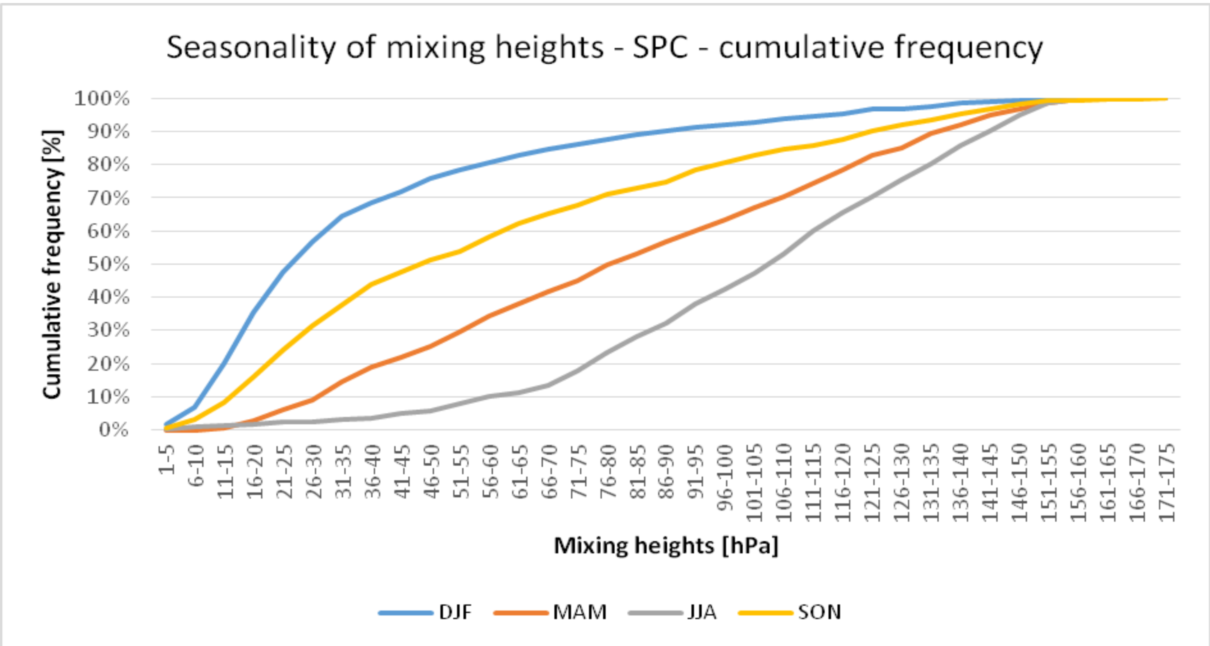


Figure 4.3.24: Cumulative frequency of mixing heights classified by season - SPC

As far as the occurrence of multiple inversion is concerned, it can be noticed that multiple layer events are not very common in SPC soundings (less than 19% of the total), as it is reported in Table 4.3.2:

SPC	1 layer	2 layers	3 layers
# days	2576	545	28
Rel. Freq. [%]	81,8%	17,3%	0,9%

Table 4.3.2: Number of days with simultaneous inversions – S. Pietro Capofiume

4.4 Rivolto Military Airport (LIPI) station

Values in this section have a low interest degree on a climatologic scale. It was not possible to make trend evaluations due to the lack of data on a climatologic scale both on annual and seasonal basis. However, it was possible to make a brief overview of the characteristics of thermal inversion in this side of the Po Valley region.

4.4.1 Data availability

Rivolto station is located in the North-Eastern part of the Po Valley, nearly halfway between cities like Udine and Pordenone, in the Friuli Venezia Giulia region, in a rural area at 52 m a.s.l.. In the database considered, data collection starts from June 2016, so there are only six months available (Figure 4.4.1); however, data have good quality characteristics.

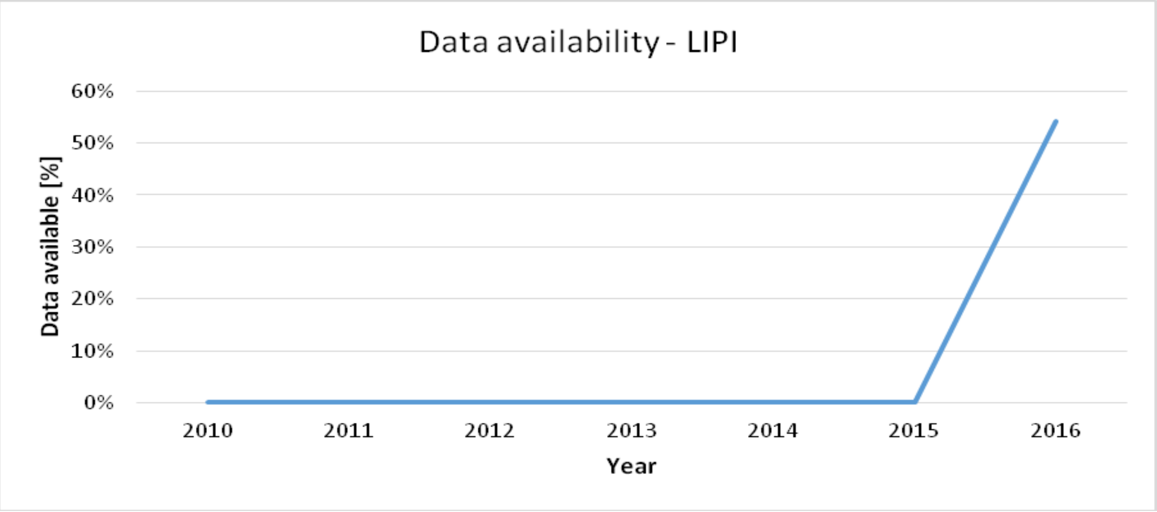


Figure 4.4.1: Data availability of Rivolto station

Even if the coverage is very short, it is possible to notice that inversions have occurred in a high percentage during the last winter, as it is shown in Table 4.4.1:

Rivolto (LIPI)	**Thermal Inversions**			
Total	85 (42,9%)			
Six-month	**Autumn - Winter**		**Spring - Summer**	
	53 (43,4%)		32 (42,1%)	
Seasonal	**SON**	**DJF**	**MAM**	**JJA**
	30 (33%)	23 (74,2%)	-	32 (42,1%)

Table 4.4.1: Number of thermal inversions' days and relative frequency on data available – 2016

4.4.2 Duration of events

The frequency of duration of events is strongly affected by the short period of soundings availability, but in this 6-month selection some eight-day events has already occurred (Figure 4.4.2):

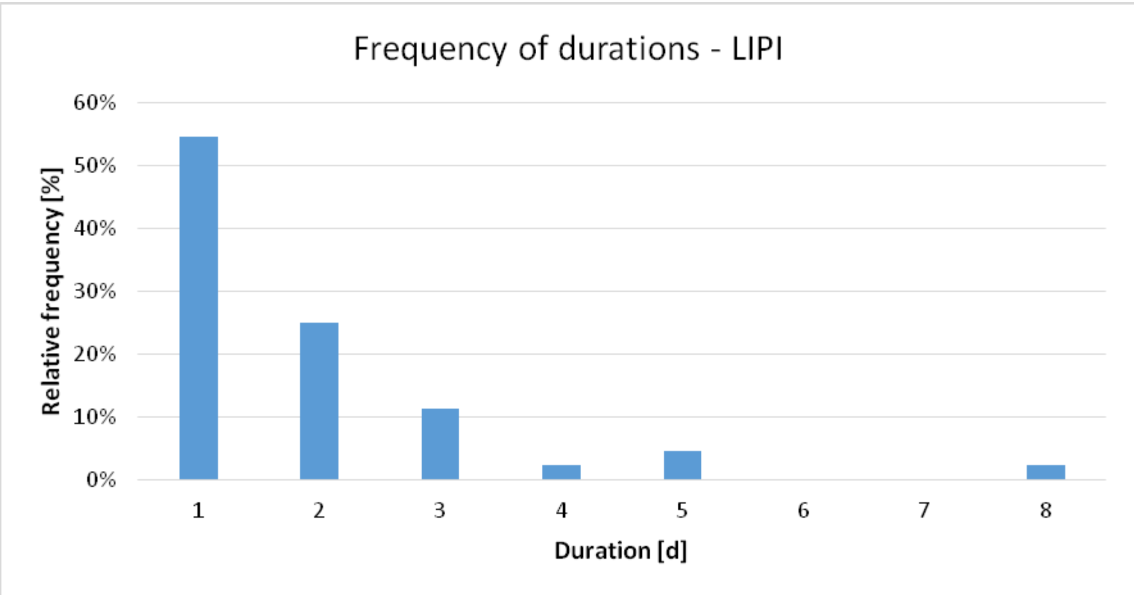


Figure 4.4.2: Overall durations in Rivolto

4.4.3 Characteristics of thermal inversions

In this case, only the overall evaluation has been carried on, due to the little magnitude of data available (Figure 4.4.3):

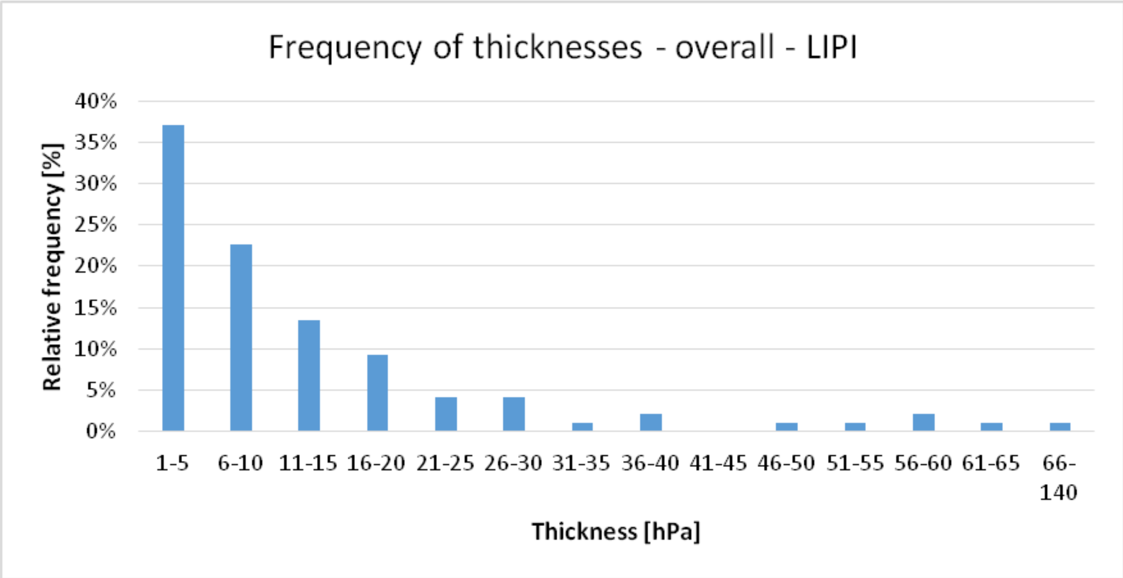


Figure 4.4.3: Thicknesses of all kind of inversions in Rivolto

Only three events of radiation inversion has occurred since June 2016, so this graph above is also a good representation also of the subsidence inversions' distribution. It can be noticed that nearly 75% of inversion layers have a thickness lower than 15 hPa (below 150 m from ground level), but this is not considering any spring data. A brief evaluation has been carried on for the mixing height distribution:

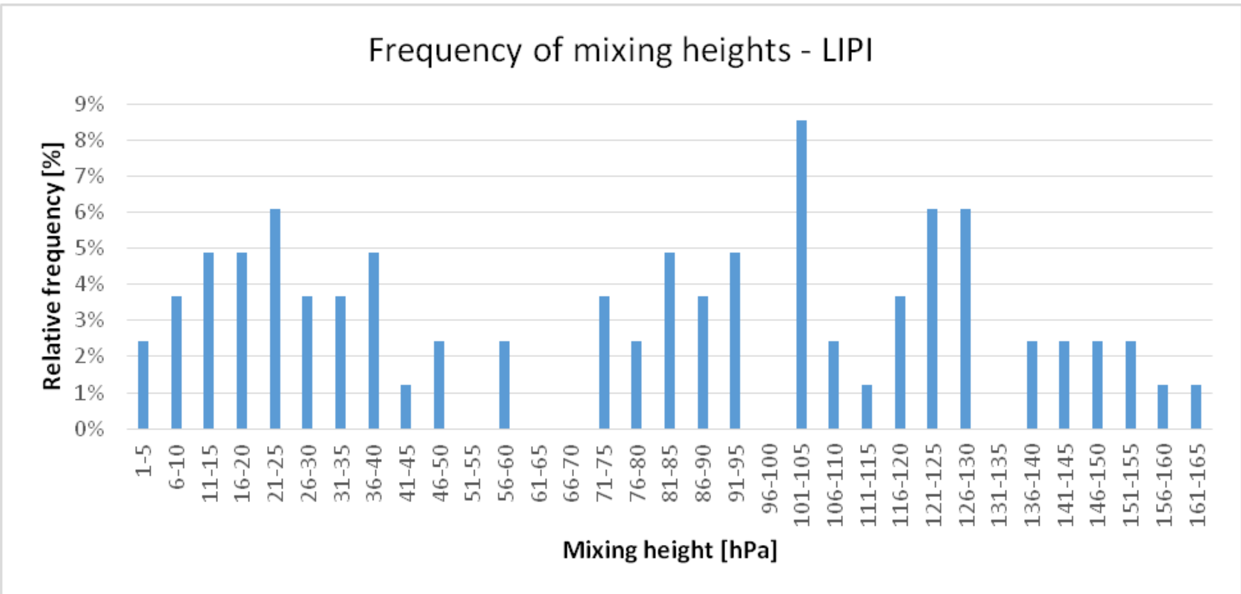


Figure 4.4.4: Mixing height distribution in Rivolto

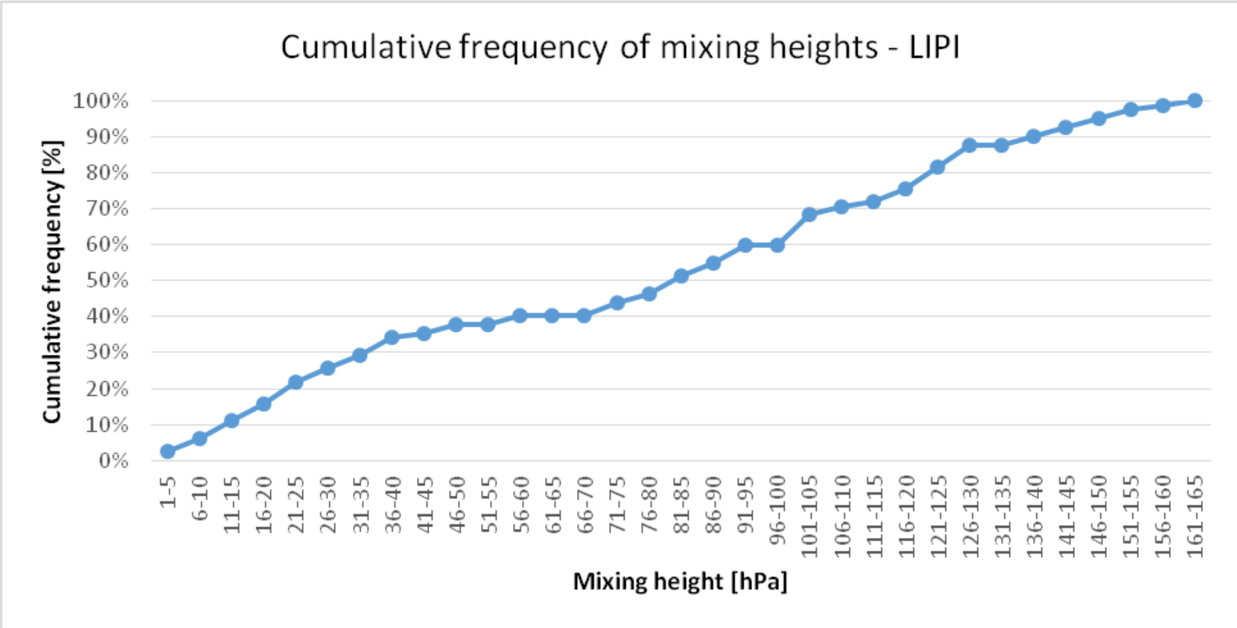


Figure 4.4.5: Cumulative distribution of mixing heights divided per classes in Rivolto

It has to be highlighted that these graphs above (Figure 4.4.4-4.4.5) are not representative for any kind of trend or behaviour on a climatologic scale, but it seems that quite high mixing height have occurred in recent months. However, some data can be compared to longer scale sounding collections (like the frequency of single/multiple layers' occurrence here below in Table 4.4.2), taking into account the large uncertainties correlated.

LIPI	1 layer	2 layers	3 layers
# days	74	10	1
Rel. Freq. [%]	87,1%	11,8%	1,2%

Table 4.4.2: Number of days with simultaneous inversions – Rivolto

4.5 Regional analysis and models

4.5.1 Data availability

As reported in the previous paragraphs, LIMZ station has a good coverage only in two periods: from 2003 to 2010 and from 2014 to 2016; LIML station has a very good coverage throughout these years, because it has never missed more than 52 days per year of measurements in the 32 years between 1985 and 2016; in SPC station, soundings were taken more constantly from 1986 to 2006, but in the last 10 years data were acquired at 12Z only during bad weather conditions (ARPA Emilia Romagna, 2016); LIPI station has not any data available before of May 2016, so there is a limited collection of information to work on. For these reasons, only LIML's collection of data has been used to make assessments on any trends during the period considered (1985-2016), as reported in Figure 4.5.1:

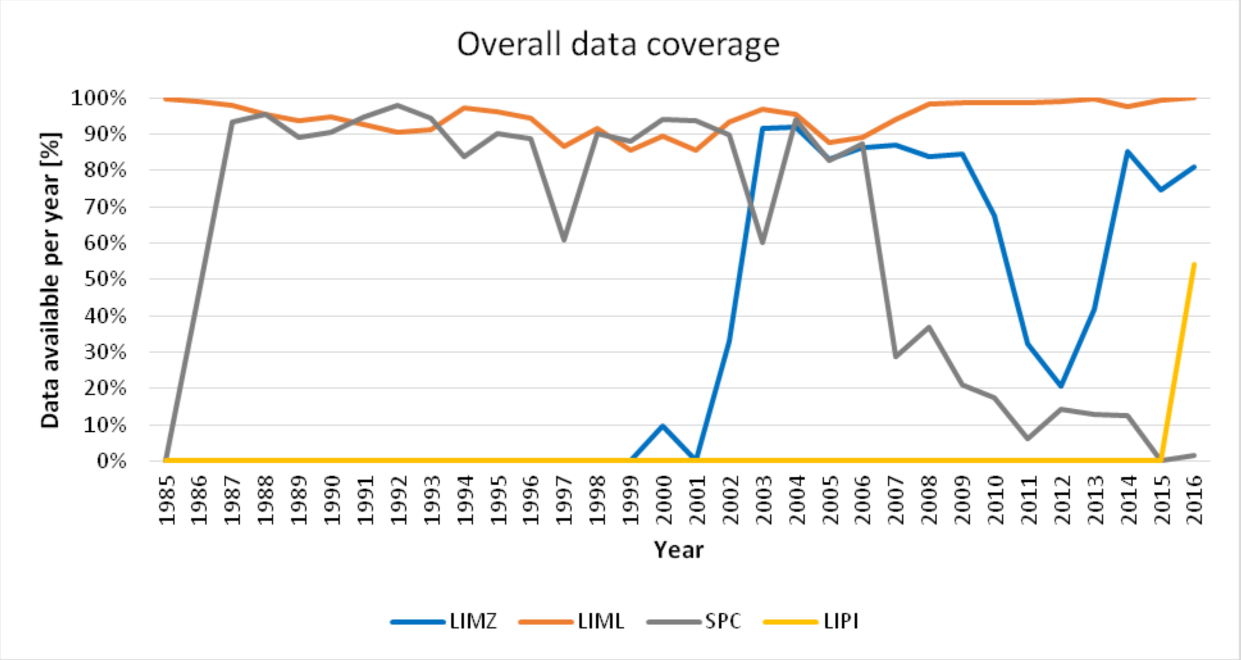


Figure 4.5.1: Data coverage trend (1985-2016)

Furthermore, data in each station are not taken in continuous way: there may be some missing data that can lead to errors in some evaluations. For this reason, good quality soundings in space and time are needed in future to have a better comprehension of this phenomenon.

4.5.2 Days of thermal inversion

Considering the number of inversion days and their frequency of occurrence (Table 4.5.1), it seems that there are similarities, in particular between data from LIML and SPC stations. As mentioned before, data from LIPI station only refer to 2016: however, the frequency of occurrence is in reasonable agreement with those of the other station were longer time series are available.

Station	LIMZ	LIML	SPC	LIPI
Total	1448 (37,6%)	5141 (46,5%)	3149 (44%)	85 (42,9%)
DJF	624 (60,4%)	2027 (73,7%)	1365 (77,9%)	23 (74,2%)
MAM	241 (26,9%)	932 (33,5%)	491 (26,3%)	-
JJA	215 (23,8%)	808 (28,9%)	409 (22,6%)	32 (42,1%)
SON	368 (36%)	1374 (50,3%)	884 (51,4%)	30 (33%)

Table 4.5.1: Overall days of inversion and frequency on data available

Due to the limited data coverage extension, LIPI station was not considered in all of the following analyses. After the overall assessment of the presence of inversion, it has been evaluated that January is the most critical month for all the three stations with useful data (Table 4.5.2):

Station	LIMZ	LIML	SPC
% Inversions (January)	66,4%	79,2%	85,1%

Table 4.5.2: Frequency of inversions on data available in January for each station

For these high-frequency rates, thermal inversion are a real concern when air quality parameters for human and environmental health have to be respected, with the current level of emission of pollutants.

Data coverage is not equally distributed among the three station considered, and this can be a very important factor when data are compared in quantitative terms. For this reason, data has been selected considering a minimum 75% of data coverage for each year/season and, only on seasonal basis, data has been adjusted with their actual data availability.

Station	LIMZ (2003-2009 + 2014-2016)	LIML (1985-2016)	SPC (1987-2006)
Avg. inversions days per year	113 ± 13	161 ± 17	140 ± 21

Table 4.5.3: Number of inversion days per year on average

The number of days with a thermal inversion seems to be quite similar between LIML and SPC and also SPC and LIMZ (Table 4.5.3); conversely, a larger difference is observed between LIML and LIMZ on annual basis.

Station	LIMZ	LIML	SPC
DJF	48 ± 5	63 ± 7	69 ± 9
MAM	21 ± 8	29 ± 6	22 ± 7
JJA	19 ± 6	25 ± 6	20 ± 6
SON	26 ± 6	43 ± 8	41 ± 7

Table 4.5.4: Number of inversion days per season on average

Station	LIMZ	LIML	SPC
DJF	54 ± 8	66 ± 7	75 ± 9
MAM	23 ± 8	30 ± 6	23 ± 8
JJA	22 ± 7	27 ± 5	21 ± 6
SON	31 ± 6	46 ± 7	45 ± 8

Table 4.5.5: Number of inversion days per season on average – data adjusted

On a seasonal basis (Table 4.5.4-4.5.5), the number of inversion days is very similar if LIML and SPC stations are compared. There are some divergences between data from LIMZ and the other two stations, especially during the colder seasons; this might be due to the geographical location of the station: LIML and SPC are located in areas that have similar characteristics, while LIMZ is closer to the Western Alps and there is a slight splitting between Piedmont and Lombardy due to Langhe-Roero-Monferrato's hills.

Data reported above have been assessed with statistical methods: after the verification of the normality (by using the Kolmogorov function) and the homoscedasticity condition (by using the Levene's test) the ANOVA and the related post-hoc test have been applied. In summer, Kruskal-Wallis test and the related Dunn post-hoc test have been carried on due to the violation of the basic assumptions of the ANOVA; results are reported in Table 4.5.6 where the H_0 hypothesis is the equality of the three mean values. It has to be highlighted that the post-hoc test identifies which mean is statistically different from the others:

Station	ANOVA (Kruskal-Wallis)	Tukey-Kramer (Dunn)
Annual	Reject H_0	Reject H_0
DJF	Reject H_0	Reject H_0
MAM	Reject H_0	Reject $H_0^{(*)}$
JJA	(Reject H_0)	(Reject H_0)
SON	Reject H_0	Reject $H_0^{(**)}$

Table 4.5.6: Results of ANOVA and t-tests; $^{(*)}$=LIMZ+SPC test excluded; $^{(**)}$=LIML+SPC test excluded

So, it can be noticed that mean values on annual basis cannot be considered as the same, so there are statistically significant differences between stations; on a seasonal basis, it is possible to stand that mean values are never comparable (only SPC is similar to the others twice), so also here there are differences between these stations.

4.5.3 Inversion events

The number of inversion events seems to be more similar than the inversion days between the three stations considered on annual basis (the minimum level of 75% of data coverage for each period is valid also here). Results are reported in Table 4.5.7:

Station	LIMZ (2003-2009 + 2014-2016)	LIML (1985-2016)	SPC (1987-2006)
Avg. inversion events per year	56 ± 6	66 ± 7	50 ± 6

Table 4.5.7: Number of inversion events per year on average

On seasonal basis, data coming from all the three station can be compared (even if the adjusted series is considered), with good similarities as a result (Table 4.5.8-4.5.9):

Station	LIMZ	LIML	SPC
DJF	15 ± 4	13 ± 3	10 ± 3
MAM	14 ± 4	18 ± 3	13 ± 4
JJA	13 ± 3	17 ± 3	15 ± 3
SON	15 ± 2	19 ± 3	15 ± 3

Table 4.5.8: Number of inversion events per season on average

Station	LIMZ	LIML	SPC
DJF	16 ± 4	14 ± 3	10 ± 3
MAM	15 ± 4	19 ± 3	14 ± 4
JJA	16 ± 4	18 ± 3	16 ± 3
SON	17 ± 3	20 ± 3	16 ± 3

Table 4.5.9: Number of inversion events per season on average – data adjusted

The application of ANOVA and t-test on different samples gives these results reported in Table 4.5.10, with the same null hypothesis H_0 mentioned in the previous paragraph:

Station	ANOVA	Tukey-Kramer
Annual	Reject H_0	Reject $H_0^{(**)}$
DJF	Reject H_0	Reject $H_0^{(*)}$
MAM	Reject H_0	Reject $H_0^{(**)}$
JJA	Reject H_0	No reject $H_0^{(*)}$
SON	Reject H_0	Reject $H_0^{(**)}$

Table 4.5.10: Results of ANOVA and t-tests; (*)=LIMZ+LIML test excluded; (**)=LIMZ+SPC test excluded

From this kind of evaluation, it is possible to notice that there are not common features on the number of inversion events both on annual and seasonal basis. The Tukey-Kramer post hoc test shows that LIMZ and SPC have similar features on the number of inversion events (with the exception of wintertime), while LIML has not many common characteristics in this particular field with the other two stations.

4.5.4 Characteristics of thermal inversions

An important similarity between these stations is that there is a common distribution of single/multiple layers' occurrence, even in Rivolto (LIPI), as it is reported in Table 4.5.11:

Station	LIMZ	LIML	SPC	LIPI
1 layer	1269 (87,6%)	4430 (86,2%)	2576 (81,8%)	74 (87,1%)
2 layers	175 (12,1%)	683 (13,3%)	545 (17,3%)	10 (11,8%)
3 layers	4 (0,3%)	25 (0,5%)	28 (0,9%)	1 (1,2%)

Table 4.5.11: Comparison between single/multiple layers occurrence

The free mixing height has been compared between the four stations taking into account the seasonality of the cumulative distributions (Figure 4.5.2): in this evaluation, it has been found that the three curves referred to winter season are very similar under a climatologic point of view, as it is shown below; other seasons have not this particular feature:

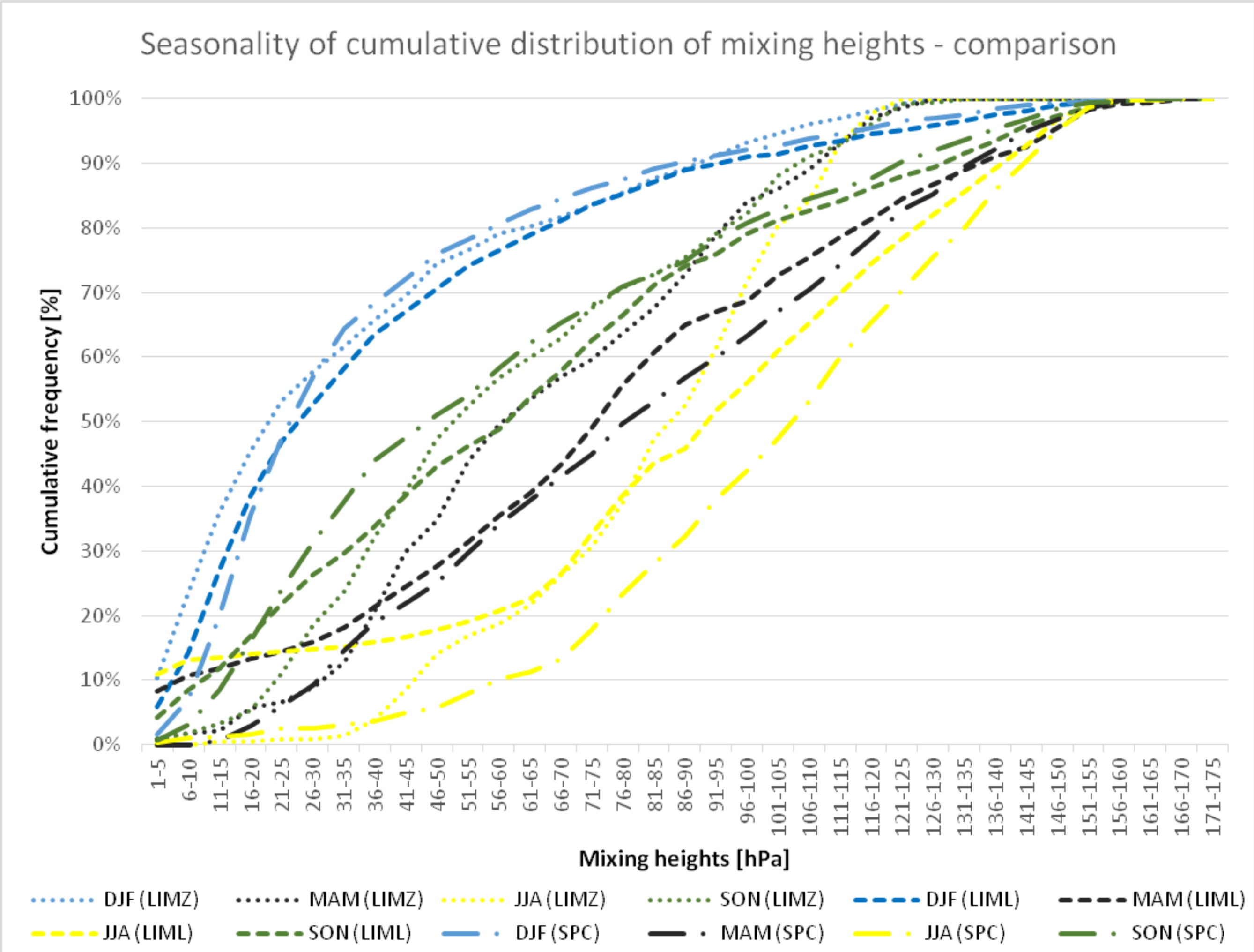


Figure 4.5.2: Comparison between free mixing heights calculated in LIMZ, LIML and SPC stations (classification by season)

Thicknesses between the four stations have been compared in the graphs below (Figure 4.5.3-4.5.5) by using a general overview, and by dividing systems into radiation inversions and subsidence one. It has to be reminded that LIPI values are not so interesting from a statistical point of view, but they are reported anyway for completeness:

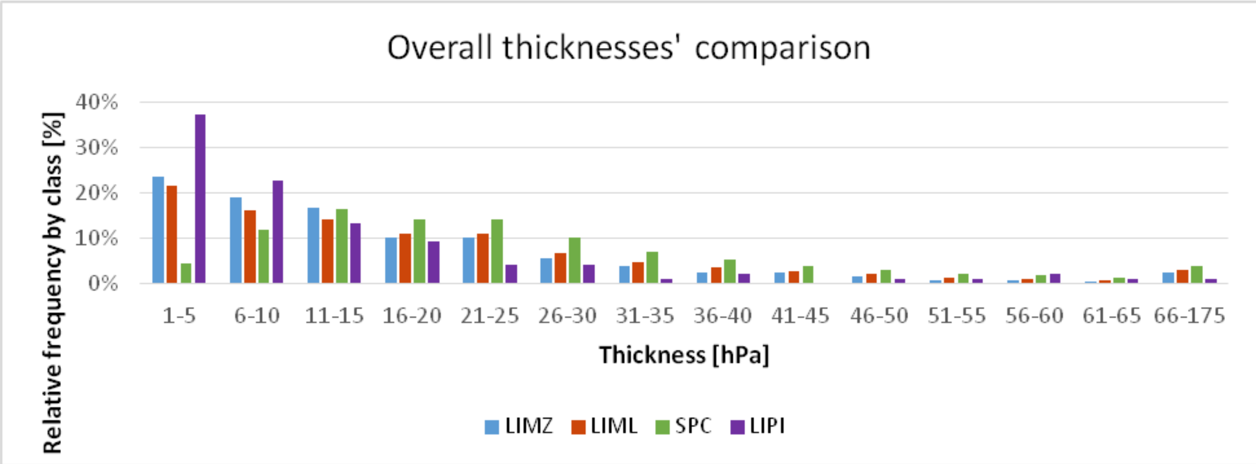


Figure 4.5.3: Comparison between overall thicknesses

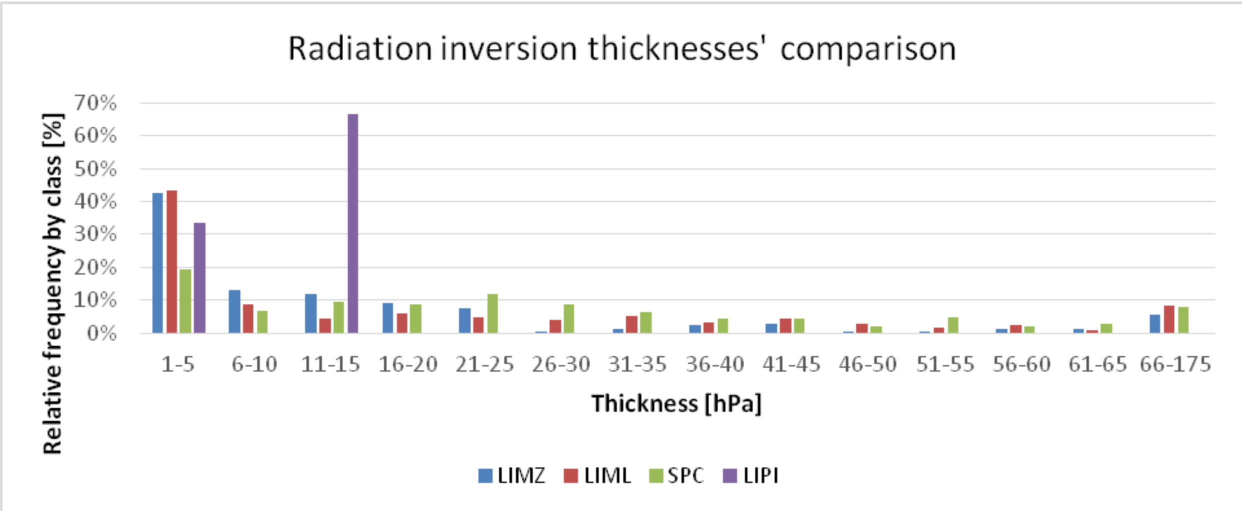


Figure 4.5.4: Comparison between radiation inversion's thicknesses

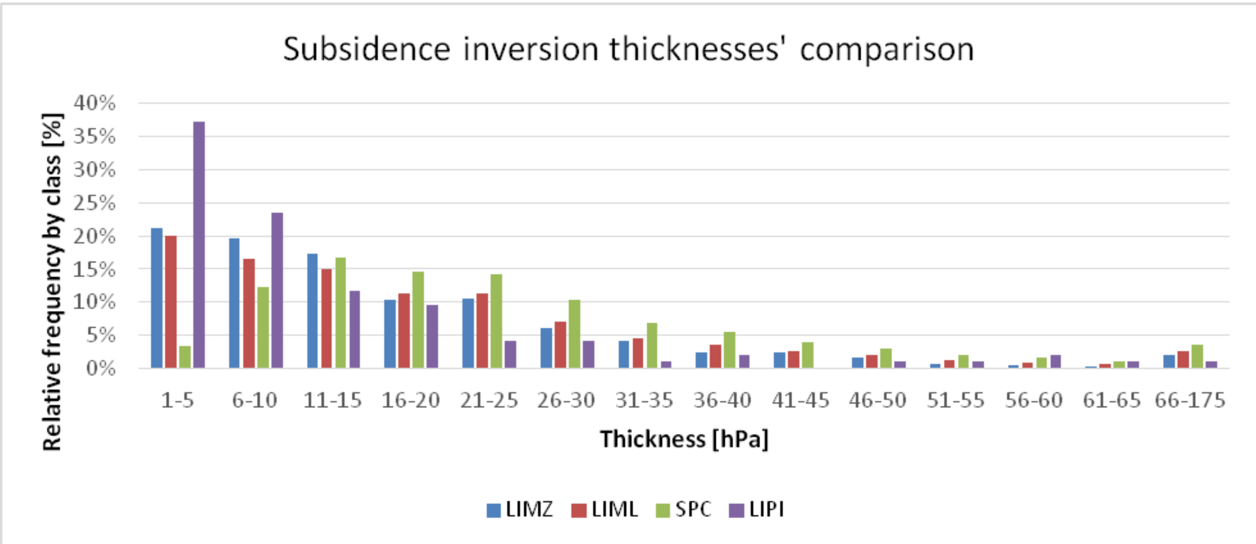


Figure 4.5.5: Comparison between subsidence inversion's thicknesses

From this kind of data, it is possible to notice that, in SPC station, there are relatively higher thicknesses for a range that goes from 16 hPa and over, so there is generally a thicker layer of strong stability in this area. Relatively smaller thicknesses can be found in LIMZ and LIPI data, while LIML seems to have an intermediate behaviour. There are similarities between mixing heights distributions, in particular on a seasonal basis, where wintertime ones are not so much thick if compared to other seasons (LIPI data cannot be evaluated in that sense).

4.5.5 Duration distribution model

A definition of a model for the distribution of events' duration has been carried on three stations (LIMZ, LIML and SPC). Two kind of models have been examined, a descending exponential model and a hyperbolic one because it has been verified that the number of events decrease with the related duration; so, the two models used are defined generally as:

$$y = a * e^{-bx} \quad [-]$$

$$y = \frac{c}{d * x} \quad [-]$$

where:

- *a, b, c, d* are coefficients estimated by the minimum square error criteria and maximum 7-days duration data;
- variable x is the duration of events (measured in days);
- variable y is the estimated number of events of "x" days duration;
- *b* coefficient has a unit of measure 1/days, and like the other three coefficients, has been obtained empirically.

Only years with good coverage of data have been considered (above 75% on annual basis) to reduce errors. For this reason, the evaluation in Cuneo Levaldigi is based only on 2003-2009 and 2014-2016 data, in Milano Linate all data has been taken into account and in S. Pietro Capofiume all data considered come from 1987-2006 period, excluding 1997 and 2003. Model fitting was separately performed for each station: numerical values of the coefficients are reported in Table 4.5.13 (for LIMZ). The fitting of the models to observed durations is shown in Figure 4.5.6-4.5.7 (LIMZ station); the same representation has been done for LIML and SPC stations:

LIMZ (exponential)		*LIMZ (hyperbolic)*	
a	**b**	**c**	**d**
90,15	1,02	103,75	3,84

Table 4.5.12: Coefficients estimated for the two models – Cuneo Levaldigi

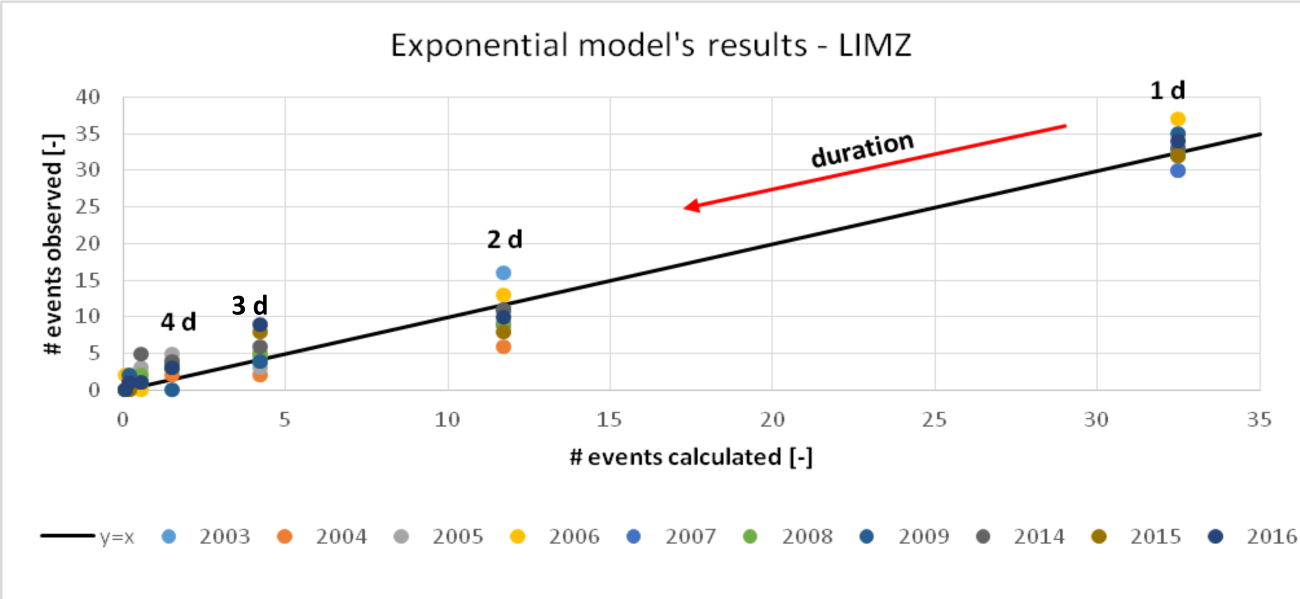


Figure 4.5.6: Comparison between data calculated by the exponential model and data observed – Cuneo Levaldigi

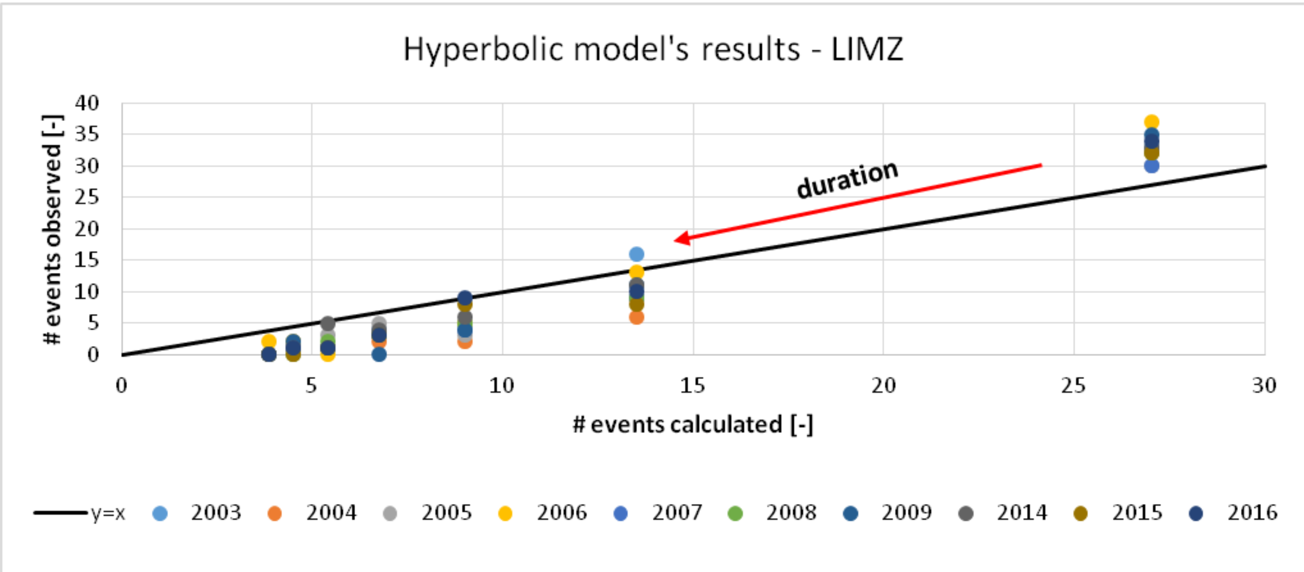


Figure 4.5.7: Comparison between data calculated by the hyperbolic model and data observed – Cuneo Levaldigi

As it is shown above, the exponential model seems to be better in fitting the data collected than the hyperbolic one, with an overall correlation factor equal to 0,99.

LIML (exponential)		*LIML (hyperbolic)*	
a	**b**	**c**	**d**
87,28	0,90	161,01	5,27

Table 4.5.13: Coefficients estimated for the two models – Milano Linate

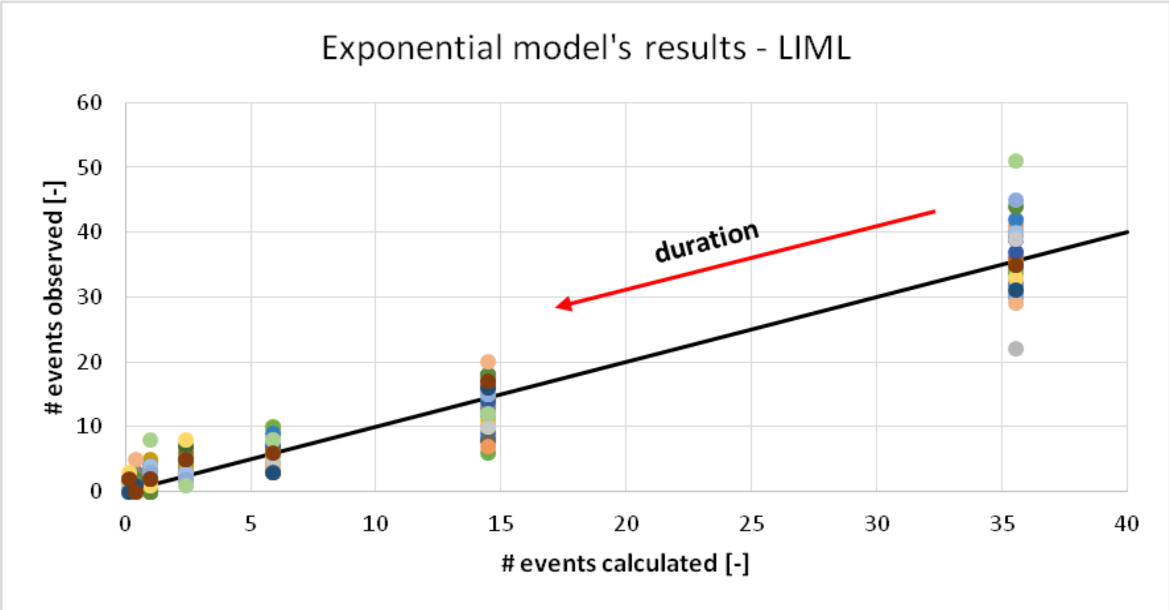


Figure 4.5.8: Comparison between data calculated by the exponential model and data observed – Milano Linate

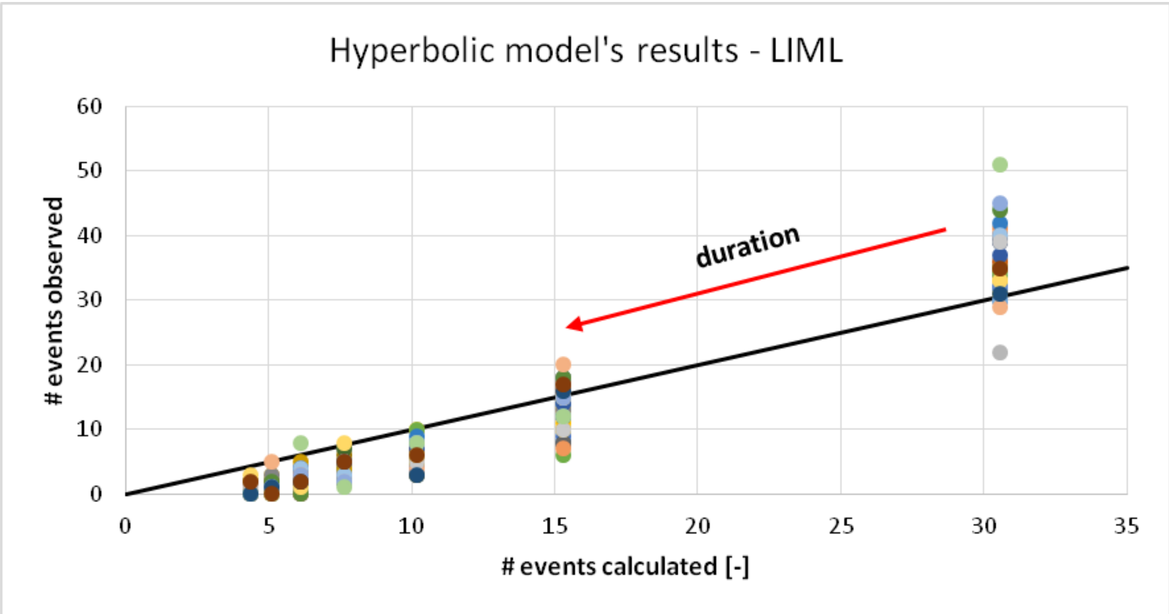


Figure 4.5.9: Comparison between data calculated by the hyperbolic model and data observed – Milano Linate

Also in Milano Linate the exponential model seems to better in terms of fitting data acquired (R^2 = 0,985) than the hyperbolic one. In San Pietro Capofiume the situation is basically the same (R^2 = 0,98), so the exponential model is generally accepted.

SPC (exponential)		*SPC (hyperbolic)*	
a	**b**	**c**	**d**
85,15	1,11	130,72	5,68

Table 4.5.14: Coefficients estimated for the two models – S. Pietro Capofiume

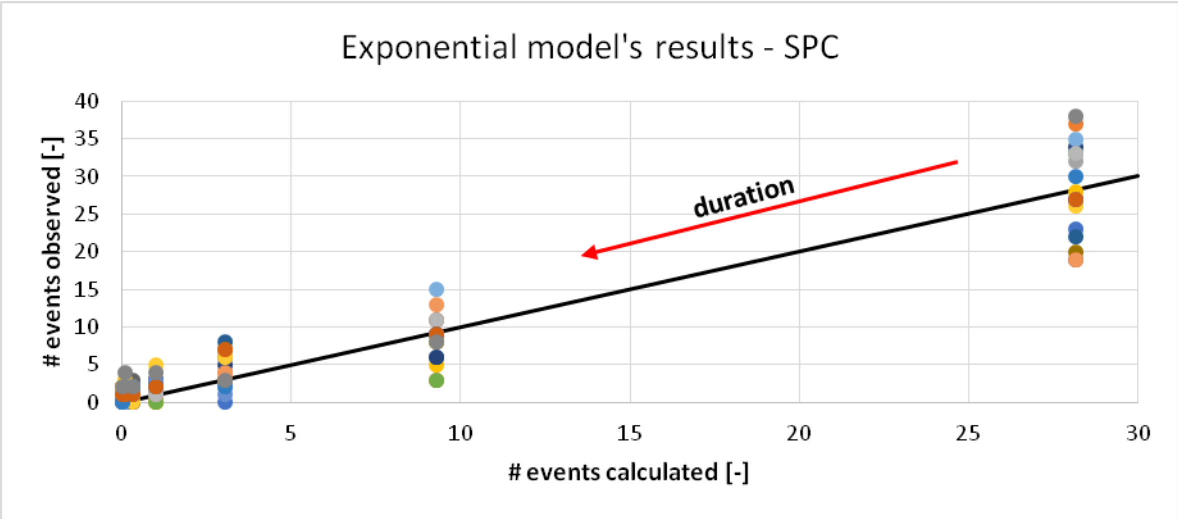


Figure 4.5.10: Comparison between data calculated by the exponential model and data observed – S. Pietro Capofiume

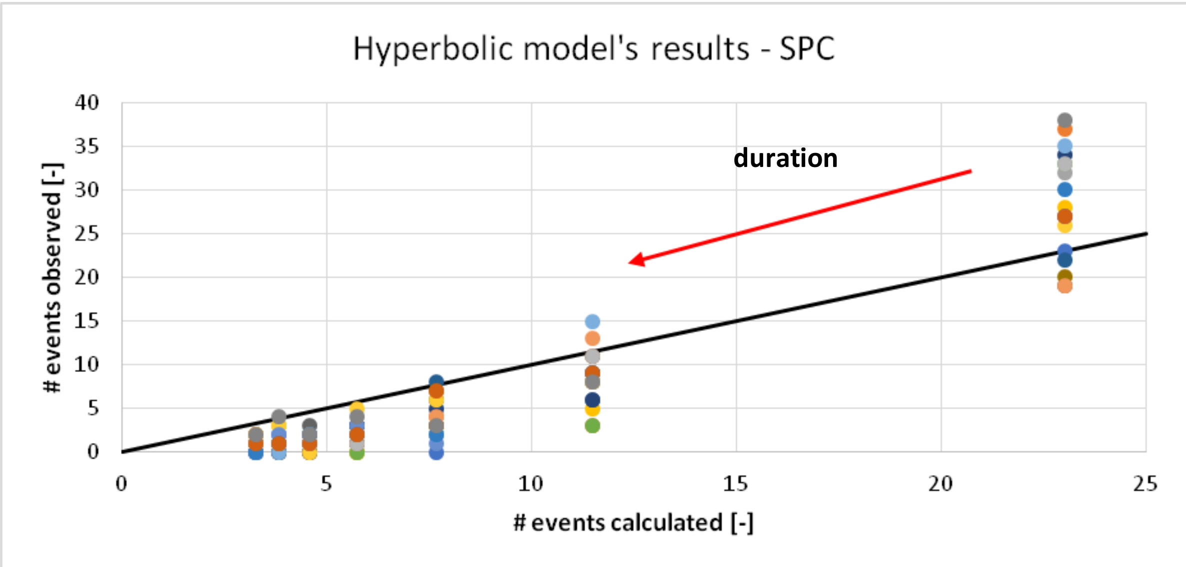


Figure 4.5.11: Comparison between data calculated by the hyperbolic model and data observed – S. Pietro Capofiume

At this point the three exponential models can be compared; the LIML station seems to have a greater number of events for each duration, but it has to be reminded that the other two station have a low level of data coverage despite the selection of data has improved their quality. Therefore, it is possible to conclude that there can be a single model to represent the number of events per duration (considering 7-or-less day events) valid for the whole Po Valley region. The comparison between LIMZ, LIML and SPC in terms of the mean number of events per year by duration shows that there are not significant differences, on annual basis (Table 4.5.16 and Figure 4.5.12):

Duration | Station	LIMZ	LIML	SPC
1	33 ± 2	36 ± 6	28 ± 6
2	10 ± 3	13 ± 4	8 ± 3
3	5 ± 2	6 ± 2	4 ± 2
4	3 ± 1	4 ± 2	2 ± 1
5	2 ± 2	2 ± 2	1 ± 1
6	1 ± 1	1 ± 1	1 ± 1
7	0 ± 1	1 ± 1	1 ± 1
>7	1 ± 1	3 ± 1	4 ± 1

Table 4.5.15: Number of events by duration for each station (mean and standard deviation) – annual basis

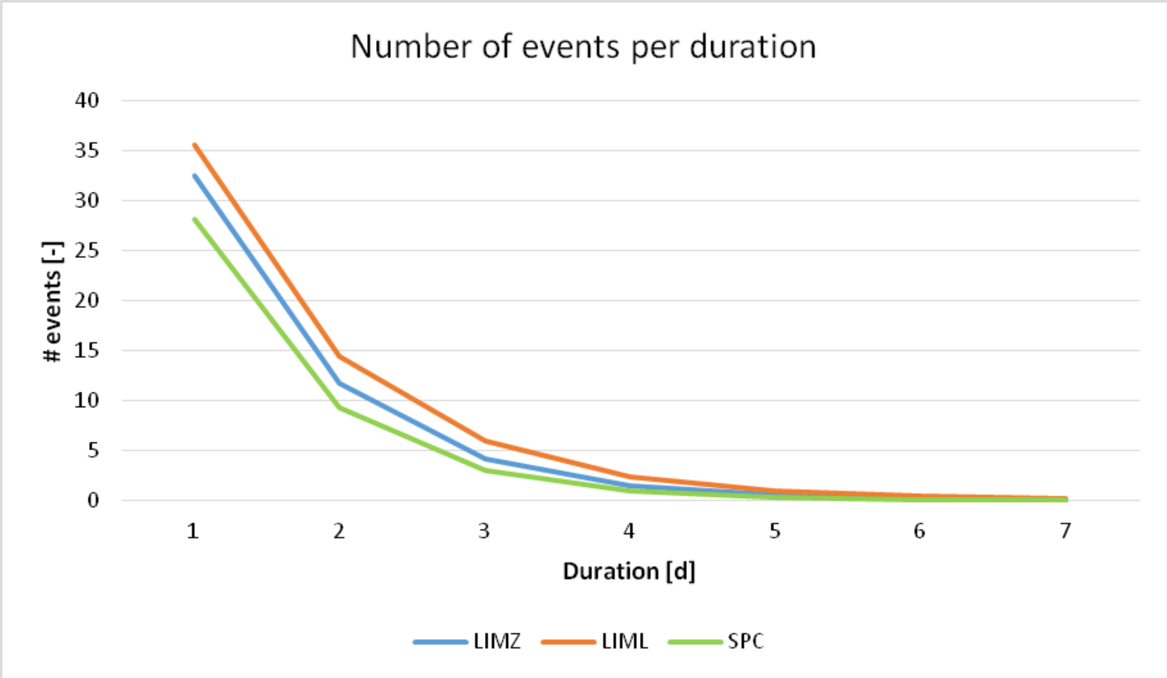


Figure 4.5.12: Comparison between the three models discussed previously

All data from the station have been merged together to calculate a "regional" model (R^2=0,98), that gives generally a little overestimation of both LIMZ and SPC events and an underestimation of LIML ones. The equation found is:

$$y = 86{,}09 * e^{-0{,}96x} \quad [-]$$

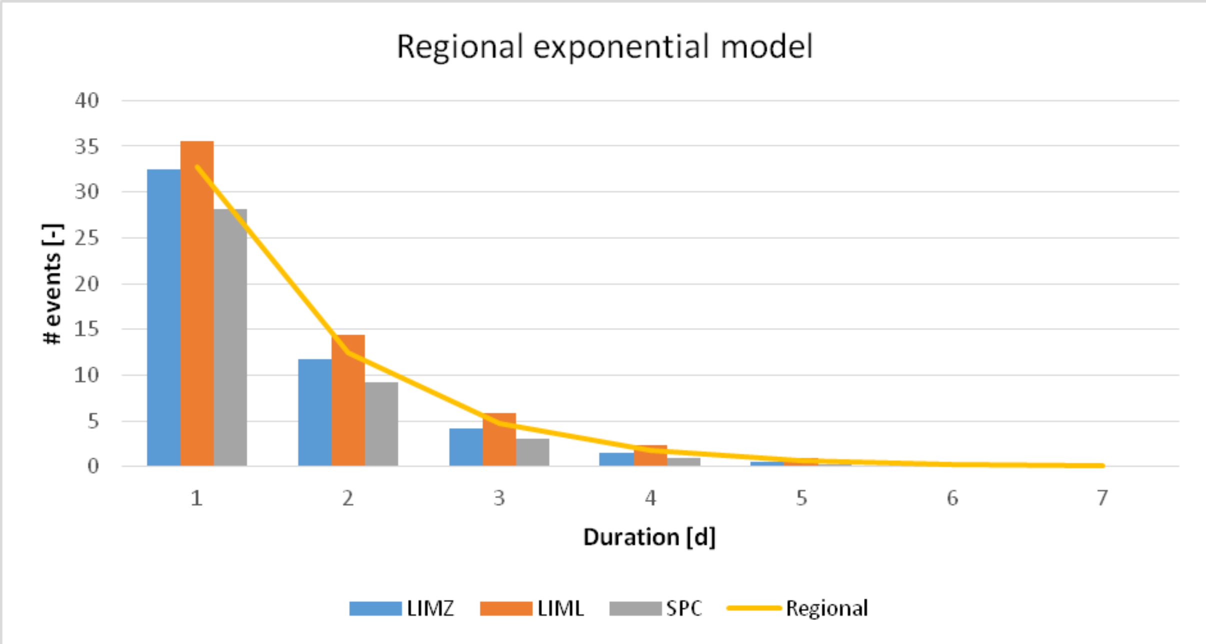


Figure 4.5.13: Regional model for number of events by duration distribution in the Po Valley region

4.5.6 Simultaneous presence of inversion in the Po Valley region

Data coming from LIMZ, LIML and SPC stations have been merged on a calendar to evaluate the number of simultaneous occurrence of a thermal inversion. Three different analysis have been done, because of the lack of data coverage in some periods: the first one takes into account LIML and SPC data from 1986 to 2001, the second one LIMZ, LIML and SPC data from 2002 to 2006 and the third one only LIMZ and LIML data from 2007 to 2016. It has to be highlighted the fact that the simultaneous presence of inversions obtained considering two or three seasons can have a great variability (given by the data availability). In this case, the data coverage is calculated on annual basis considering days where measurements have been taken at the same time in the stations considered (Figure 4.5.14-4.5.16).

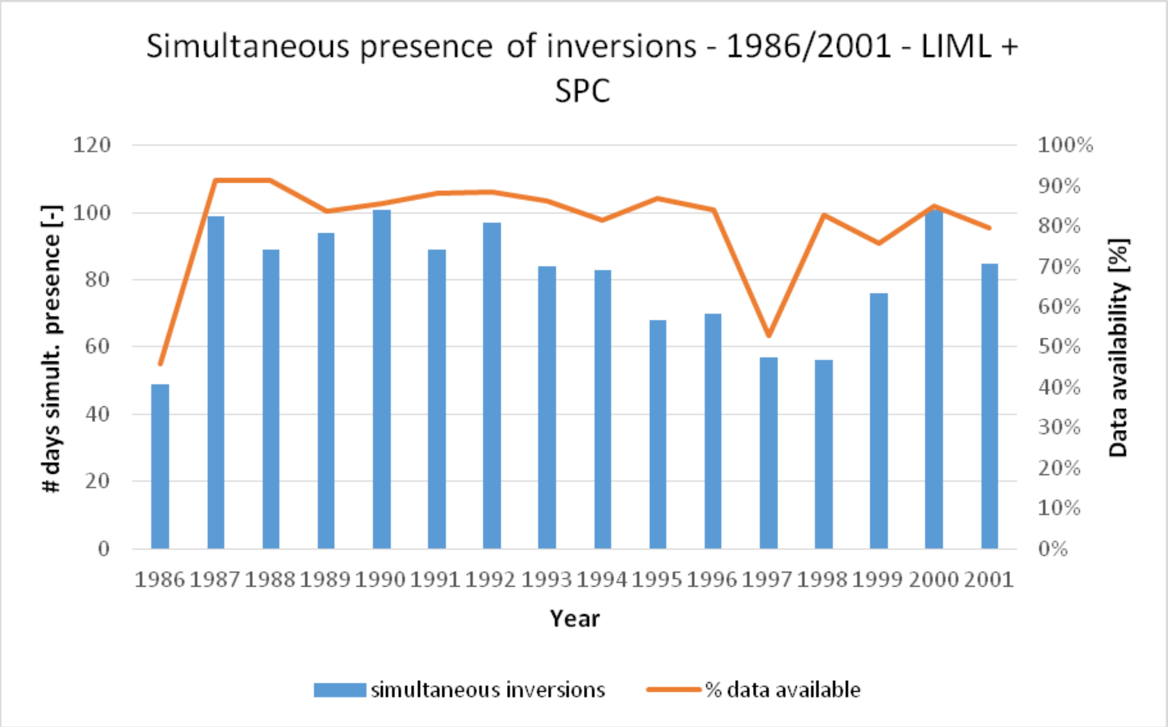


Figure 4.5.14: Simultaneous presence of inversions in Milano Linate and San Pietro Capofiume

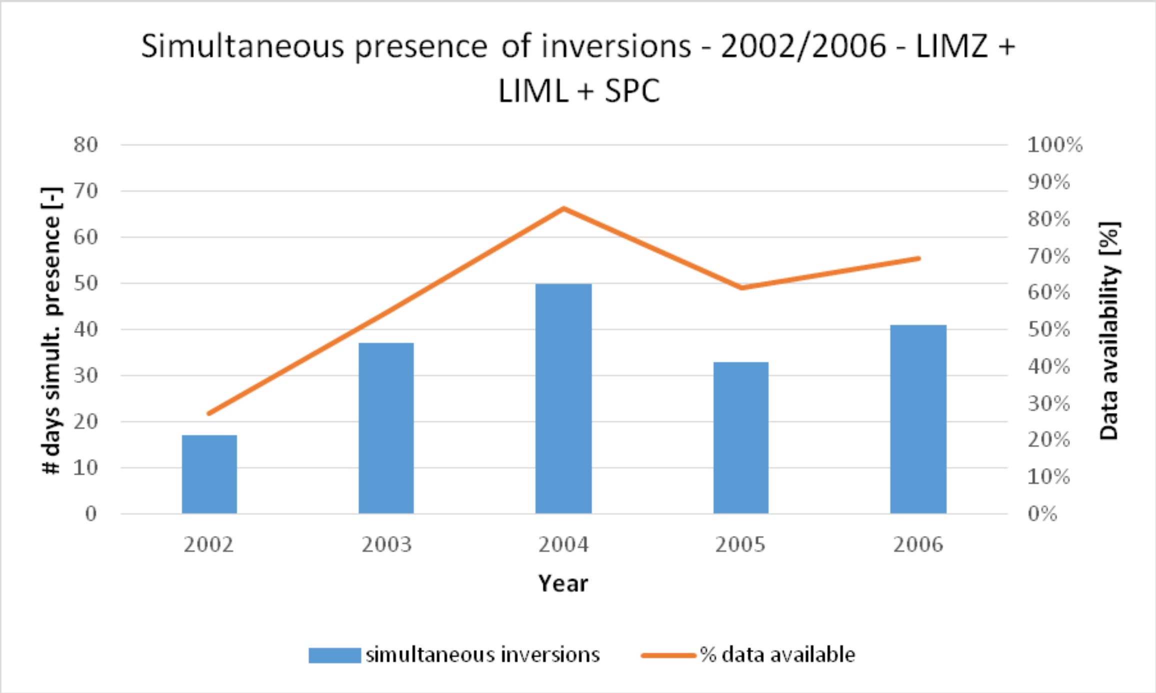


Figure 4.5.15: Simultaneous presence of inversions in Cuneo Levaldigi, Milano Linate and San Pietro Capofiume

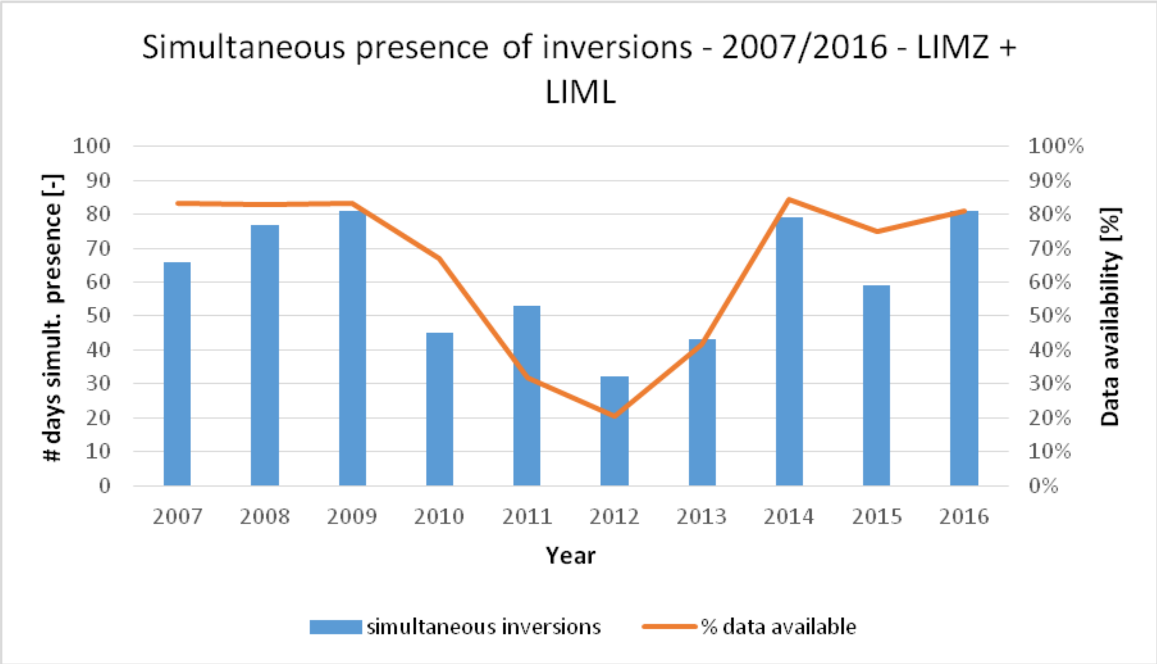


Figure 4.5.16: Simultaneous presence of inversions in Cuneo Levaldigi and Milano Linate

The number of simultaneous presence seems to be comparable between the three station even if the period considered is different: so, from this point of view, all stations considered can be evaluated as a system with internal homogeneity. Values have a significant drop when all stations are simultaneously considered, so this can be a combined effect of the lack of continuous data and the inherent differences between these areas. However, differences between the two combinations LIML+SPC and LIMZ+LIML have been found with similar levels of data coverage: in fact, there are more concurrent inversions between the first couple of stations than the second one (giving that periods of reference are different).

At this point, an overall evaluation of the duration of simultaneous events has been carried on: for each of the three periods considered, it was defined a "simultaneous event" a one-or-more consecutive days when the inversion has been found at the same time in the stations involved. Results have been reported here below in Figure 4.5.17-19:

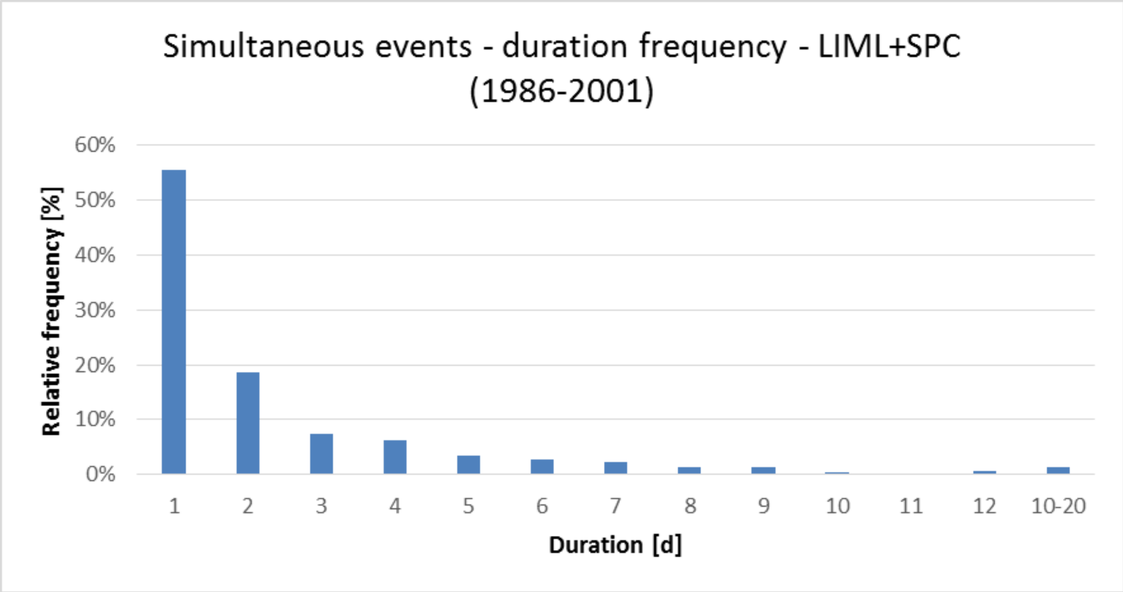


Figure 4.5.17: Duration distribution of simultaneous events - LIML + SPC - period 1986/2001

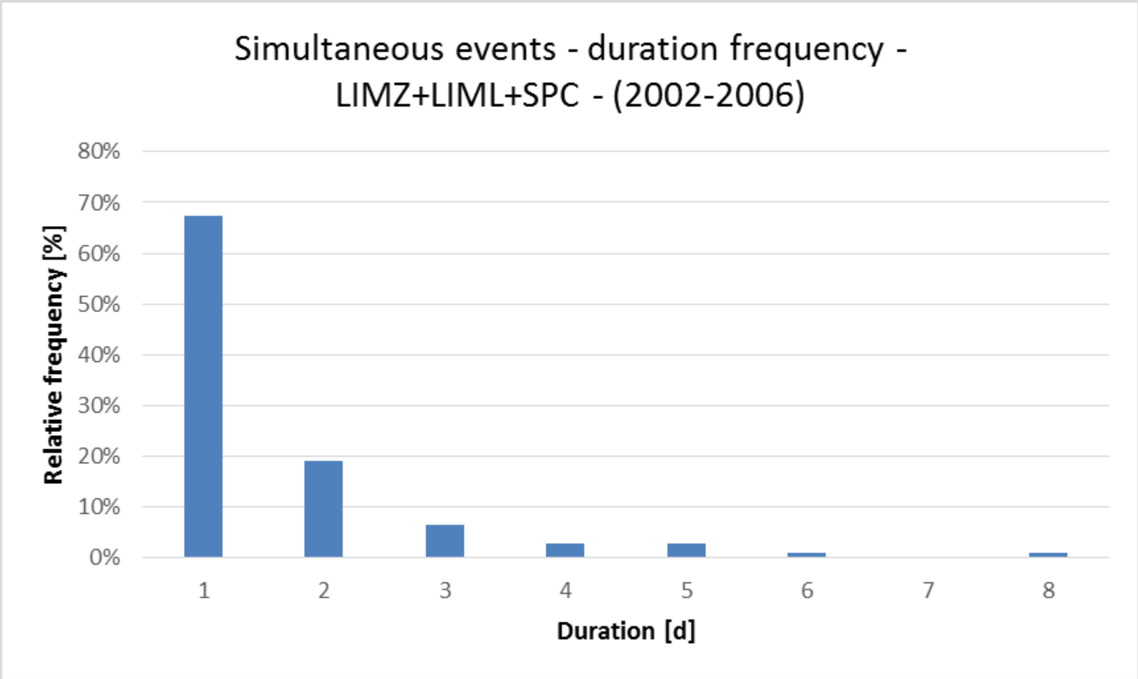


Figure 4.5.18: Duration distribution of simultaneous events - LIMZ + LIML + SPC - period 2002/2006

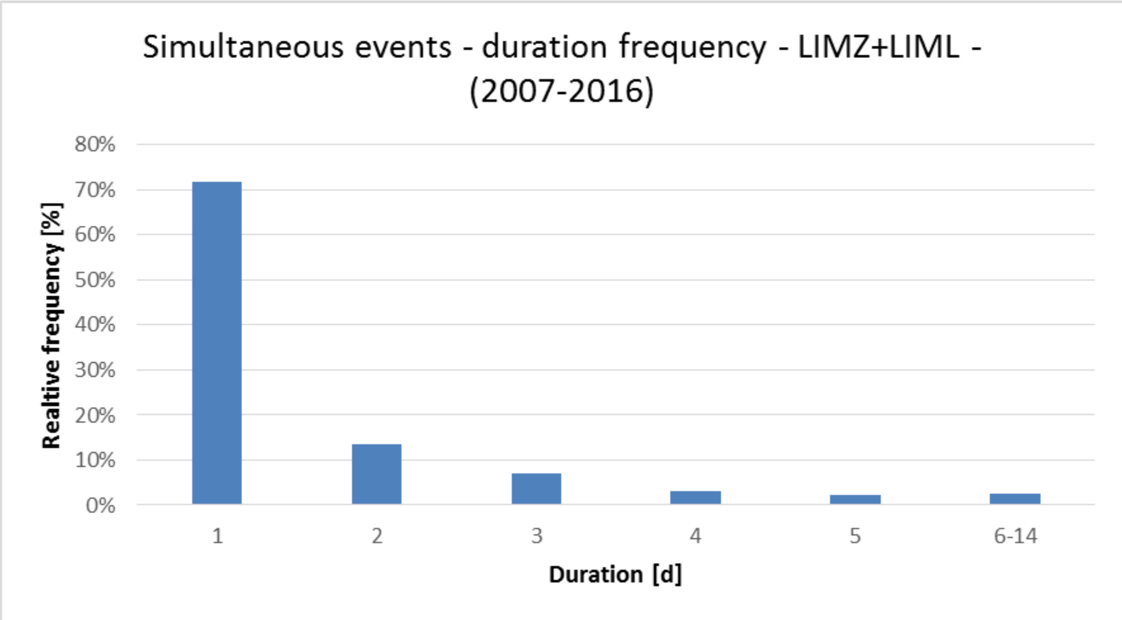


Figure 4.5.19: Duration distribution of simultaneous events - LIMZ + LIML - period 2007/2016

From these graphs above, a great contribution in all of these cases is given by very "short" simultaneous events (more than 75% are 1-or-2 days events). There are similarities in all the three reference period considered, and giving the fact that stations considered are not the same and the data coverage is variable (see Figure 4.5.14-4.5.16), this behaviour is quite observable.

4.6 Conclusions

Results obtained by the assessment of different characteristics of the vertical profiles of the atmosphere over the Po Valley region lead to these conclusions:

- The frequency of inversion days is quite common over all the Po Valley region in all seasons;
- January is the most critical month in terms of inversion occurrence over the entire region;
- From data available (from 1985 to 2016), the mean number of inversion days is not comparable among all the three stations (LIMZ, LIML, SPC), both on annual basis and on seasonal basis;

- The average number of inversion events is different among the three stations in any season considered from 1985 to 2016;
- Single layer inversions are a typical and common feature all over the Po Valley region;
- Mixing heights calculated from soundings on the three stations have very similar characteristics in terms of depth only during wintertime (when it is the shallowest), whereas differences have been found in the other seasons;
- Radiation inversions are typically very thin (most part in the 1-5 hPa thickness range) all over the PO valley;
- Subsidence inversions have a more widespread distribution in terms of thickness but values are comparable between LIMZ, LIML and SPC;
- In all stations the exponential model is more suitable than the hyperbolic model to fit the number of events of inversion by their duration, giving as a result a regional model for this feature;
- Simultaneous inversion events happen rather frequently all over the Po Valley region (85-100 days per year on average, with a 80% data coverage), but the major contribution is given by short simultaneous events (less than 2 days);
- In Milano Linate (LIML), some additional evaluations have been carried on:
    - There is a significant trend in the number of inversion days in spring (+3 days/decade) and summer (+2 days/decade);
    - There is a significant trend on annual basis of the number of events (+3 events/decade), but on seasonal basis trend is statistically significant only in spring (+1 event/decade);
    - Radiation inversions are less frequent than subsidence inversions;
    - There is a significant decreasing trend in the mixing height depth in spring and summer (about -45 m/decade).

So, according to these results, there are signs of a slight increasing trend of stable conditions in the lower atmosphere: this situation is likely due to the effects of climate change, with extreme events (very high stability on one side for long time ranges and high-energy instability systems concentrated as hotspots) on the rise. The entire region can be considered also as one single system in terms of wintertime inversion features (i.e. mixing height, number of inversion layers and the mutual rate of occurrence between subsidence inversions and radiation one) and also for more general aspects (i.e. duration of inversion events, simultaneous inversion occurrence in different timeframes). In the future, a monitoring of these characteristics that have been investigated and also an assessment on others not included in this work can be useful to have a better comprehension of these behaviours in this particular region.

5 THERMAL INVERSIONS AND RADON POLLUTION

5.1 Radon-222 as an index of free mixing height

In this chapter, an evaluation of the relationship between Radon pollution phenomena and occurrence of thermal inversion has been assessed. Radon-222 (the most common and stable isotope) is a radioactive natural gas, odourless, colourless, and it is a product of the decay radium, with a half-life of about 3,8 days. Radon is very heavy and, for this reason, it is a health concern because it can accumulate very easily in insufficiently ventilated rooms, basements and mines, so it can be breathed and it can promote the growth of lung cancer (International Agency for Research on Cancer, 1988). It is common to find it in some construction materials (tuff and some granites), and it can filter through walls very easily with concentrations (that are expressed in Bq/m^3) that can reach very high levels in indoor locations. This gas can be also found in the outdoor environment, but usually at lower concentration levels. Ambient concentration data for Radon-222 have been provided by the University of Milan, Department of Physics, that carries on routinely measurements in the university campus in Milan. Measurement are performed with a system capable to collect airborne particulate matter (that is a crucial substrate for the Rn-222) and detect particle-phase radon, thus assessing its concentration in the lower atmosphere with hourly resolution. Thanks to a box modelling approach, from radon concentrations it is possible to estimates the free mixing height equivalent on an hourly basis. These kind of measurements can be used as a proxy variable to detect thermal inversion events, taking in consideration that the concentration tends to be not uniformly distributed because of mass diffusion's phenomena. It has to be highlighted the fact that Radon emission can be considered uniform over the entire Po Valley region (because of its geological features) and also quite constant throughout time, even if ground surface features (land use, presence of ice and water) can affect the emission rate at the local scale. Furthermore, Rn-222 emission is spatially diffused, differently from particular matter, and so it is not so much point-of-source affected.

Data available on hourly basis are detected from a station located in Città Studi (Milan), so data coming from LIML station have been used to make some comparisons. This preliminary investigation has been developed for year 2013, because of the good data coverage by both the two stations. In Figure 5.1.2, the time pattern of the estimated mixing height (at 12 local time) resulting from Rn-222 measurements and from radiosonde data (at 12 UTC).

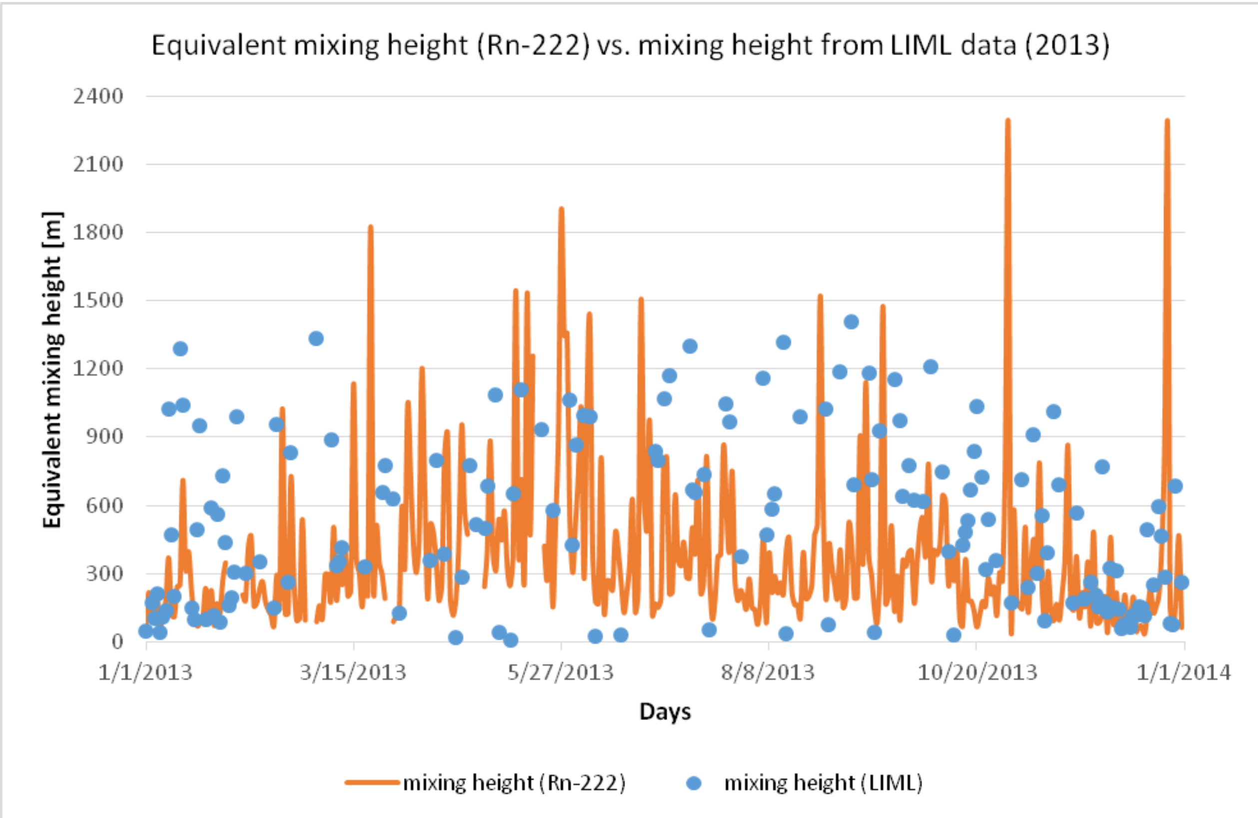


Figure 5.1.1: Equivalent mixing height trend in 2013 - LIML - data from radiosonde and radon measurements

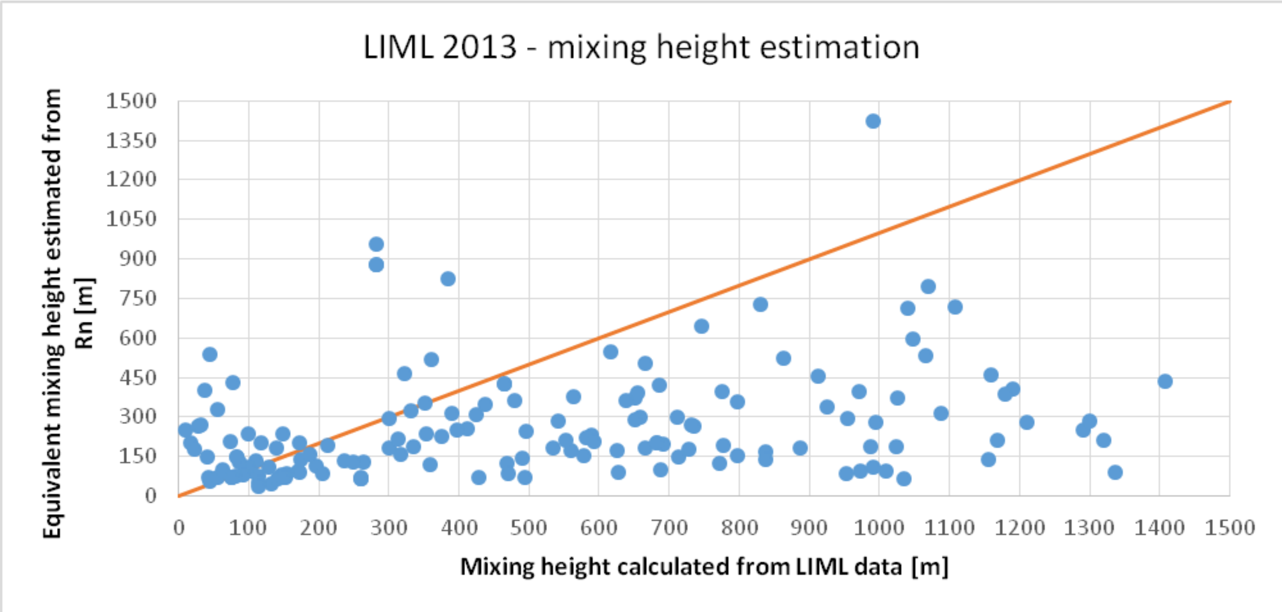


Figure 5.1.2: Equivalent mixing height estimation from radon and radiosonde data in 2013 (Milan)

It can be noticed that there are at least three different behaviours:

- A general overestimation of equivalent mixing height from Rn-222 data in the first 50 m from ground level: models generally have big uncertainties in the lowest layer of the atmosphere;
- A good agreement for mixing layer depth in the 100-400 m range from ground level between the two approaches;
- A general underestimation of mixing height from Rn data for mixing layer depth over 400 m: this can may be due to the mass diffusion mechanism mentioned before.

A focus has been carried on the estimated mixing height under 1000 m from ground level, by a grouping of data each 50 m in the LIML data series, as it is shown in Figure 5.1.3:

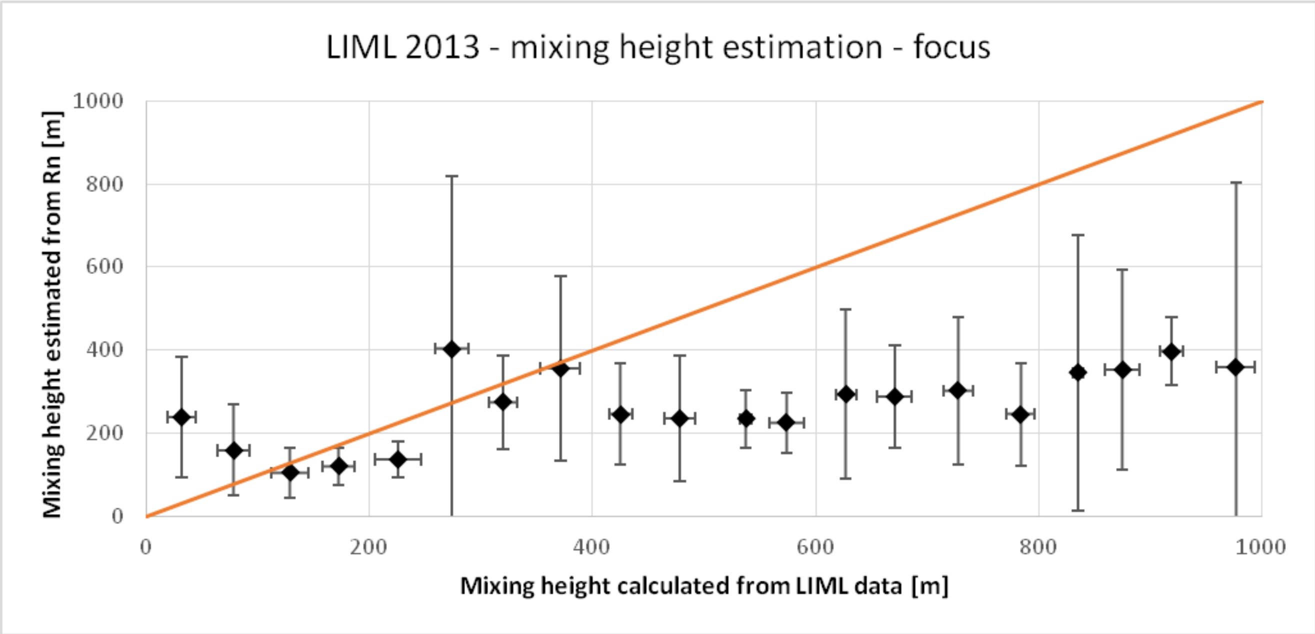


Figure 5.1.3: Focus on 2013 mean grouped data (LIML + radon measurements); each point represents the mutual mean values estimated in the two methods, considering a 50 m frame, with their respective uncertainties.

Some uncertainties are very high due to the small sample of data used, but there is a good similarity in some low mixing layer depths, except for the overestimation in the first two layers from ground level (i.e.: up to 100 m) provided by the approach based on Rn-222 data.

Additional investigations comparing the information of the mixing layer depth given by the two approaches were focused on inversion events. These data have been selected also in terms of events: in fact, 8 events of 4+ consecutive days have happened in 2013 in Milano Linate; in these cases, the mutual variation between radon concentration (daily mean) and mixing height calculated from radiosonde data have been assessed: for each event, the variation between *i* and *i+1* day is calculated referring to the *i*-day, considering all the duration of the event.

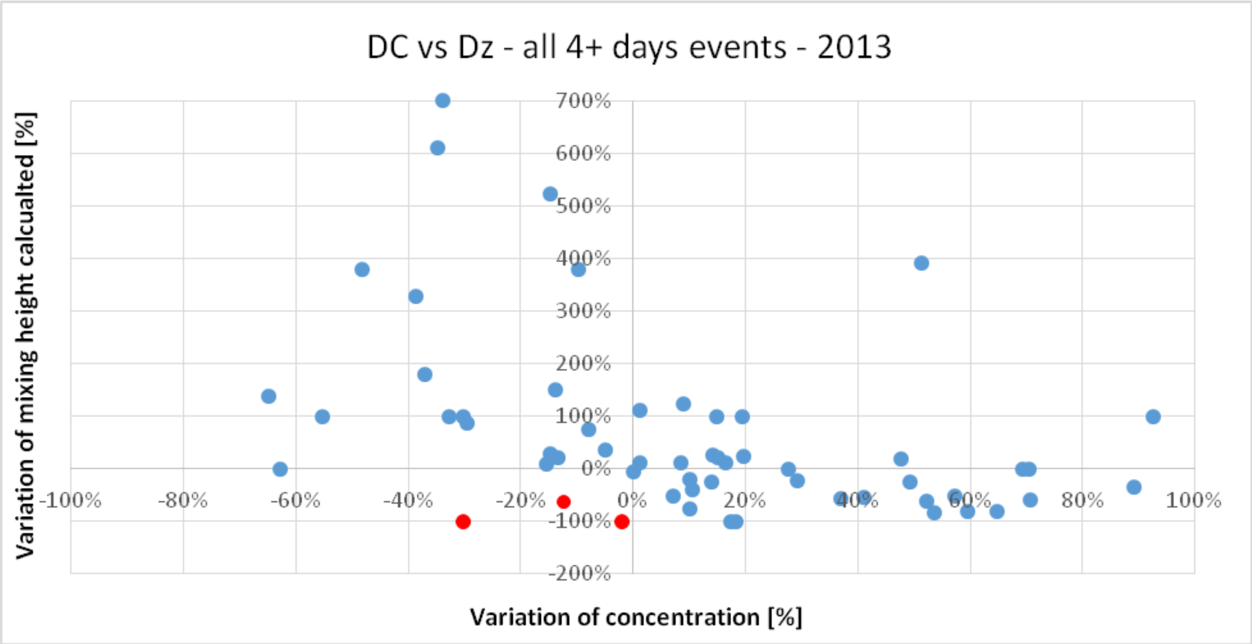


Figure 5.1.4: Mutual variation of mixing height calculated from radiosonde data and radon concentration (only 4+ days event in 2013)

Each couple of values is basically distributed in 3 of the 4 quadrants of the graph reported in Figure 5.1.4; in the second quadrant are represented the cases of the increase of the free mixing height and a related decrease of concentration of radon measured: it has to be highlighted that the variation is less than proportional, so that mass diffusion effects may prevail over the complete mixing; in the fourth quadrant there are situations where there is an increase of concentration and a related decrease of the mixing layer, with a quite widespread distribution of this mutual variation; the first quadrant can be viewed as a situation where there is an accumulation of the radon in the atmosphere, even if there is an upward "movement" of the inversion layer; the last case is in the third quadrant where there is a mutual drop of the two variables considered: two of the three cases identified are related to a downward movement of the inversion layer to the ground level, and one is related to an event in January when an intense event of very light rain occurred, combined to 10-12 km/h wind gusts, so that particles in the atmosphere may be removed by wet mechanisms, reducing the estimated concentration of radon.

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Thank you so much,

Simone

7 APPENDIX

7.1 Data representation

Data may be represented not only by the absolute number of days where an inversion has occurred but also by relative frequency terms. This kind of evaluation has to be validated by a good coverage in the reference period considered, otherwise there is not a great significance of the assessment. In general, trends might be different if compared to the ones found with the number of days of inversions. Here an example of this representation has been provided in Figure 7.1.1-7.1.5:

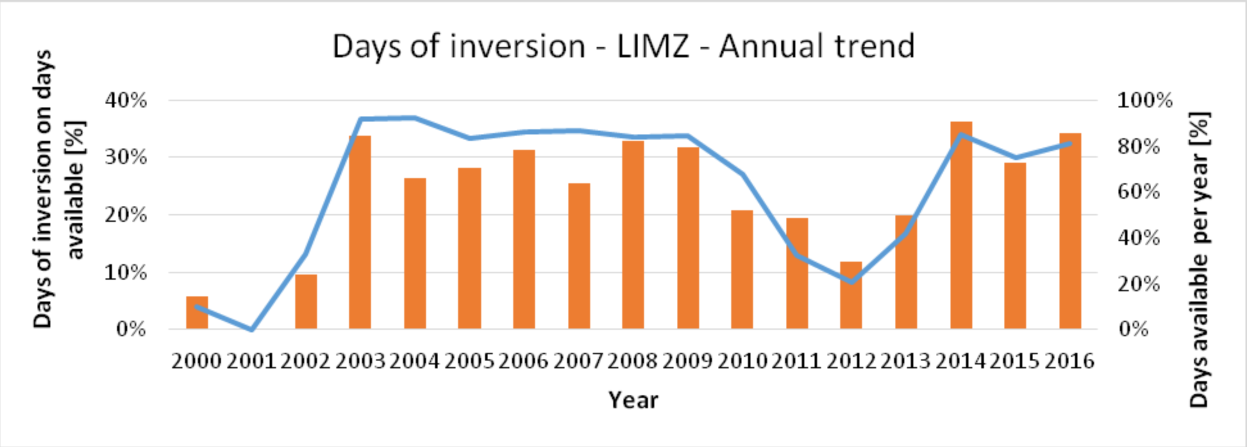

Figure 7.1.1: Days of inversion trend in Cuneo Levaldigi – Frequency

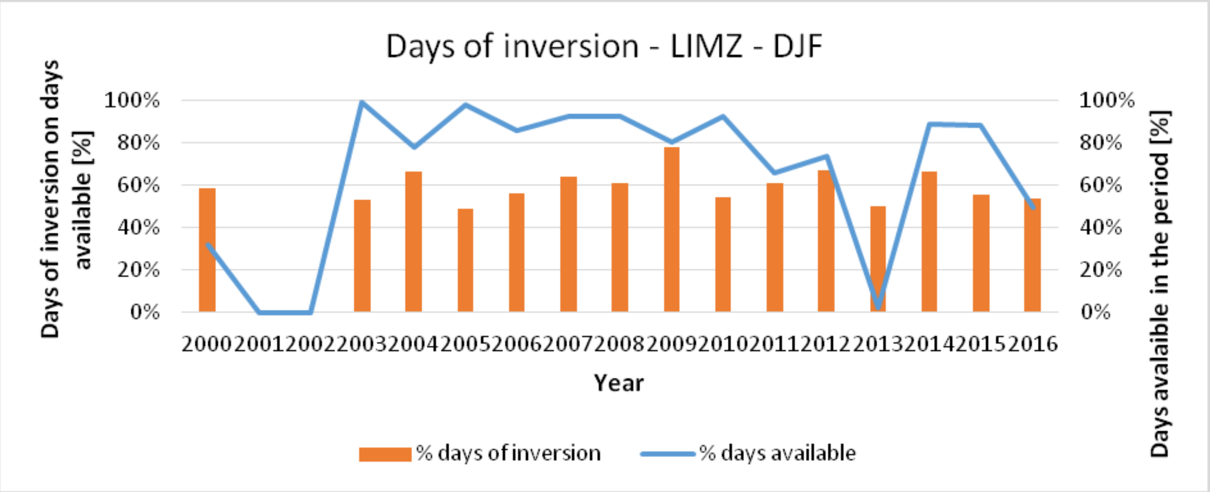

Figure 7.1.2: Days of inversion in Cuneo Levaldigi - Winter trend – Frequency

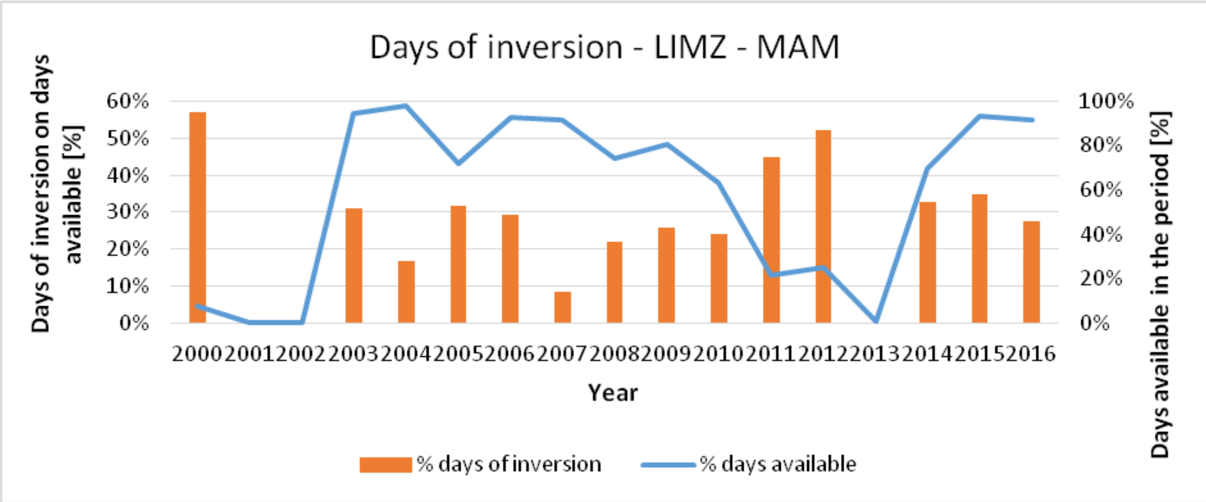

Figure 7.1.3: Days of inversion in Cuneo Levaldigi - Spring trend – Frequency

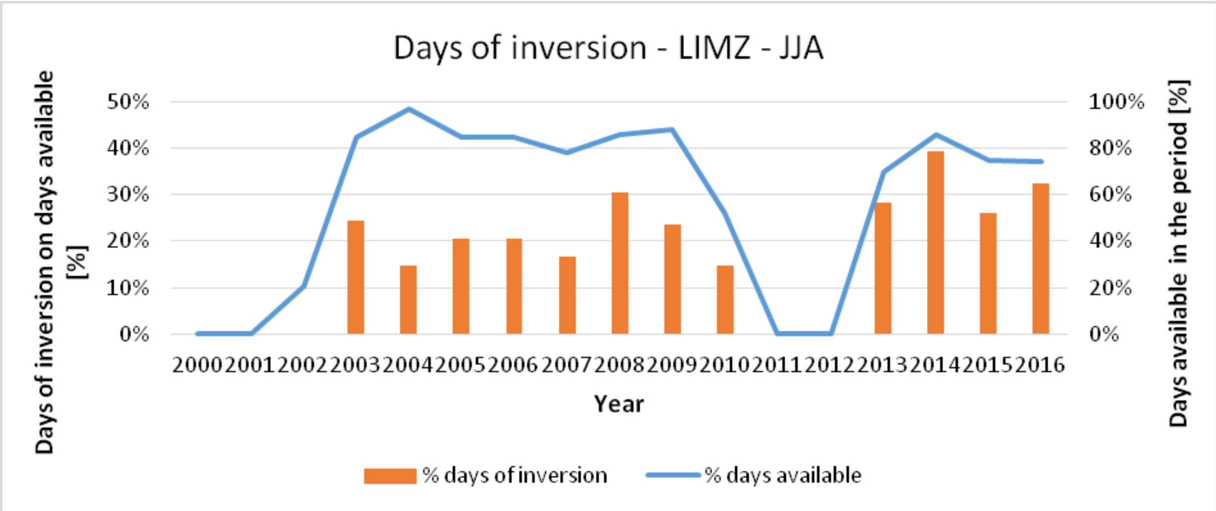

Figure 7.1.4: Days of inversion in Cuneo Levaldigi - Summer trend – Frequency

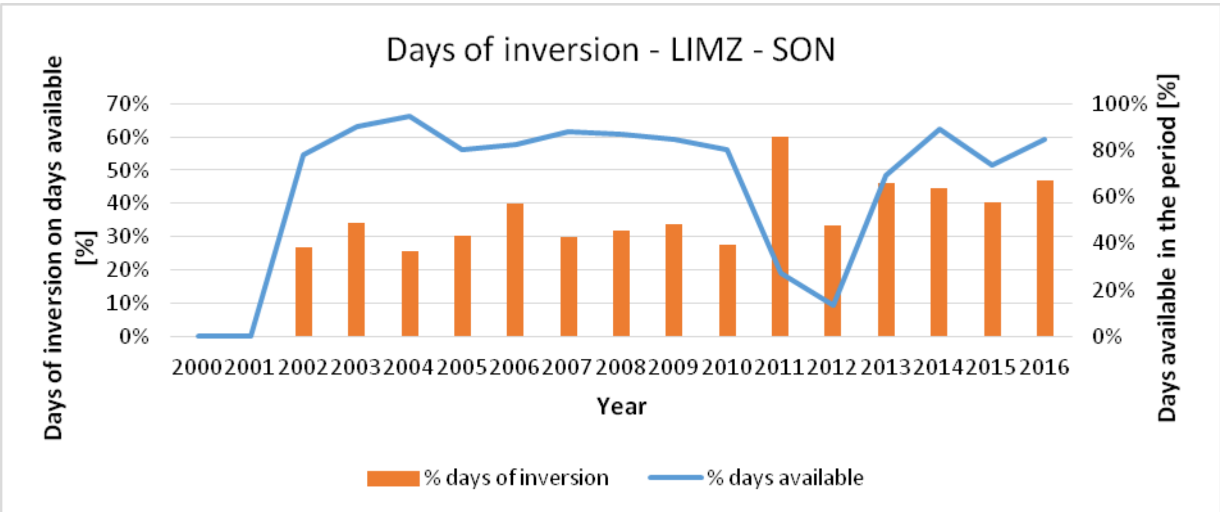

Figure 7.1.5: Days of inversion in Cuneo Levaldigi - Autumn trend – Frequency

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