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Climatology of Alpine north foehn

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Abstract

The foehn wind occurs in the presence of a strong synoptic-scale flow that develops across mountain ranges, such as the Alps. These particular wind events strongly influence air quality, air temperature and humidity. The characteristics of foehn are highly dependent on local topography, which makes it hard to predict. Accurate forecasts of foehn are very important to be predictet, so that the population and the infrastructure of a certain area can be protected in case severe windstorms develop. Although it might be generally thought that this phenomena is fully understood and classified, there are still many unknown aspects, especially concerning the foehn in the southern part of the Alps, called "north foehn". Nowadays, there is a lack of climatological studies on the north foehn that could help improve forecasts and warnings. Therefore, it is of extreme interest to expand the research about the climatology of the north foehn to the south Alpine region, especially in the canton of Ticino and the four south valleys of the canton of Grisons.

The goal of this Master's thesis project consisted in the identification of the north foehn events in the southern part of the Alpine region. Starting from the automatic foehn detection, a data set of the north foehn cases over 5-20 years for several stations of the SwissMetNet, the Centro Meteo Lombardo, the MeteoGroup and the Canton Ticino in middle and low latitude was prepared. The automatic identification of north foehn was based on the definition of station-specific quantitative thresholds. After identifying the foehn events, the foehn was statistically analyzed at each station. The phenomenon was analyzed in various aspects such as the temporal variability, the intensity and the geographical variability. The results of the climatology show that the north foehn has a strong seasonal and diurnal cycle. In fact, March is the month with the highest total frequency and the north foehn occurs more often in the afternoon. Another important factor influencing the north foehn is the topography of the region. By comparing nearby stations we noticed that the same foehn events were identified with only small differences in duration, initiation or end of the foehn case. On the other hand, the distance of the station from the Alpine crest and the orientation of the valley are the main influential factors. The wind speed, the wind gusts, the monthly frequency and maximum duration of north foehn events are more intense near the Alpine crest and where the valley has a north-to-south orientation.

To test the robustness of the results and the uncertainty of the applied method a sensitivity study was performed. The sensitivity study indicates that relative humidity is the most sensitive parameter when applying the automatic identification of foehn. Therefore, special attention must be given to this parameter.

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1 Introduction

1.1 Motivation

The foehn is defined by *Quaile* (2001) as a "warm, dry wind that descends in the lee of a mountain range". For this Master's thesis project a climatology of the north foehn events in the southern part of the Alps was conducted. Excluding gusts which precede storms and front's passages, the foehn is the strongest wind that blows in this region, largely influencing its climate (*Zenone*, 1960). The foehn is characterized by specific wind, temperature and humidity behaviors and it has an enormous damage potential (*Gutermann et al.*, 2012). In fact, during a strong foehn case heavy precipitation on the upwind side of a mountain range can cause severe damages due to floods while gusty winds can cause losses in agriculture and severe damages at buildings (*Drobinski et al.*, 2007). For example, on February 2nd 2013, a strong north foehn case with stormy winds reaching a maximum speed of 110 km/h at low altitudes has caused several damages like the uncovering of a shed, the folding of a traffic light, the fall of plants and branches in Locarno and the break of an electrical cable causing a blackout in Brissago. In addition to damages caused by the intensity of the wind, the foehn has a strong impact on temperature, causing an increase in the melting of the snow which consequently raises the risk of avalanches (*Pangallo*, 2000). On the other hand, the increase in temperature caused by foehn can favor tourism in the region. For all these reasons, special attention was given to the foehn by meteorologists.

The societal impact of the foehn is almost as strong as the climate impact. A connection can often be made between the foehn wind and some secondary effects. In fact, not only does the foehn have an impact on air quality, temperature, melting of snow, etc. but it also has an effect on spreading fires, road accidents, human health and animal's behavior. Of those, one of the most impressive ones is the spreading of fires (*Richner and Hächler*, 2013). In fact, warm and very dry air combined with high wind speed efficiently favors the propagation of fires (*Richner and Hächler*, 2013). Furthermore, the foehn wind can be dangerous for flying and, in addition, car and train accidents can be caused by gusty foehn winds (*Richner and Hächler*, 2013). The foehn also has in impact on people's health. In the Alpine area, people often blame illness, accident, crime, and particularly headaches on the foehn. It is known that slight atmospheric pressure oscillations, which occur naturally, can influence human mental activity (*Delyukov and Didyk*, 1999). Hence, it is possible that foehn has a similar effect. Recent research has proven that the only possible cause is actually the pressure fluctuations induced by gravity waves during the foehn (*Richner and Hächler*, 2013). Although there is no proof of any cause-and-effect relationship, statistical analyses of pressure fluctuations and human health show that there is a statistically significant correlation between the two (*Richner and Hächler*, 2013).

As the effects of foehn are important a precise forecast is essential in order to protect the population

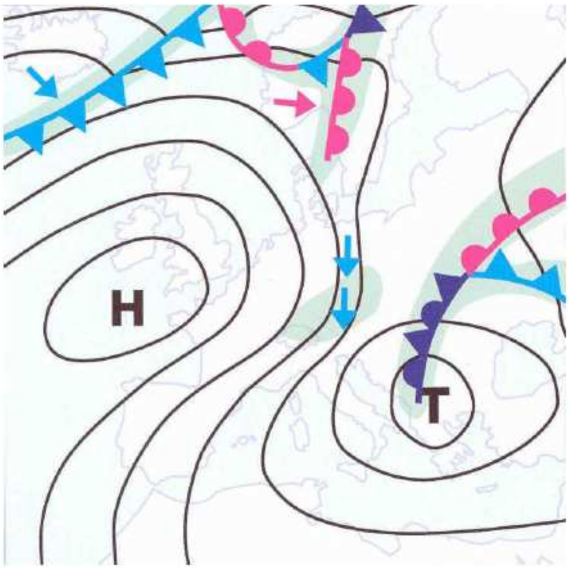


Figure 1: Synoptic chart of the north foehn over central Europe - Typical conditions during north foehn episodes over the Alps. Solid lines: lines of constant surface pressure (isobars); H: center of the high-pressure system; T: center of the low-pressure system; thick blue lines: cold fronts; thick pink lines: warm fronts. (Figure adopted from M. Buzzi, 2014)

and the infrastructures of a certain area. However, Switzerland has a very complex topography and therefore, a very accurate forecast is difficult. Although it might be generally thought that this phenomena is fully understood and classified, there are still many unknown aspects. Nowadays, there is a strong lack of climatological studies on the north foehn. Therefore, it is of extreme interest to expand this type of research about north foehn especially in the region of Ticino, northern Italy (Lombardy and Piedmont) and the four south valleys of the Canton of Grisons in order to improve forecasts and warnings.

1.2 The Alpine region and basic theory of the north foehn

When a large-scale flow hits a mountain chain, it can partly be blocked and partly flow over the ridge, and thus, a variety of different flow features emerge (*Smith*, 1979). In the Alpine region, the feature with the biggest impact is the foehn. The foehn is a meteorological phenomenon occurring practically in all extended mountain ranges. The word *foehn* is a generic term which prevailed as a scientific term for a downslope wind that is strong, warm, and dry (*Richner and Hächler*, 2013). The World Meteorological Organisation (WMO) defines the foehn as a "wind [which is] warmed and dried by descent, in general on the lee side of a mountain" (*Richner and Hächler*, 2013).

Generally, depending on the main synoptical flow and the orientation of the alpine chain, two main foehn directions can be distinguished. The typical foehn, called "south foehn" (on the north side) is characterized by wind coming from south; the "north foehn" (on the south side) is characterized by wind coming from north. As it can be seen in Figure 1, the typical synoptic conformation of the north foehn can be generalized as the opposite of the south foehn, meaning that a low pressure system is located over south-eastern Europe and a high pressure system is located over the Atlantic and western Europe (*Ambrosetti et al.*, 2005). A strong temperature gradient forms between the northern and the southern part of the Alps, causing a strong pressure gradient that the atmosphere tries to compensate

for (*Schrott and Verant*, 2004). Due to the breaking in of cold air masses the pressure on the north side of the Alps increases, while it is almost unaffected on the southern part of the Alps (*Frey*, 1992). The cold air masses flow over the Alpine ridge and, if the pressure gradient is strong enough, the north foehn forms (*Frey*, 1992). The resulting overflow of the mountains triggers a process which leads to a rapid increase in temperature and a significant decrease in air humidity on the lee side.
To summarize, the three main factors characterizing the foehn according to *Schrott and Verant* (2004) are:

1. strong wind gusts
2. increase in temperature
3. decrease in relative humidity.

These three factors are extremely useful to identify the initiation of a foehn event in a defined station. However, in our case, the temperature increase is considered indirectly. Temperature is taken into account when calculating the difference in potential temperature between a reference station and the other stations of the study region, as it will be explained later in detail. However, the increase in temperature only has a small impact during north foehn, since it is not always so strong. In some extreme cases the temperature is even lower after flowing over the mountain. This is due to the origin of the air coming from polar regions and for this reason it is very cold.
As it will be explained later, by using these parameters in combination with others, such as potential temperature, it is possible to identify north foehn.

1.3 Literature review

At the end of the 18th century, meteorologists began to be interested in foehn, especially in the Alpine region (*Gutermann et al.*, 2012). Julius von Hann was the first scientist to formulate the thermodynamic foehn theory (*Seibert*, 2005). For many decades, the foehn was the extraordinary example used to explain the thermodynamic processes and the role of latent heat in the atmosphere (*Richner and Hächler*, 2013). The classical theory explains that, driven by the synoptic scale pressure gradient, humid air is forced towards a mountain range. The air is forced to ascend and cools dry-adiabatically until saturation is reached. Hereafter, the air rises wet-adiabatically until the air reaches the crest of the mountain range. As a consequence, clouds form and precipitation occurs. Afterwards, the air descends in the lee of the mountain following the dry adiabatic lapse rate, since the air has dried out. Consequently, the air reaches temperatures that are higher than the original temperature on the windward side. In reality, the foehn winds often do not follow this classical textbook theory that is attributed to *Hann* (1866). Regarding this, *Seibert* (2005) concludes that Hann's explanation was modified and adapted by scientists especially in the first half of the 20th century and many different theories were developed afterwards.
In relatively densely populated regions, many researches have been conducted, especially in Europe (*Gutermann et al.*, 2012). Two main research groups formed in the 19th century: Austria and Switzerland were the two hotspots for foehn research (*Richner and Hächler*, 2013). Innsbruck (Austria) is the place where scientists like Hann, Ficker, Hoinkes, Kuhn, Steinacker, Seibert, Hoinka conducted their researches (*Richner and Hächler*, 2013), while in the Swiss Alps it is mainly Billwiller, Frey, Gutermann who have made observations and developed their theories (*Richner and Hächler*, 2013). The first

studies about the foehn in general were conducted in the northern region of the Alps: in the Valais, in the bernese Oberland, in the valley of the Reuss, in the valley of the Rhine and in Innsbruck (*Schrott and Verant*, 2004). If we focus on the north foehn, probably the oldest study was done by Robert *Billwiller* (1902) whose results were published in the book "der Bergeller Nordfhn". Billwiller's book is divided into two main chapters. In the first chapter, he analyzes the influence of the north foehn on the climate of the region. In the second chapter he moves on to the analysis of the air distribution and weather situation during north foehn events. He concludes that there are different forms of occurrence of the foehn. The scale of north foehn phenomena on the southern part of the Alps is indeed as rich in nuances as for the south foehn (*Billwiller*, 1902). *Billwiller* (1902) defines two types of foehn formation: i) the north foehn by north-south gradient in the Alpine region; ii) the north foehn by absence of north-south gradient which is called "Anticylonic foehn". In the first case, the north foehn can form either when a depression is located in the southern part of the Alps, or when a high pressure zone approaches the northern part of the Alps. In the second case, the north foehn can form as warm and dry air coming from the central part of an anticyclone located over the Alps which descends the mountain ridge (*Billwiller*, 1902).

In 1953, Karl Frey studied the development of south and north foehn in the region of the Alps. The research goal was to discuss the spatial distribution of the meteorological features during the development of south and of north foehn situations (*Frey*, 1953). The research element was a network of mountain and valley stations of the Swiss Alps (*Frey*, 1953).

The most recent research project on the north foehn was conducted by *Ambrosetti et al.* (2005). He worked on a MeteoSwiss project with the main goal of performing a climatology of the north foehn. His project differs from ours, since the climatology was performed only considering five stations of the Po basin located in Italy and Switzerland where manual observations were available. His results include yearly, seasonal and monthly frequencies of north foehn in the area for the period 1991-2003, from which a number of conclusions were drawn: i) winter and spring are the most affected seasons; ii) the Alpine area is the most influenced by the foehn; iii) the phenomenon has a strong variability. The third conclusion can be explained by considering that air masses crossing the mountains increase their velocity and arrive in the southern part of the Alps with undulations that can exclude some stations (*Ambrosetti et al.*, 2005). In fact, it can happen that foehn is detected in the plain but not in Locarno-Monti. This can be explained by different factors: i) the direction of the dominant currents; ii) the position of the station; iii) the presence of layers of cold air in the basin of the Lake Maggiore (*Ambrosetti et al.*, 2005). The obtained results show that the foehn is an important environmental factor not only for the Alpine area but also for the whole Po Valley (*Ambrosetti et al.*, 2005).

Finally, even though *Schrott and Verant* (2004) cite various researches of different scientists, such as *Hann* (1891), *Billwiller* (1902), *Trabert* (1903), *Hoinkes* (1951), *Frey* (1953), *Kuhn* (1978), *Steinacker* (1983), *Wankmüller* (1995), it was not possible to find the related articles and books. *Schrott and Verant* (2004) explain that *Erler* (1943) was the first researcher to show that the north foehn is strongly linked to the cold front passage northern of the Alps. In addition, some Italian scientists devoted themselves to researching the north foehn in northern Italy: *Crestani* (1923), *Bossolasco* (1950), *Gandino et al.* (1990), *Geier* (2001). It might then appear that the phenomenon of the north foehn is well known in the region of the Alps. Nonetheless, the majority of the studies focus on the south foehn, especially because of its higher increase in temperature.

As stated by *Gatti* (1996), if it was possible to exactly estimate parameters, such as temperature and pressure, the forecasts would be infallible. Unfortunately, there is a lack of climatological studies, especially concerning the north foehn, which, in addition to model-based studies, could help improve forecasts and warnings in case of intense events. Therefore, the research about the climatology of the north foehn in the southern part of the Alps really needs to be expanded.

1.4 Objectives of the project

This Master's thesis project consists of the identification of the north foehn events in the southern part of the Alpine region with subsequent statistical analysis. Starting from the automatic foehn detection, a data set of the north foehn cases over 5-20 years for several stations of the SwissMetNet, the Centro Meteo Lombardo, the MeteoGroup and the Canton Ticino, located in middle and low latitude was prepared. The main objectives of this study were the following:

1. apply the automatic foehn selection method to several meteorological stations in the southern part of the Alps
2. identify all foehn events over 5-20 years (depending on the length of the time series)
3. statistically characterize the north foehn at each station.

The most important aim of this project was to partly fill the lack of climatological studies on the north foehn. The method is based on the use of automatic measurement stations and the results could be used in the future to automatically identify the north foehn at each station, as it is already the case for some stations located north of the Alps.

2 Stations and Data

2.1 Location of the stations

The area of study was chosen as a consequence of the desire to fill the lack of climatological researches in the southern part of the Alps. Moreover, the study region features the following characteristics that make it suitable for a climatological study of this type:

- the presence of many stations at different altitudes and different location types (valley, flat land, different orientation of the valley)
- the availability of a sufficiently long data set
- the presence of additional stations, which were important to calculate parameters used as additive criteria to distinguish the north foehn.

It should be mentioned that topography plays a major role during foehn cases as the spatial conditions of the meteorological elements in the study area are strongly influenced by it (*Drobinski et al.*, 2007). In fact, as explained by *Richner and Hächler* (2013), foehn areas are primarily defined by topography: the better a valley axis is aligned with the main synoptic flow the easier the airflow penetrates into the valley. Major valleys perpendicular to the ridge represent the areas with the highest foehn frequency (*Richner and Hächler*, 2013). In general, valleys have a strong channelling effect on the flow and and there, wind speed can be higher near the ground than it is above because the cross section decreases as the flow further penetrates into the valley (*Richner and Hächler*, 2013). The characteristics of the north foehn are highly dependent on local topography and, as it can be seen in figure 2, the region of Ticino, Grisons and Po Valley is delimited by the Alps in the north, which makes the north foehn a recurring event. The location of the stations of interest in Ticino, northern Italy and south valleys of Grisons are shown in figure 3. These automatic meteorological stations are located over the whole southern region of the Alps. The data were obtained from measurements made at stations belonging to the SwissMetNet, the MeteoSwiss automatic network, called ANETZ from about 1980 to 2004 and SMN from 2005. To expand the data set we used data from some Swiss and Italian stations belonging to the Centro-Meteo-Lombardo (CML), to the Canton Ticino (CT), to the MeteoGroup (MG) and to the Agenzia Regionale per la Protezione dell'Ambiente (ARPA). Unfortunately, after some preliminary analysis we chose not to use the data gained from the ARPA, since not all the necessary parameters were available. The station Altdorf (ALT) was used in order to calculate the difference in pressure with each station of the study region, as it will be explained later. Furthermore, at least one station at the main Alpine crest was needed. Station Gütsch, located at the Alpine ridge in the Canton Uri at an altitude of 2289 masl was chosen as it represents the higher level wind direction that should come from the northern sector (290°-89°) (*Gutermann*, 1970). This station was needed to determine the flow

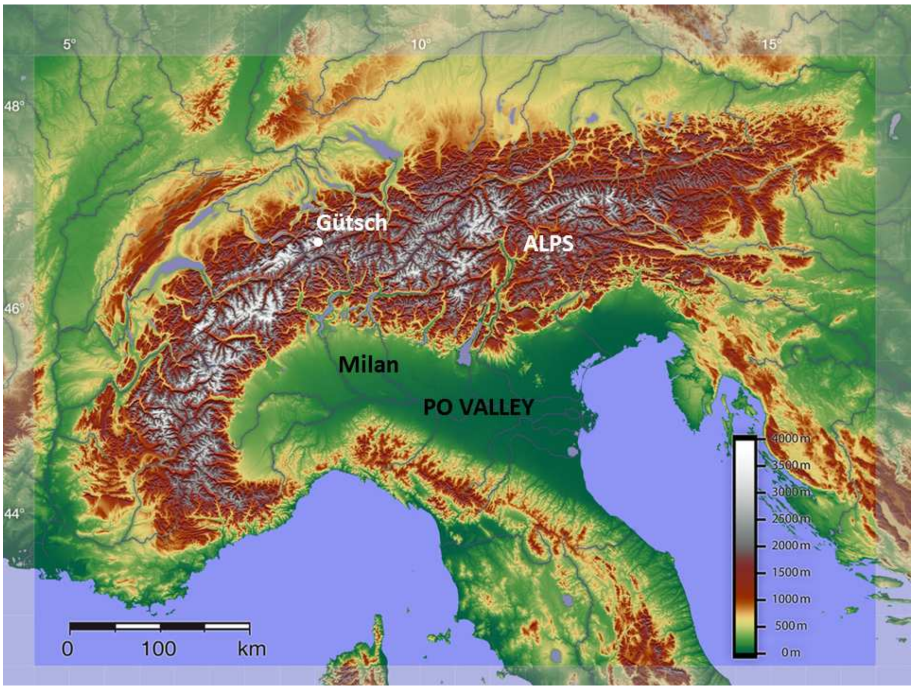


Figure 2: Topographic map of the Alps. The region of the Po Valley is delimited by the Alps in the north, which makes the north foehn a recurring event (Figure adapted from *Wikipedia* (2015)).

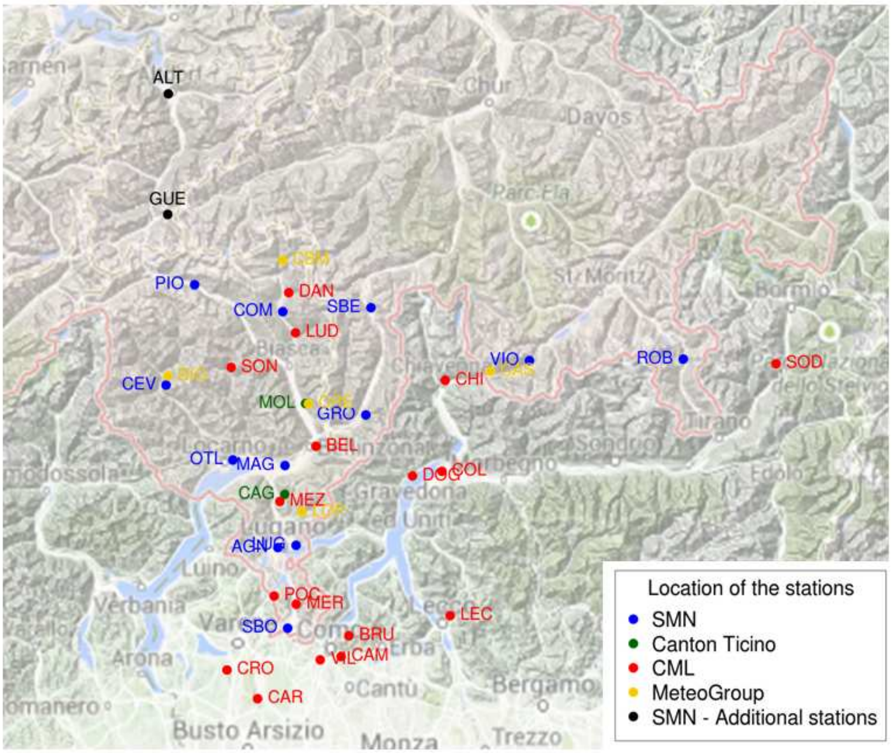


Figure 3: Location of the stations in the study region. The stations illustrated in the figure were used to collect the data. Green dots: Canton Ticino stations; Red dots: Centro-Meteo-Lombardo stations; Yellow dots: MeteoGroup stations; Blue dots: SwissMetNet - Complete measuring stations (wind, temperature and rain); Black dots: additional SwissMetNet stations.

through the Alpine ridge (north-to-south flow) and to exclude local situations such as Alpine breezes. All the information regarding the used stations are shown in table 1.

Table 1: List of the stations used for the study

Network	Abbreviation	Location	Altitude [masl]	Time span
SMN	AGN	Agno (TI-CH)	279	01.01.2009-31.08.2014
	ALT*	Altdorf (UR-CH)	438	
	CEV	Cevio (TI-CH)	417	01.11.2013-31.08.2014
	COM	Comprovasco (TI-CH)	575	01.01.1993-31.08.2014
	GRO	Grono (GR-CH)	324	01.11.2012-31.08.2014
	GUE*	Gtsch (UR-CH)	2283	
	LUG	Lugano (TI-CH)	273	01.01.1993-31.08.2014
	MAG	Magadino-Cadenazzo (TI-CH)	203	01.01.1993-31.08.2014
	OTL	Locarno Monti (TI-CH)	367	01.01.1993-31.08.2014
	PIO	Piotta (TI-CH)	990	01.01.1993-31.08.2014
	ROB	Robbia-Poschiavo (GR-CH)	1078	01.01.1993-31.08.2014
	SBE	San Bernardino (GR-CH)	1639	01.01.1993-31.08.2014
	SBO	Stabio (TI-CH)	353	01.01.1993-31.08.2014
	VIO	Vicosoprano (GR-CH)	1089	01.01.1993-31.08.2014
CML	BEL	Bellinzona (TI-CH)	225	03.10.2008-31.08.2014
	BRU	Brunate San Maurizio (CO-I)	870	30.05.2009-18.07.2014
	CAM	Camerlata (CO-I)	285	19.06.2010-19.07.2014
	CAR	Rovate di Carnago (VA-I)	334	01.01.2009-19.07.2014
	CHI	Chiavenna (SO-I)	343	01.01.2008-19.07.2014
	COL	Colico Lago (LC-I)	205	29.04.2008-20.07.2014
	CRO	Crosio della Valle (VA-I)	300	03.08.2007-30.04.2014
	DAN	Dangio (TI-CH)	788	01.07.2008-18.07.2014
	DOG	Dongo (CO-I)	201	22.05.2009-19.07.2014
	LEC	Lecco Centro (LC-I)	225	18.03.2004-18.07.2014
	LUD	Ludiano (TI-CH)	470	11.01.2011-18.07.2014
	MER	Meride (TI-CH)	569	26.06.2009-19.07.2014
	MEZ	Mezzovico (TI-CH)	417	10.08.2008-18.07.2014
	POC	Porto Ceresio (TI-CH)	277	20.07.2009-19.07.2014
	SOD	Sondalo (SO-I)	910	22.10.2011-20.07.2014
	SON	Sonogno (TI-CH)	916	16.06.2012-19.07.2014
	VIL	Villaguardia (CO-I)	368	09.02.2008-19.07.2014
MG	BIG	Bignasco (TI-CH)	202	25.04.2008-31.08.2014
	CAS	Castasegna (GR-CH)	1233	05.04.2007-31.08.2014
	CBM	Campo Blenio (TI-CH)	285	31.10.2009-31.08.2014
	CRE	Cresciano (TI-CH)	334	07.09.2008-31.08.2014
	LOP	Lopagno (TI-CH)	343	09.07.2009-31.08.2014
CT	CAG	Camignolo (TI-CH)	435	01.01.2004-31.08.2014
	MOL	Moleno (TI-CH)	255	01.01.2004-31.08.2014

*: reference stations; CH: Switzerland; CO: Como; GR: Grisons; I: Italy; LC: Lecco; SO: Sondrio; TI: Ticino; UR: Uri; VA: Varese

2.2 Measured data

The data for the analysis largely come from the database system of MeteoSwiss (data warehouse DWH). In addition, some other data were provided by the CML, the CT and the MG. The data available to us have either a 10-minute or 1-hour resolution but for most of the stations we used hourly aggregation data. The only exceptions were stations Agno (AGN), Camignolo (CAG) and Moleno (MOL), for which we used 10-minute resolution data, because the time span of data set provided by the station was quite short. Despite the short data set, we decided to still use these stations because they are located in the study region and the quality of the measurements is good. As it can be seen in table 1, the data time span varies from station to station, depending on when it was installed.
At each station the following parameters are measured:

- Wind speed FF [m/s]
- Wind gusts FFF [m/s]
- Wind direction DD [°]
- Temperature T [°C]
- Relative humidity RH [%]
- Pressure P [hPa]

All the parameters cited above are used to identify the foehn cases and they are directly measured at each station, while the potential temperature was derived from the formula:

$$\theta = (T + 273.15) \cdot (\frac{1000}{P})^{0.286}$$

where T is the temperature of the air and P is the surface pressure. Hereafter, we calculated the difference in potential temperature (TPOTDIFF) between GUE, which characterizes the Alpine crest, and each valley station, in order to distinguish the foehn cases from the Alpine breezes.
For a similar purpose another parameter was calculated:

$$dp\_alt = P\_ALT - P\_STA$$

where P_ ALT is the pressure at station ALT and P_ STA is the pressure at each station of the study region. This parameter was used as additional criteria for the automatic selection of north foehn cases. Firstly, in order to calculate the difference in pressure, it was necessary to reduce the pressure. To do this we used the barometric formula:

$$p(h_1) = p(h_0)\left(1 - \frac{a\Delta h}{T(h_0)}\right)^{\frac{Mg}{Ra}}$$

where $p(h_1)$ is the reduced pressure and $p(h_0)$ is the pressure at the station. T is the temperature at the station and M is the molar mass of Earth's air, g is the gravitational acceleration, R denotes the universal gas constant and a is the wet lapse rate. As common altitude h_{ref}, used to calculate Δh, we used 350 masl. However, for the stations belonging to the CML we already had the reduced pressure at our disposal and hence, we had to derive the pressure at the station from the formula.

3 Foehn Index

The definition of foehn event can be problematic in a foehn climatology, since it strongly depends on the subjective choice of the researcher. However, the Alpine Research Group Foehn Rhine Valley/Lake Constance AGF has adopted an objective definition for foehn identification (*Richner and Hächler*, 2013). The opinion of the majority of people shows that foehn is clearly defined, but there is a problem of demarcation in individual cases (*Hächler et al.*, 2011). Generally, there are no accepted thresholds, neither for the primary typical foehn parameters nor for wind direction, wind speed, temperature and humidity at a selected location (*Hächler et al.*, 2011). It is therefore the scientist's choice to determine the thresholds for the analysis and the interpretation of the results. The resulting foehn statistic of different editors is therefore not directly comparable. Over time, the AGF has agreed on a list of criteria to define the initiation, the duration and the end of a fohn event (*Hächler et al.*, 2011). Based on quantitative criteria, the AGF member Bruno *Dürr* (2008) has developed a computerized and automated process to identify foehn events for selected stations of the SMN. This method is in use at MeteoSwiss since the beginning of 2008. The method requires station-specific quantitative limits which have to be overcome in order to speak of foehn (*Hächler et al.*, 2011). The advantages of using the automated foehn identification are the following: i) objective distinction between the foehn and the remaining winds; ii) minimization of time effort; iii) it is the best way to reproduce the foehn identification using an objective method (*Dürr*, 2008). As a result, a high temporal resolution data can be provided, which allows the analysis of the properties of the foehn and can generally be used to improve foehn prediction (*Dürr*, 2008).

Using a similar method as proposed by *Dürr* (2008), the presence of foehn was automatically identified at each station of our study region. In the same way as the AGF determined the definition for south foehn, we defined objective criteria which allowed us to identify the north foehn cases. In order to do so we used the following methodology, which is described in detail in this chapter:

1. distinguish between north wind at GUE and south wind at GUE
2. define the sector of origin of the wind at the station by looking at the windrose
3. create density plot of selected variables and define thresholds that have to be overcome during north foehn
4. combine the thresholds to obtain the foehn index.

3.1 Distinction between north and south wind at GUE

As mentioned beforehand, station GUE plays a major role in the selection of the north foehn events. At this station we used wind velocity (FFGUE) and wind direction (DDGUE) together with the difference in potential temperature in order to distinguish between the north foehn and other types of wind. The first step consisted in checking DDGUE to distinguish between two situations: i) north wind at the GUE (DDGUE = [290°-89°]); ii) south wind at the GUE (DDGUE = [90°-289°]). The results that we obtained are two data set, one with the situations of north wind at the Gütsch and the other with the situations of south wind at the Gütsch.

3.2 Definition of the sector of origin of the wind

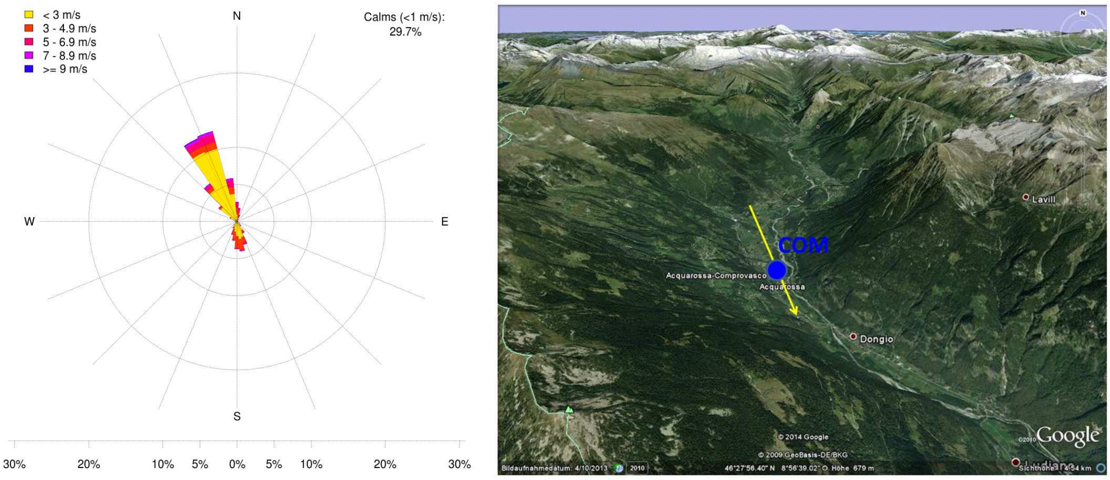
After the distinction between the two situations, the next step was to create a windrose for each station, in order to define the sector of origin of the wind during north foehn. The windrose (*Pfahl et al.*, 2014) was created using the entire data set available for each station. Figures 4-7 show the different windroses and the topographic maps which demonstrate that the topography and the orientation of the valley clearly influences the direction of the wind blowing in the area.

Station COM is located at the floor of the Blenio valley at the altitude of 575 msal. As it can be seen in figure 4, the Blenio valley has a north-to-south orientation which influences the wind direction (DD = 270°-60°). COM shows all the classical behaviors during north foehn events and it is therefore considered as the standard station.

Station LUG is located in the Sottoceneri at the altitude of 273 masl. LUG has a similar behavior as COM but is located further south. I chose to analyze in detail this station in comparison with COM in order to investigate the influence of the distance from the Alpine crest on the occurrence of north foehn. This station is located at the valley floor and the sector of origin of the wind corresponds to the orientation of the valley: DD = 270°-70°.

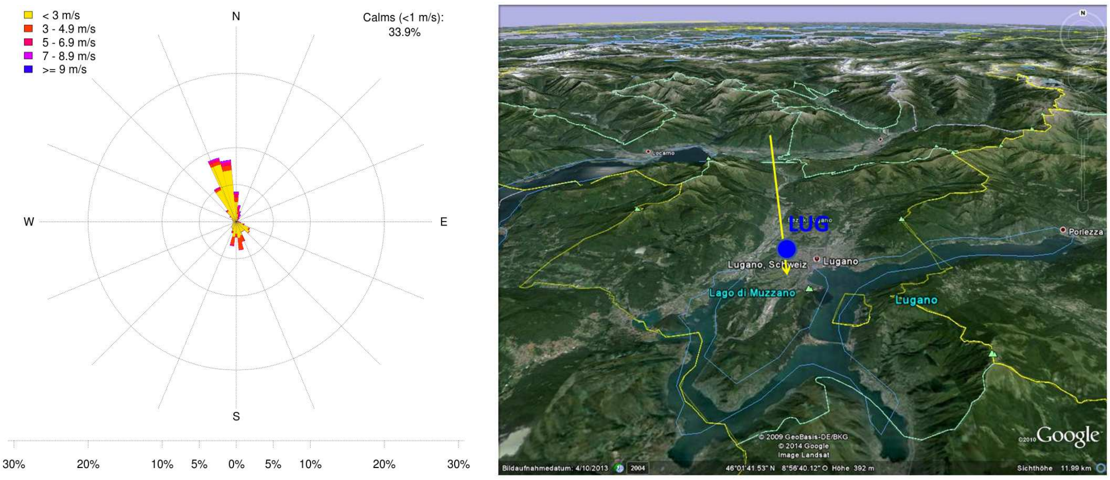
Station MAG is located in the Magadino Plain at the altitude of 203 masl. MAG is the perfect example for a station located in an east-to-west oriented valley. The north foehn can manifest itself in two situations: north foehn from the east and north foehn from the west. We therefore defined two sectors of origin of the wind and treated them as two different stations for the definition of the thresholds: station Magadino East (MAE) where DD = 0°-180°; station Magadino West (MAW) where DD = 180°-360°.

Station SBE is located near the San Bernardino Pass at the altitude of 1639 masl. Of all the stations that we used, this is located at the highest altitude. The sector of origin of the wind corresponds to DD = 250°-50°.



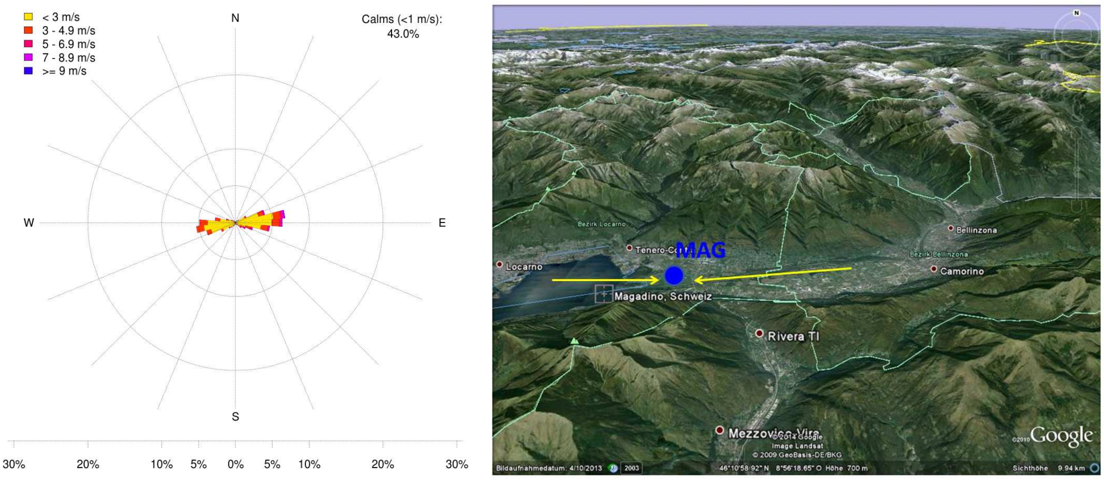
(a) Windrose Comprovasco **(b)** Map Comprovasco

Figure 4: Windrose and image from Google Earth for station Comprovasco. The windrose shows the direction of the wind considering the entire dataset (1993-2014). Blue dot: station; Yellow arrow: direction of the wind during north foehn.



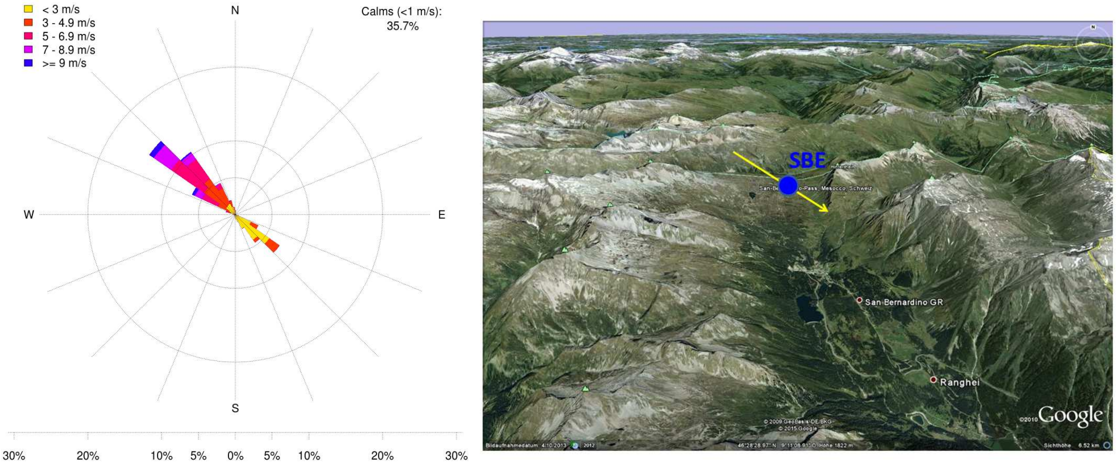
(a) Windrose Lugano **(b)** Map Lugano

Figure 5: Windrose and image from Google Earth for station Lugano. The windrose shows the direction of the wind considering the entire dataset (1993-2014). Blue dot: station; Yellow arrow: direction of the wind during north foehn.



(a) Windrose Magadino **(b)** Map Magadino

Figure 6: Windrose and image from Google Earth for station Magadino. The windrose shows the direction of the wind considering the entire dataset (1993-2014). Blue dot: station; Yellow arrow: direction of the wind during north foehn.



(a) Windrose San Bernardino **(b)** Map San Bernardino

Figure 7: Windrose and image from Google Earth for station San Bernardino. The windrose shows the direction of the wind considering the entire dataset (1993-2014). Blue dot: station; Yellow arrow: direction of the wind during north foehn.

3.3 Density plots and thresholds definition

The creation of density plots for selected variables is crucial for determining the thresholds that have to be overcome in order to speak of north foehn. The variables which are considered for defining the foehn index are FF, FFF, TPOTDIF and RH. First, to create the density plots we checked DDGUE and DD. Subsequently, two situations could be defined:

1. north wind at the Gütsch (DDGUE = [290°-89°]) and north wind at the stations
2. south wind at the Gütsch (DDGUE = [90°-289°]) and north wind at the stations.

The first situation consists in taking into account all cases with north wind at GUE. The resulting data should have a bimodal distribution, corresponding to the presence of north foehn and other types of wind, such as Alpine breezes. In this case, the threshold can be determined by calculating the minimum of the curve between the two maxima. In the second case, only situations that are surely not north foehn events were taken into account. To make sure that we did not consider north foehn cases, we used the set which only contained data with south wind at GUE. In addition, we applied the supplementary criteria of $dp\_alt < 1hPa$. In fact, the air pressure at the reference station ALT must not be higher than 1 hPa compared to the stations of the study region. To determine the thresholds when using the second strategy the marginal quantiles were used. For both situations we removed the cases where RH was higher that 90% which correspond to precipitation. Hereafter, density plots for FF, FFF, RH and TPOTDIFF, shown in figures 8-12, were created for each station and were used to determine the thresholds.

Figure 8 shows the density plots for station COM. For the parameters FF and FFF, since the bimodal distribution was not clearly visible, the thresholds were defined according to the 90-percentile of the blue curve. For RH and TPOTDIFF they were defined by calculating the minimum of the red curve.

Figure 9 shows the density plots for station LUG. Similarly to station COM, the thresholds for FF and FFF were defined according to the 90-percentile of the blue curve, while for RH and TPOTDIFF they were defined by calculating the minimum of the red curve.

As already explained, station MAG was divided into east (MAE) and west (MAW) according to the sector of origin of the wind during north foehn. Figure 10 shows the density plots for MAE. Also for this station, the red curve of FF and FFF did not have a clear bimodal distribution and the thresholds were defined using the 90-percentile of the blue curve. For RH we used the minimum of the red curve, while for TPOTDIFF we chose to use the 90-percentile of the blue curve, since the minimum was not so easily recognizable.

Figure 11 shows the density plots for MAW. The density plots of FF and FFF have the same trend as Magadino east (MAE). Hence, the thresholds have the same values. The red curves of FF and FFF did not have a clear bimodal distribution and consequently the thresholds were defined using the 90-percentile of the blue curve. For this station, the trend of the red curve in the RH graph is different, compared to the curves that we have seen so far. The peak at around 50% is not considered as foehn, but it probably represents valley breezes. Therefore, we set the threshold at the minimum located at around 30%.

Figure 12 shows the density plots for station SBE. For this station, the red graphs of FF and FFF showed a trend which reminded of a bimodal curve. However, to be consistent and have greater precision, we used the 90-percentile of the blue curve in this case too. For RH and TPOTDIFF the bimodal distribution was completely absent, hence the 90-percentile of the blue curve was used. Station SBE is located near the San Bernardino pass. Hence, the distance to the Alpine crest is small (about 5 km) and the fall of the flowing air, which is very important for downslope winds such as foehn, is only about 400 m. The adiabatic warming has not enough space and time to take place and the humidity remains high. In addition, some precipitations can be transported towards south by the wind. After some preliminary results, for all the reasons cited above, we decided to redo the foehn identification for station SBE, using the maximum of the red curve in figure 12 amounting to 70% as RH-threshold, which is more realistic. In fact, these types of stations are very sensible to the relative humidity which, if too low, considerably restricts the automatic identification of north foehn.

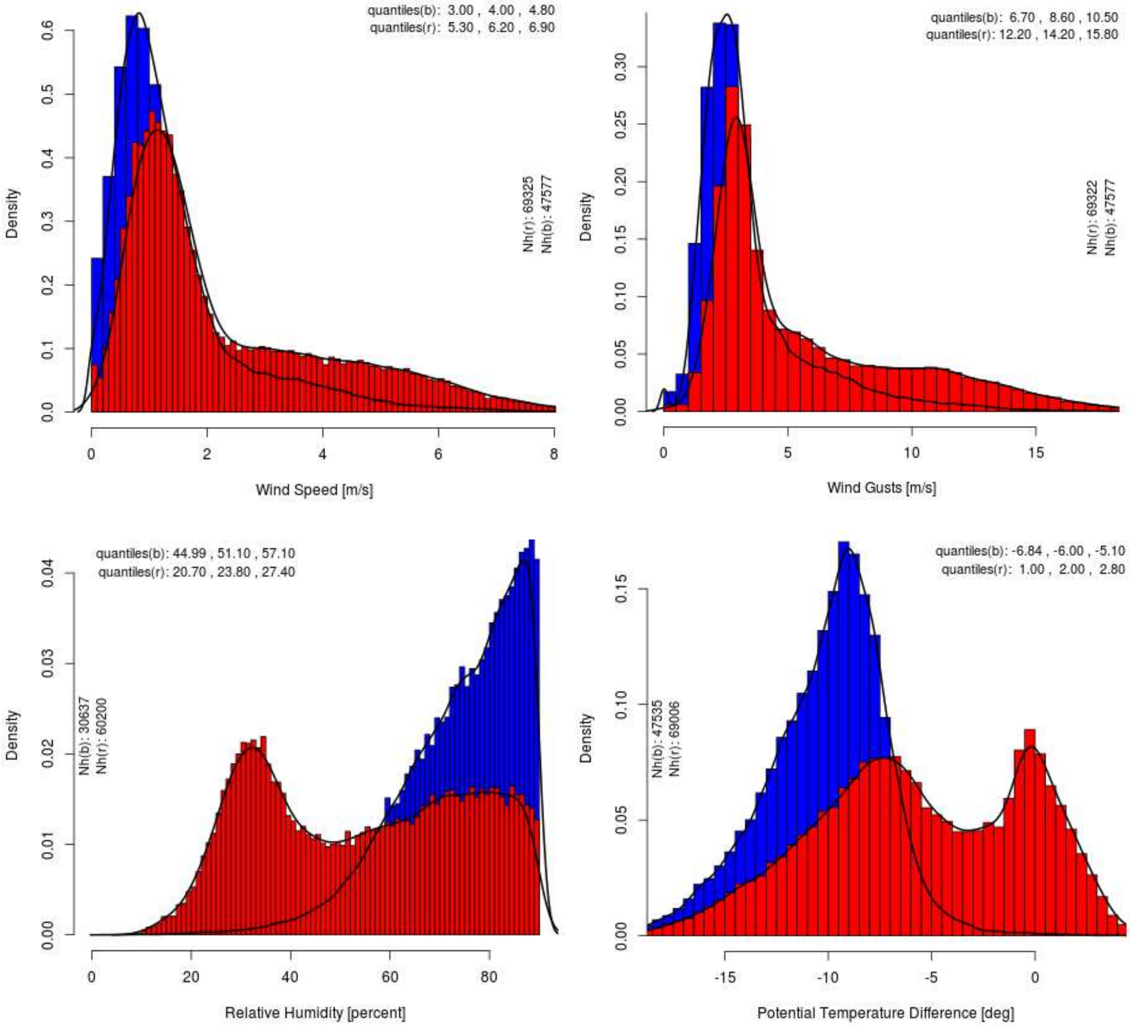


Figure 8: Density plots for station Comprovasco. Red curve: north wind at station and north wind at GUE; Blue curve: north wind at station and south wind at GUE; Nh(r): number of events with north wind at GUE; Nh(b): number of events with south wind at GUE. For wind speed, wind gusts and potential temperature difference quantiles(r) and quantiles (b) are equal to the 90-percentile, the 95-percentile and the 97.5-percentile. For relative humidity quantiles(r) and quantiles(b) are equal to the 2.5-percentile, the 5-percentile and the 10-percentile.

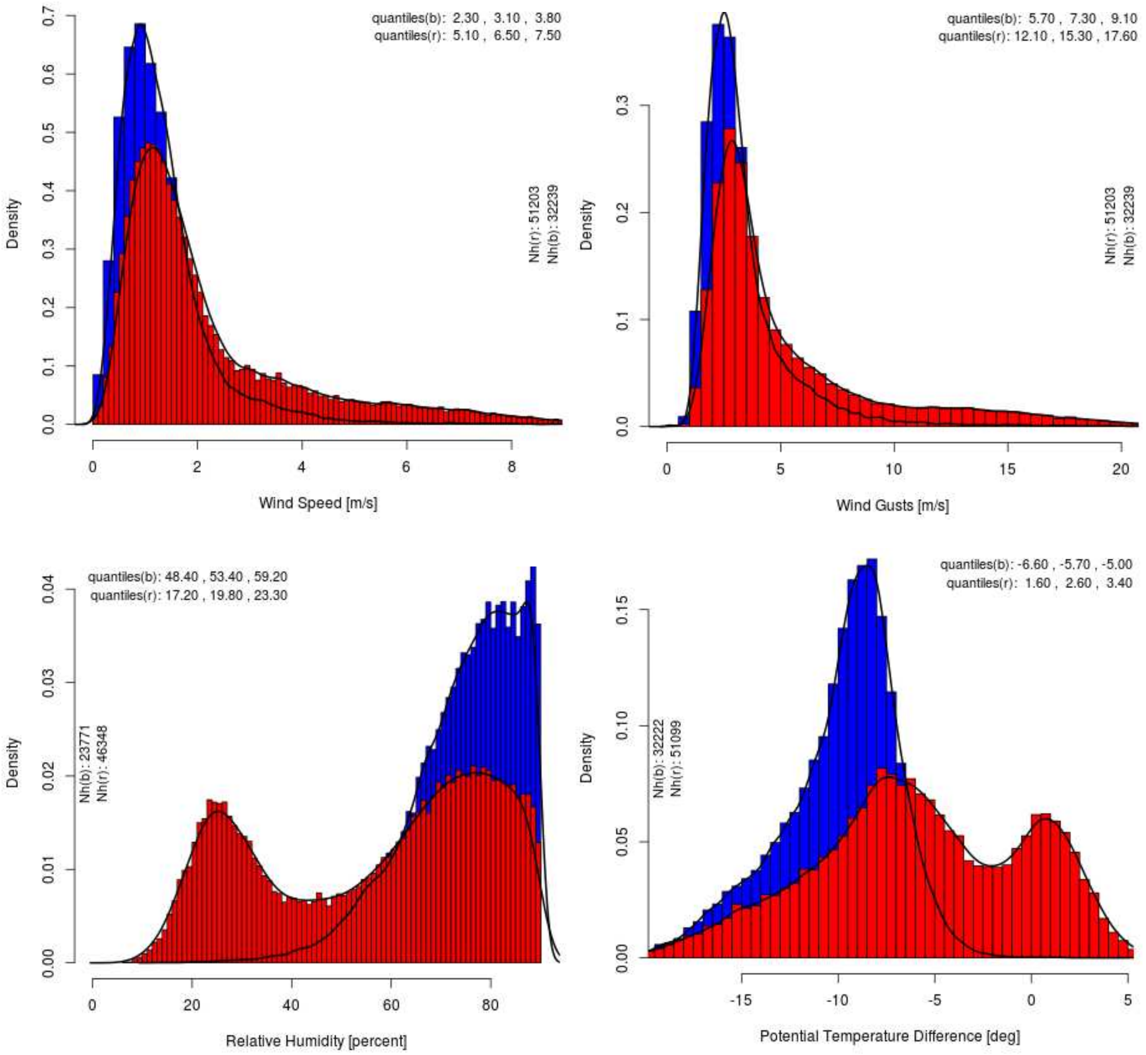


Figure 9: Density plots for station Lugano. Red curve: north wind at station and north wind at GUE; Blue curve: north wind at station and south wind at GUE; Nh(r): number of events with north wind at GUE; Nh(b): number of events with south wind at GUE. For wind speed, wind gusts and potential temperature difference quantiles(r) and quantiles (b) are equal to the 90-percentile, the 95-percentile and the 97.5-percentile. For relative humidity quantiles(r) and quantiles(b) are equal to the 2.5-percentile, the 5-percentile and the 10-percentile.

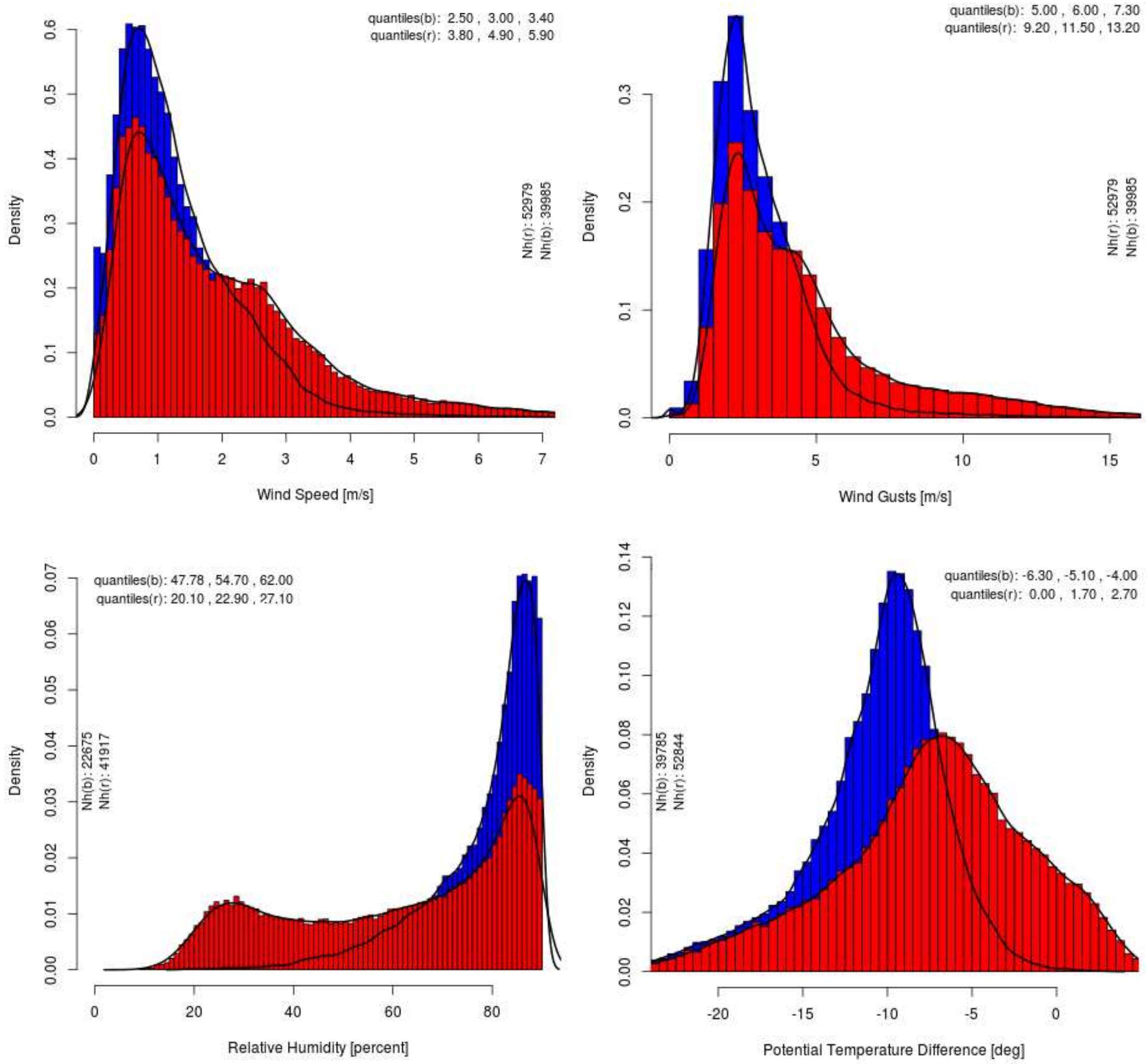


Figure 10: Density plots for station Magadino when the wind comes from the east sector. Red curve: north wind at station and north wind at GUE; Blue curve: north wind at station and south wind at GUE; Nh(r): number of events with north wind at GUE; Nh(b): number of events with south wind at GUE. For wind speed, wind gusts and potential temperature difference quantiles(r) and quantiles (b) are equal to the 90-percentile, the 95-percentile and the 97.5-percentile. For relative humidity quantiles(r) and quantiles(b) are equal to the 2.5-percentile, the 5-percentile and the 10-percentile.

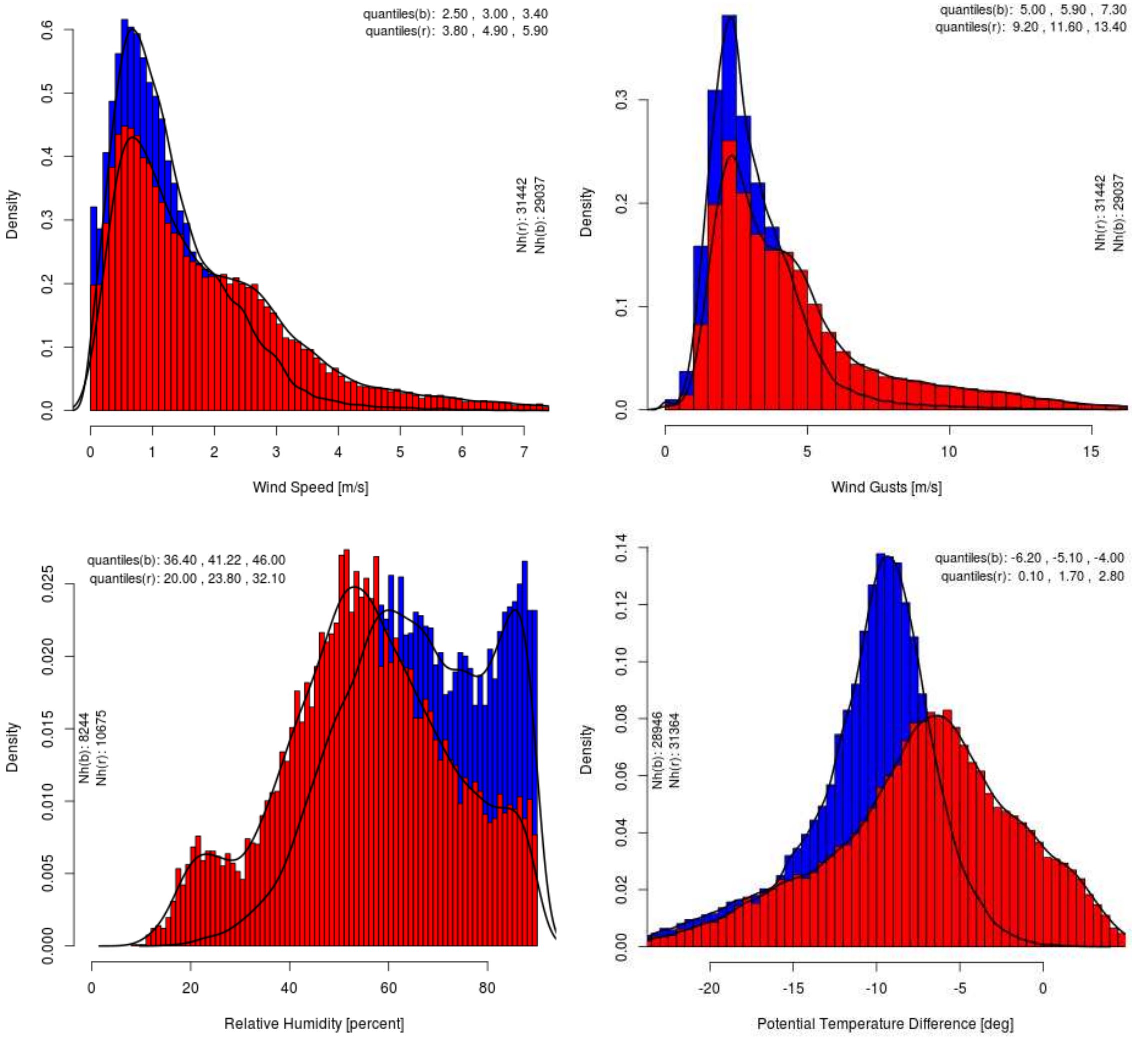


Figure 11: Density plots for station Magadino when the wind comes from the west sector. Red curve: north wind at station and north wind at GUE; Blue curve: north wind at station and south wind at GUE; Nh(r): number of events with north wind at GUE; Nh(b): number of events with south wind at GUE. For wind speed, wind gusts and potential temperature difference quantiles(r) and quantiles (b) are equal to the 90-percentile, the 95-percentile and the 97.5-percentile. For relative humidity quantiles(r) and quantiles(b) are equal to the 2.5-percentile, the 5-percentile and the 10-percentile.

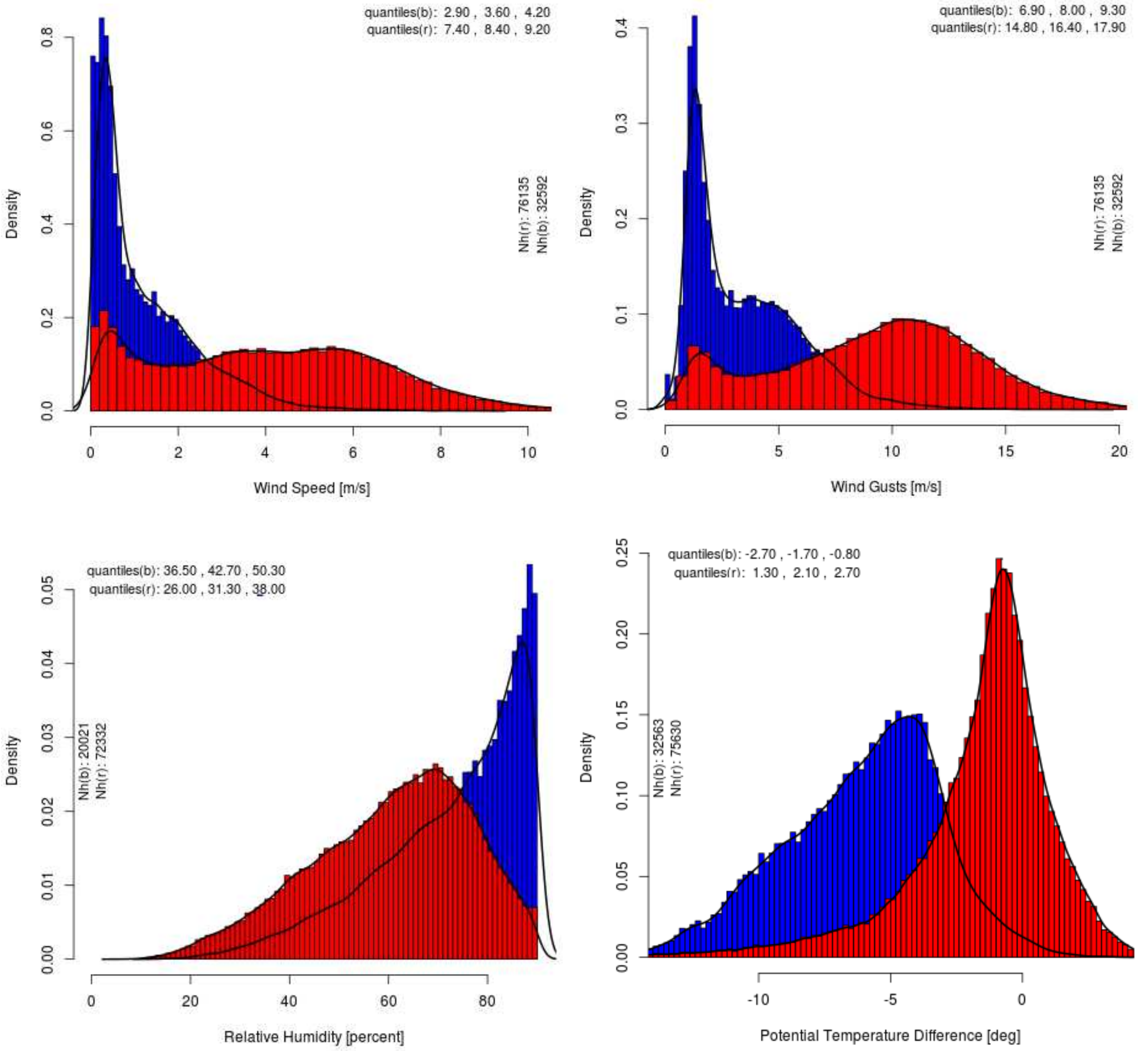


Figure 12: Density plots for station San Bernardino. Red curve: north wind at station and north wind at GUE; Blue curve: north wind at station and south wind at GUE; Nh(r): number of events with north wind at GUE; Nh(b): number of events with south wind at GUE. For wind speed, wind gusts and potential temperature difference quantiles(r) and quantiles (b) are equal to the 90-percentile, the 95-percentile and the 97.5-percentile. For relative humidity quantiles(r) and quantiles(b) are equal to the 2.5-percentile, the 5-percentile and the 10-percentile.

3.4 Foehn index definition

At this point, the thresholds for the parameters FF, FFF, RH, TPOTDIFF and DD for each station, which are shown in tables 2, as well as for DDGUE and FFGUE were available and the foehn index could be defined and applied for the automatic identification as follows:

- foehn start when DDGUE, FFGUE, FF or FFF, DD, TPOTDIFF and RH are satisfied (foehn index = 1)
- foehn continuation when both TPOTDIFF and RH are satisfied after foehn start (foehn index = 1)
- foehn end when TPOTDIFF or RH are no longer satisfied after foehn start (foehn index = 0).

The foehn index has a binary code: 1 for the presence of north foehn, 0 for the absence of north foehn. In addition, the selection method automatically fills interruptions lasting one hour by assigning the value 1 at the foehn index. As a consequence, we only have interruptions that are longer than one hour.
It was then necessary to give some definitions:

- foehn event corresponds to each hour where foehn index is equal to 1
- foehn case corresponds to a period of several foehn events, without interruptions.

This same distinction between foehn event and foehn case will also be used in chapter 4, in which the results of the climatology are discussed.
Differently from the method adopted by *Dürr* (2008), we did not differentiate between foehn trend and foehn event. However, we propose to define a fixed thresholds for FF, which can correspond to the minimum value of all FF thresholds, below which we define the phenomenon as foehn trend. Furthermore, it should be mentioned that all the obtained thresholds are strongly dependent on the chosen selection methodology. In order to evaluate this aspect a sensitivity study was performed and the results are discussed in chapter 5.
Figure 13 shows one of the ways in which the result of automatic identification of north foehn can be displayed. It is clearly visible that when the conditions for north foehn are satisfied, the system recognizes the north foehn event.

By applying the described method we were able to extract from the available data set all the north foehn events so that the climatology could be performed. The characterization of the north foehn was made with traditional statistical methods using the programming language R (*R Core Team*, 2013). After computing the foehn index and identifying the north foehn events, the following parameters were calculated and were used to create graphs which were essential for the north foehn characterization:

1. monthly frequency, which corresponds to the number of foehn events for each month, represented with boxplots
2. total frequency, which corresponds to the sum of foehn events, in comparison with the month and the hour of the day, used to investigate the diurnal cycle and seasonality of north foehn

3. foehn initiation and foehn end of each case, used to investigate the start, the stop and the duration of each case
4. monthly distributions of the wind speed and wind gusts, used to investigate the intensity of the north foehn events
5. distance of the stations from the Alpine crest, used to investigate the geographical distribution of the total frequency and the maximum duration of the north foehn events.

Table 2: Summary of the thresholds needed to derive the foehn index

Station	FF m/s [>]	FFF m/s [>]	RH % [<]	DD °[ ]	TPOTDIFF deg [>]
AGN	2.60	4.10	53.70	270-90	-4.80
BEL	1.54	3.62	49.16	360-90	-4.90
BIG	2.00	10.00	45.17	300-90	-1.84
BRU	0.50	2.00	57.08	270-360	-1.90
CAG	3.00	5.60	47.28	290-90	-2.35
CAM	1.30	2.57	53.11	260-360	-3.93
CAR	1.30	2.57	49.27	270-50	-2.52
CAS	1.11	3.06	41.60	300-90	-3.22
CBM	1.94	3.89	66.00	300-80	-3.74
CEV	2.50	5.30	44.48	290-90	-2.25
CHI	1.20	3.40	51.42	260-360	-3.90
COL	2.60	4.97	38.61	360-100	-1.08
COM	3.00	6.70	48.58	270-60	-3.24
CRE	1.11	3.89	57.02	270-50	-4.78
CRO	1.20	3.10	55.89	270-60	-3.09
DAN	0.70	1.90	60.06	280-340	-2.95
DOG	1.90	3.50	43.83	330-100	-5.10
GRO	2.10	5.00	46.16	270-90	-2.29
LEC	4.40	6.40	46.06	340-60	-2.94
LOP	0.56	2.22	51.37	30-100	-1.58
LUD	0.40	1.80	50.65	330-30	-1.78
LUG	2.30	5.70	43.22	270-70	-2.30
MAE	2.50	5.00	48.50	0-180	-6.30
MAW	2.50	5.00	28.33	180-360	-6.20
MER	1.10	3.10	53.57	260-330	-2.16
MEZ	1.60	2.70	57.56	270-350	-3.34
MOL	2.20	4.90	52.68	250-70	-4.18
OTE	2.20	5.90	38.79	80-180	-0.83
OTW	2.30	6.30	27.91	200-300	-3.19
PIO	3.91	7.60	53.27	220-340	-4.70
POC	1.80	3.60	53.43	340-60	-1.24
ROB	2.20	5.50	53.21	320-130	-2.61
SBE	2.90	6.90	50.30	250-50	-2.70
SBO	1.70	4.90	48.16	310-140	-3.35
SOD	1.11	2.31	55.60	40-140	-4.80
SON	0.70	2.00	42.96	240-340	-1.85
VIL	1.70	3.70	50.40	290-60	-1.63
VIO	2.90	5.49	45.80	320-140	-2.75

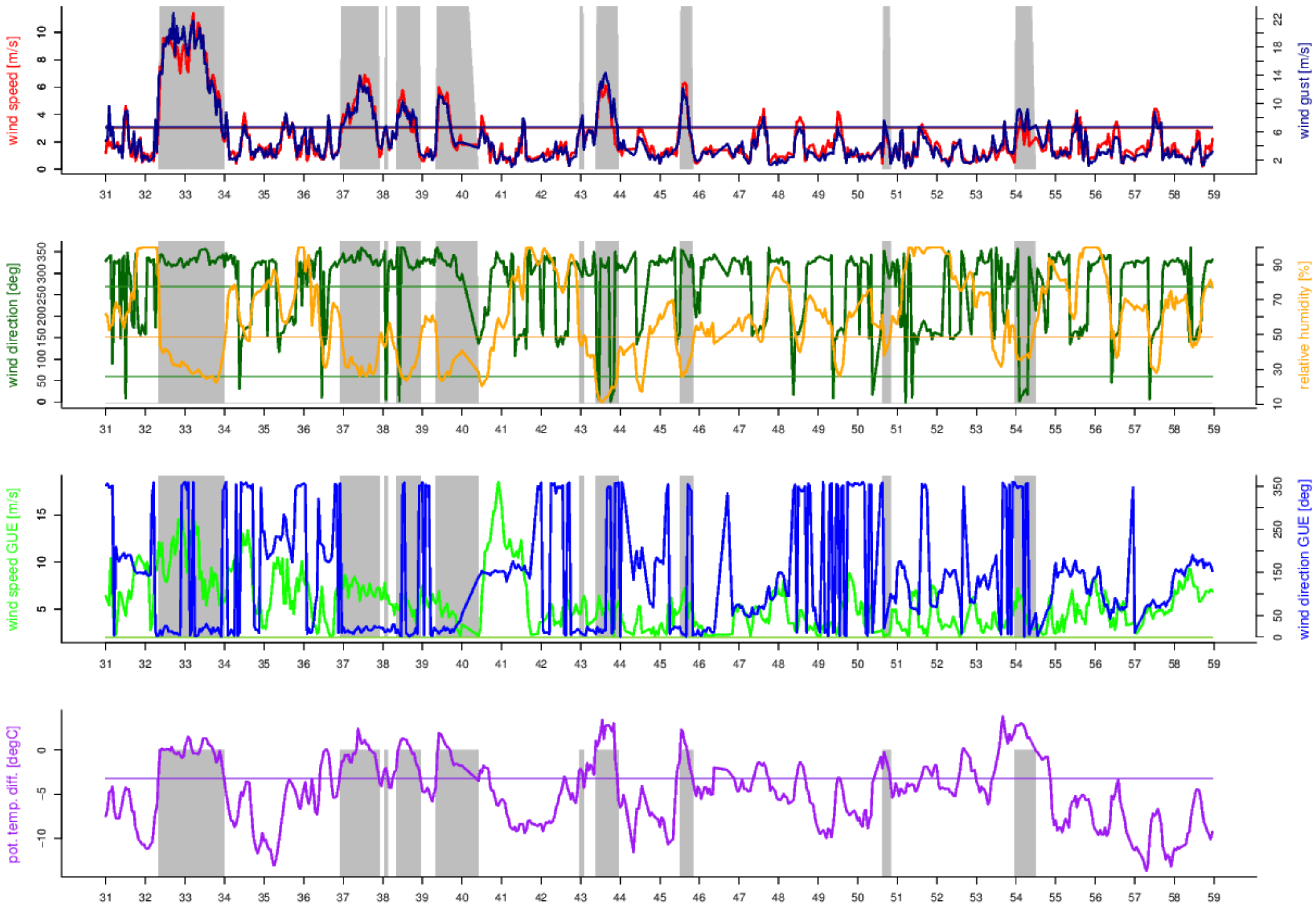


Figure 13: Example of results visualization for the automatic identification of the north foehn for station Comprovasco from the 1st to the 28th of February 2013. Coloured lines: parameters; Coloured horizontal lines: thresholds; Grey boxes: north foehn events (foehn index = 1).

4 Climatology

4.1 Hourly-based climatology

4.1.1 Temporal variability: seasonal and diurnal cycle

As already explained in the previous chapter, a foehn event corresponds to each hour where foehn index is equal to 1. Therefore, we can say that the hourly-based climatology is referred to the identified foehn events. The total frequency of north foehn was calculated for all 36 stations of the study region and the results are shown in table 3. Hereafter, only the results of the stations presented in chapter 3 are discussed.

Figure 14 shows, with boxplots, the distribution of the monthly frequency for some of the previously discussed stations. Generally, spring is the season which shows the highest number of north foehn events for all the stations. The monthly frequency of north foehn is relatively high during the summer months while the frequency of north foehn events is very low in autumn. In fact, during this season every station presents at least one month without any foehn events. For all the stations, March is the month that shows the highest monthly frequency. Among the three stations, COM has the highest mean value with 150 h in March. On the contrary, October is the month in which the frequency is the lowest with mean values between 20 h at LUG and 50 h at COM. If we look at the figure into more detail we see that April is the month with the largest variability, while October has the smallest variability. In addition, the absolute maximum lies at 300 h for COM in April. Also at station LUG, April is the month with the maximum value, while at station SBE March is prevailing as the month with maximum monthly frequency. We can therefore say that the phenomenon has a strong seasonality.

The intra-annual variability of north foehn is clearly visible in all diagrams of figure 14. In fact, all the stations display a peak in March, while in October the north foehn is almost absent. The lack of north foehn cases in autumn is probably caused by a too negative TPOTDIFF and hence, the threshold is only rarely overcome. The difference in potential temperature between GUE and each station is more negative when the air at the station has not the same origin as the air at GUE, as it might be the case of the valley breezes blowing in the region or the case of southern currents. The distributions of the monthly frequency for all the 36 stations of the study region are shown in appendix A.1.

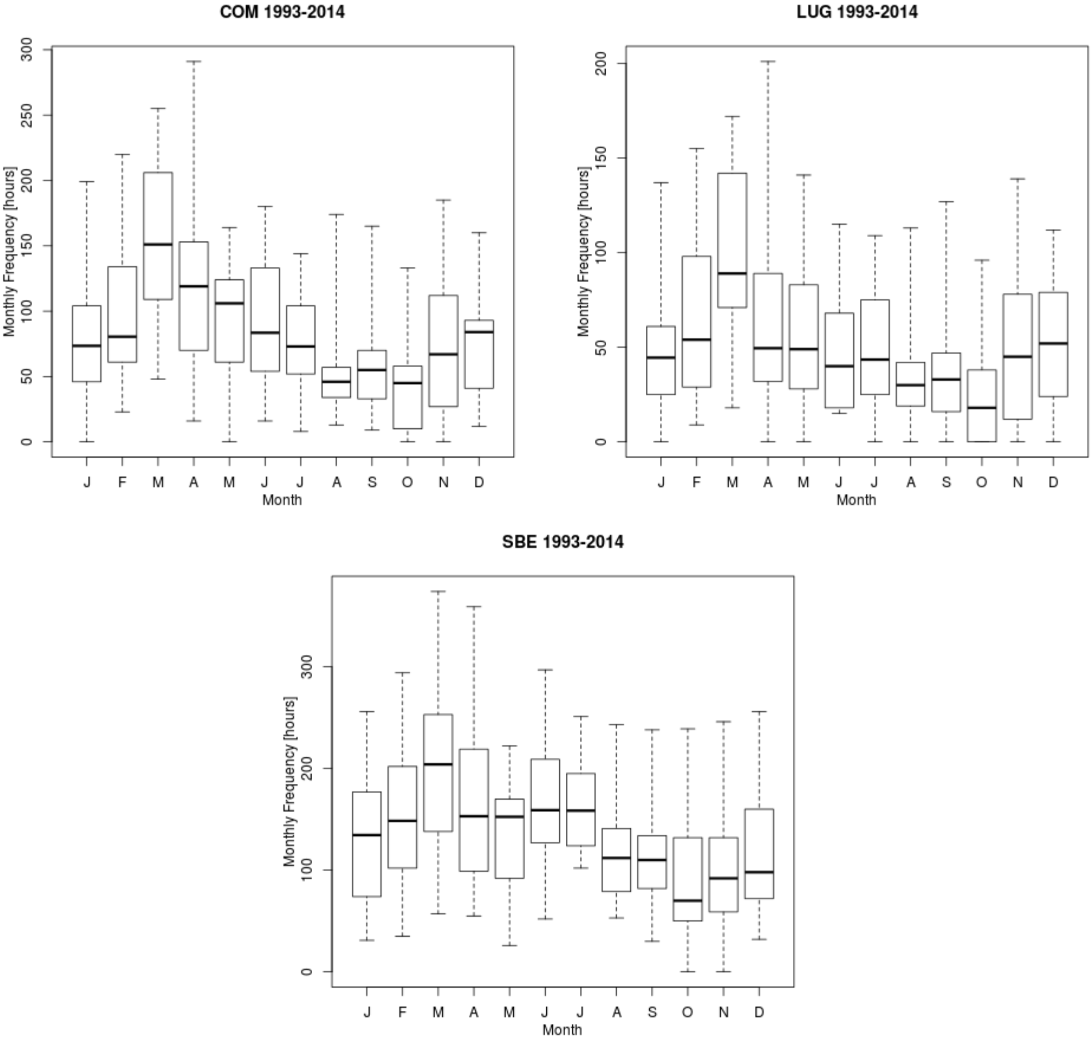


Figure 14: Distribution of the monthly frequency of north foehn for stations Comprovasco, Lugano and San Bernardino from 01.01.1993 to 31.08.2014.

Table 3: Total frequency for all the 36 stations of the study region considering the entire dataset

Abbreviation	Time span	Total frequency [h]
AGN	01.01.2009-31.08.2014	666
CEV	01.11.2013-31.08.2014	298
COM	01.01.1993-31.08.2014	1027
GRO	01.11.2012-31.08.2014	272
LUG	01.01.1993-31.08.2014	620
MAG	01.01.1993-31.08.2014	769
OTL	01.01.1993-31.08.2014	751
PIO	01.01.1993-31.08.2014	1292
ROB	01.01.1993-31.08.2014	1294
SBE	01.01.1993-31.08.2014	1629
SBO	01.01.1993-31.08.2014	578
VIO	01.01.1993-31.08.2014	504
BEL	03.10.2008-31.08.2014	683
BRU	30.05.2009-18.07.2014	676
CAM	19.06.2010-19.07.2014	467
CAR	01.01.2009-19.07.2014	468
CHI	01.01.2008-19.07.2014	1128
COL	29.04.2008-20.07.2014	265
CRO	03.08.2007-30.04.2014	363
DAN	01.07.2008-18.07.2014	869
DOG	22.05.2009-19.07.2014	167
LEC	18.03.2004-18.07.2014	345
LUD	11.01.2011-18.07.2014	554
MER	26.06.2009-19.07.2014	410
MEZ	10.08.2008-18.07.2014	765
POC	20.07.2009-19.07.2014	128
SOD	22.10.2011-20.07.2014	553
SON	16.06.2012-19.07.2014	347
VIL	09.02.2008-19.07.2014	418
BIG	25.04.2008-31.08.2014	585
CAS	05.04.2007-31.08.2014	812
CBM	31.10.2009-31.08.2014	1193
CRE	07.09.2008-31.08.2014	764
LOP	09.07.2009-31.08.2014	169
CAG	01.01.2004-31.08.2014	913
MOL	01.01.2004-31.08.2014	864

Figure 15 shows the distribution of the total frequency of north foehn events depending on the season and on the hour of the day, thanks to which seasonal and diurnal variation could be investigated. If we concentrate on the diurnal cycle we see that north foehn occurs mostly in the afternoon, with the frequency peak shifting a few hours back and forth, depending on the station. The earliest peak occurs at station SBE around 11am-1pm and the latest one at station LUG around 4-6pm.
The number of foehn events (frequency) varies between stations: Comprovasco has the highest frequency with values reaching almost 300 h; Lugano has a maximum of about 200 h; and SBE has a maximum of about 150 h of north foehn. It can be assumed that the time at which we see the peak in frequency is dependent on the distance from the Alpine ridge. In fact, SBE is the station located nearest to the crest, while LUG is situated further south. Unfortunately, this trend was not observed in all the analyzed stations and therefore, further analysis are needed in order to be able to confirm this theory.
The hourly distribution of foehn events has the same pattern for each month. The north foehn fades out during the day and the frequency dramatically decreases during the night. Hence, it is clear that in autumn, when the number of north foehn events is low, we can reach a total frequency of 0 h in the early hours of the day (2-8am). SBE features a substantial difference from the other stations by showing a second peak in July. For all these reasons, a clear diurnal cycle is recognizable.

If we now look at figure 16 the same general pattern described before is recognizable in the boxplots for station MAW and MAE. As already explained in chapter 3.2, stations MAW and MAE correspond to station MAG. However, since MAG is located in a valley with an east-to-west orientation, the north foehn can manifest itself in two situations: north foehn from the east (MAE) and north foehn from the west (MAW). For the comparison, we therefore treated MAE and MAW as two different stations according to the sector of origin of the wind. By comparing the two situations in Magadino we see that the period in which we have the highest number of north foehn events is again March. However, there is a strong difference in the values: the median for MAE amounts to 100 h and for MAW it amounts to 20 h. The maximum value amounts to 200 h for MAE, while MAW only has around 100 h of north foehn. The data for station MAW show that north foehn is almost absent in the autumn months.
If we look at the distribution of the total frequency for the two situations (figure 17) the first difference that we see is the values of the total frequency. MAW reaches a maximum of about 100 h, while MAE can reach values of about 160 h. MAW has a limited period in which north foehn can occur: between 8am and 9pm in spring, and between 11am and 6pm in autumn. Outside this period, no north foehn event was identified in Magadino when the wind was coming from the west. The last noteworthy difference is that MAW shows the maximum peak sooner in the afternoon (3-4pm).

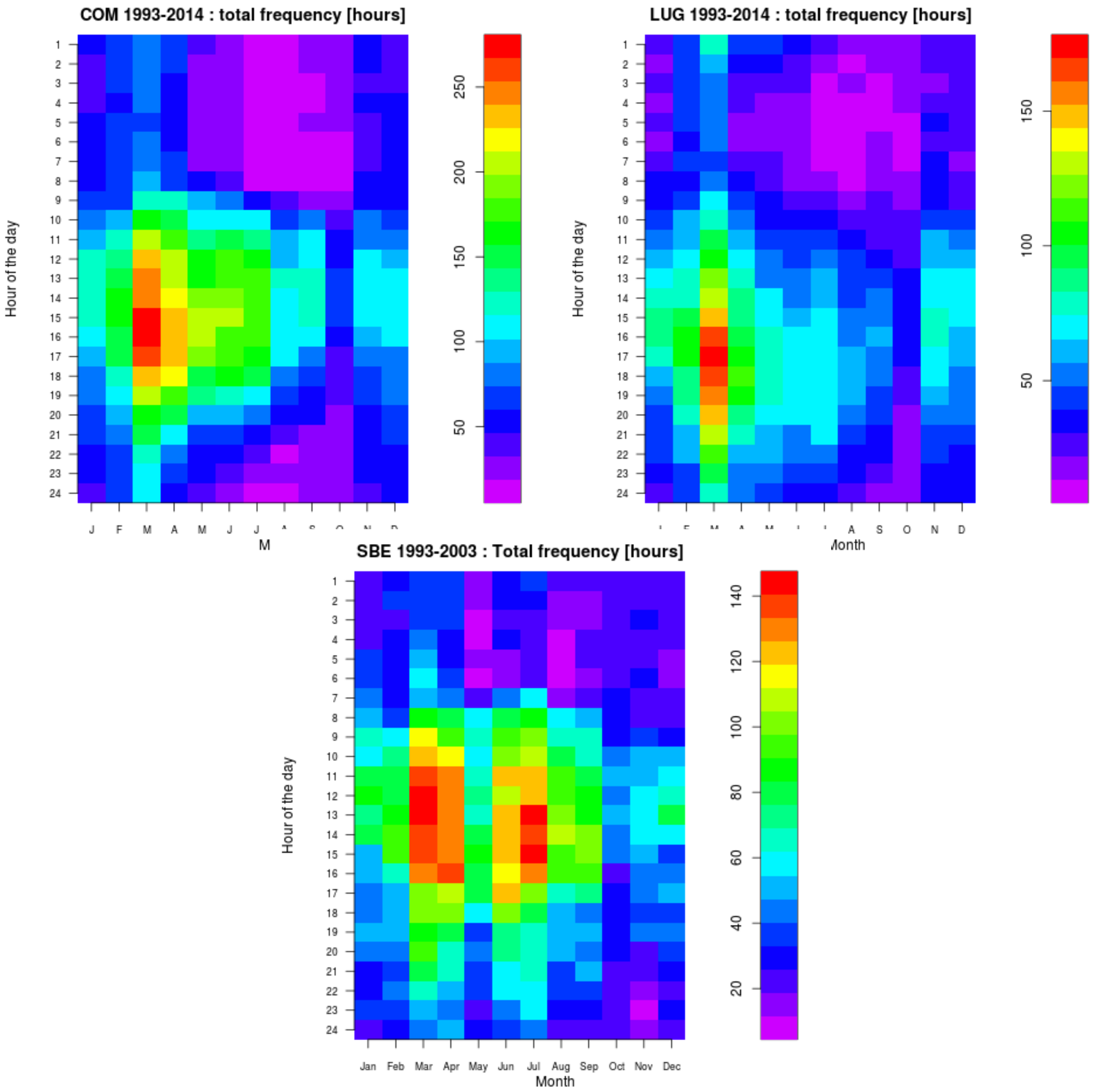


Figure 15: Distribution of the total frequency of north foehn for stations Comprovasco, Lugano and San Bernardino from 01.01.1993 to 31.08.2014. The distributions show the dependency of the total frequency of north foehn with the hour of the day and the months.

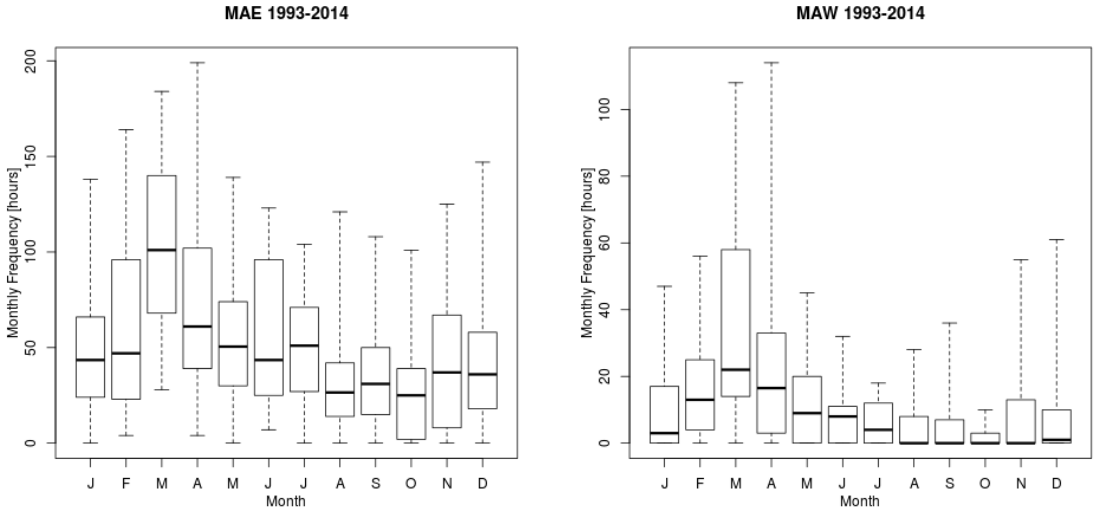


Figure 16: Comparison of the monthly frequency distribution of north foehn between station Magadino when the wind comes from the east sector (MAE) and when the wind comes from the west sector (MAW) considering the period from 01.01.1993 to 31.08.2014.

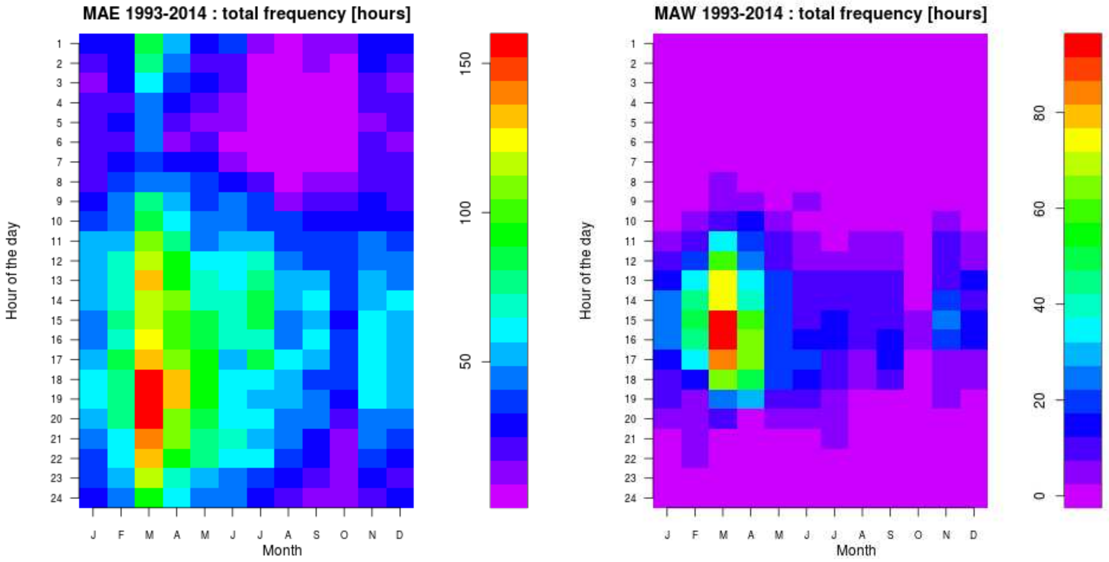


Figure 17: Comparison of the total frequency distribution of north foehn for station Magadino when the wind comes from the east sector (MAE) and when the wind comes from the west sector (MAW) considering the period from 01.01.1993 to 31.08.2014. The distributions show the dependency of the total frequency of north foehn with the hour of the day and the months.

4.1.2 Interannual variability of foehn events

Figure 18 illustrates the monthly frequency for each station from January 1993 to August 2014. At first glance, we do not see a general trend of the studied phenomenon. For station COM we see a slight decrease in the number of events but station MAG, on the contrary, shows a slight increase in the monthly frequency. It can therefore be concluded that the phenomenon in the last 20 years has remained fairly constant when considering the monthly frequency and a trend is not visible. If we focus on the interannual variability, we see that 1997 and 2001 were the years with the maximum peaks of events in March. At station COM, MAG and SBE the peak in 1997 is the most easily recognizable, while at stations LUG the peak in 2001 stands out. Both peaks occurred in the first 10 years of the data set. On the other hand, the last 10 years are rather constant and no extreme in the monthly frequency is visible. If we focus on the months of May of the last 20 years (figure 19) we clearly see an increase in frequency, with the only exception of the year 2008. May has become more important during the last 20 years and this is also visible in figure 20. If we consider the period from 1993 to 2003, March was undoubtedly the prevailing month. The period of maximum frequency was limited to the months of March and April, although we see a second green area of medium frequency in the months of June and July and a small peak in September. In the period between January 2004 and August 2014, we suddenly have two clear peaks (March and May) and the green area, which corresponds to about 80 h, expands homogeneously from January to July and from 10am to 7pm. This is the confirmation that the month of May and in general the spring period are gaining in strength. By checking each individual month of May from 2004 to 2014, we did not notice the predominance of a specific year in which the number of foehn events was considerably higher with respect to the other years. Therefore, the most logical conclusion is based on the fact that the number of foehn events has gradually increased during the last 20 years. A first hypothesis about the reason of this increase of foehn events in May is based on the number of events of north wind at Gütsch which could also have increased in the last 20 years. However, further analysis must be conducted. In appendix A.2, figures 37 and 38 show the comparison of the monthly frequency distributions for the other analyzed stations (LUG, SBE and MAG).

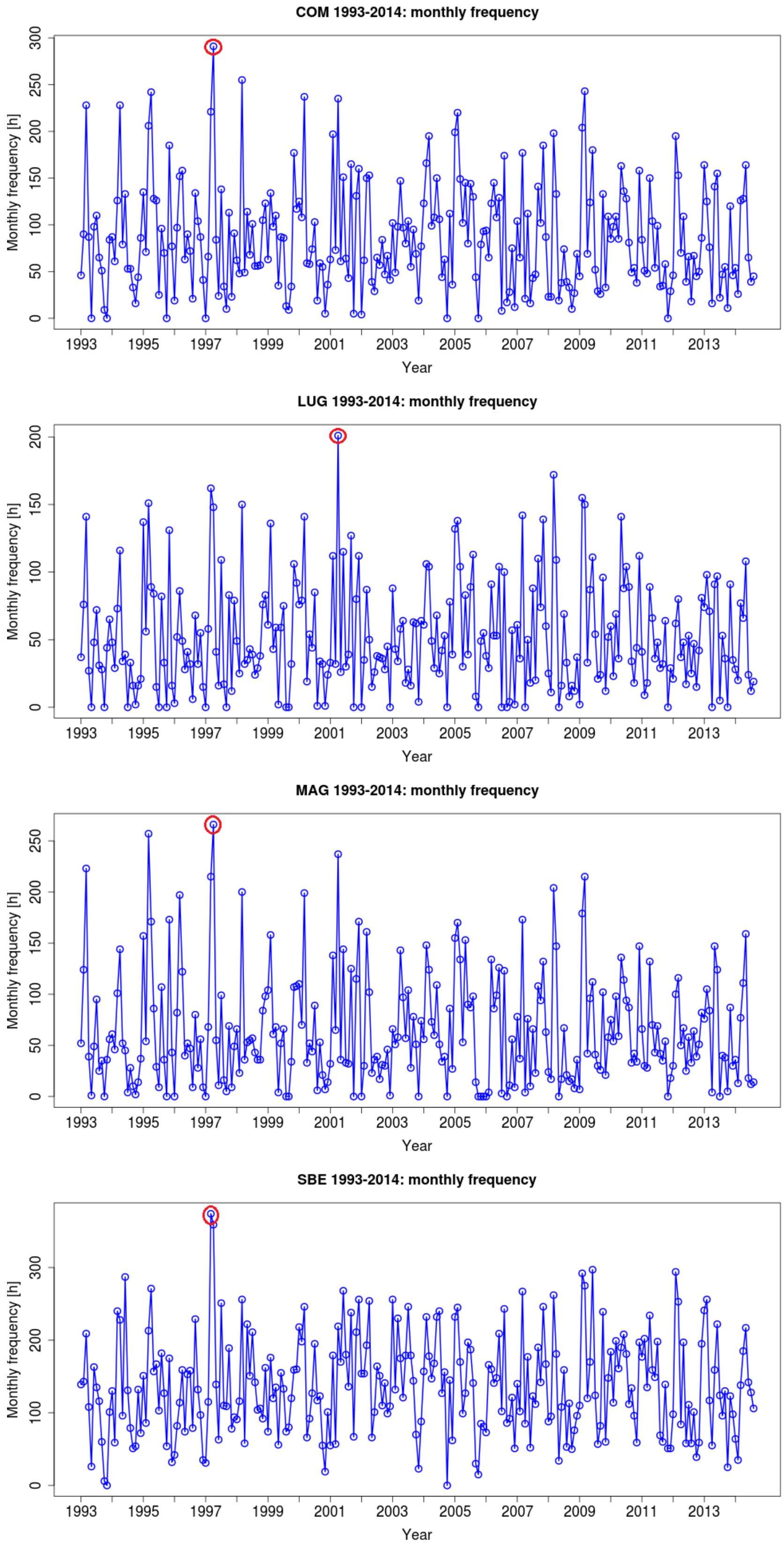


Figure 18: Monthly frequency for the stations Comprovasco, Lugano, Magadino and San Bernardino from 01.01.1993 to 31.08.2014.

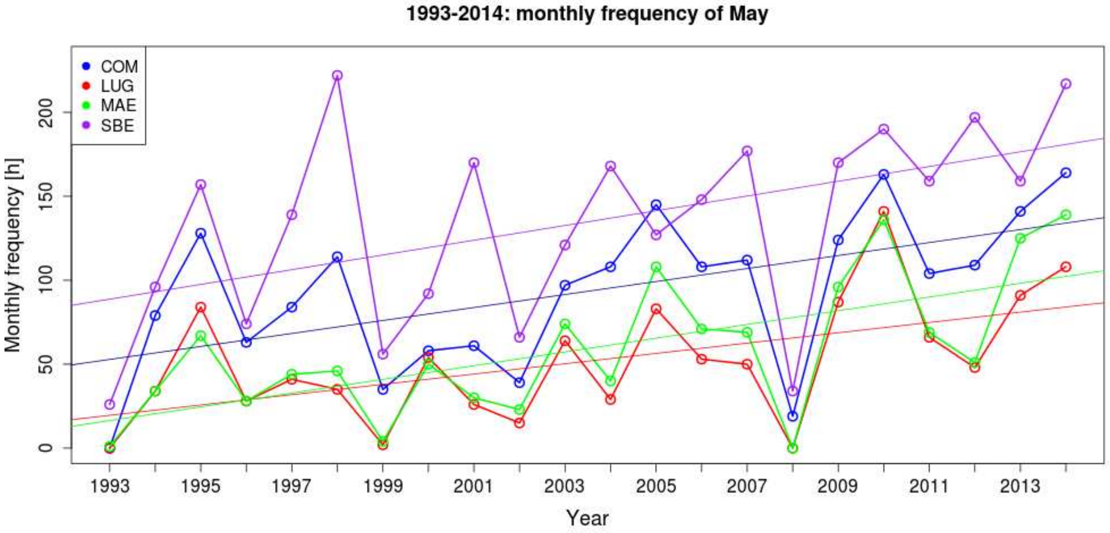


Figure 19: Monthly frequency of May for stations Comprovasco, Lugano, Magadino and San Bernardino for the period from 01.01.1993 to 31.08.2014.

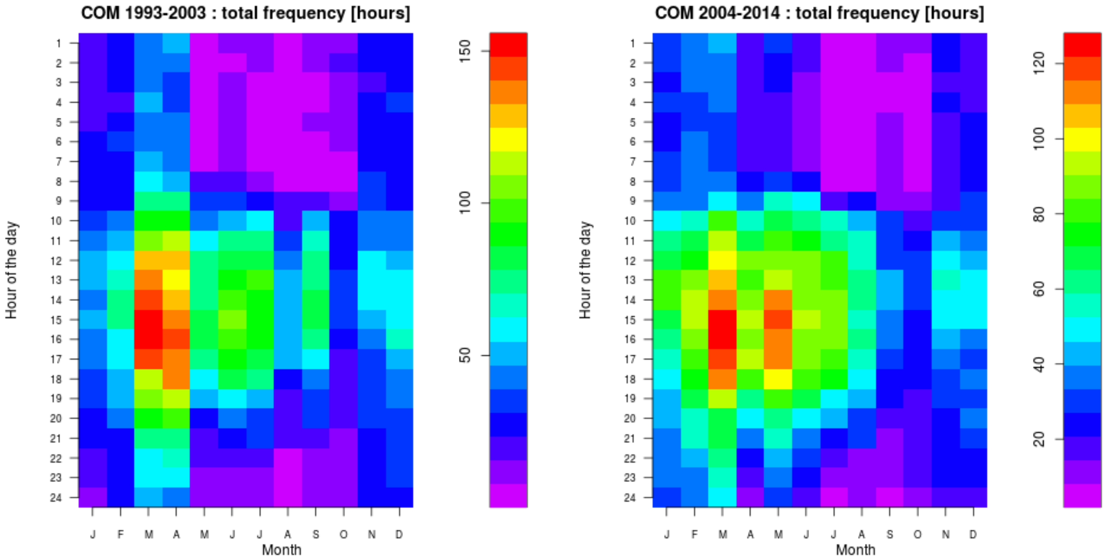


Figure 20: Monthly frequency for station Comprovasco. Comparison between the period 1993-2003 and 2004-2014 (year 2014 is not complete).

4.2 Case-based climatology

As explained in the previous chapter, north foehn cases are defined as periods of several foehn events without interruptions. Hence, a very interesting aspect to be analyzed is the duration of the various north foehn cases. The distribution of the duration of the north foehn cases was analyzed by looking at the density plot of the duration during the period from January 1993 to August 2014 (figure 21). The duration has a long tail distribution, which indicates that we have several shorter cases, while the long lasting cases are rare. The longest case for each station lasted 102 h in COM, 99 h in LUG and 111 h in SBE. The three curves have a very similar trend. In fact, the mean of the duration is exactly the same for COM and SBE (10 h), whereas the average duration is slightly longer for LUG (11 h). The

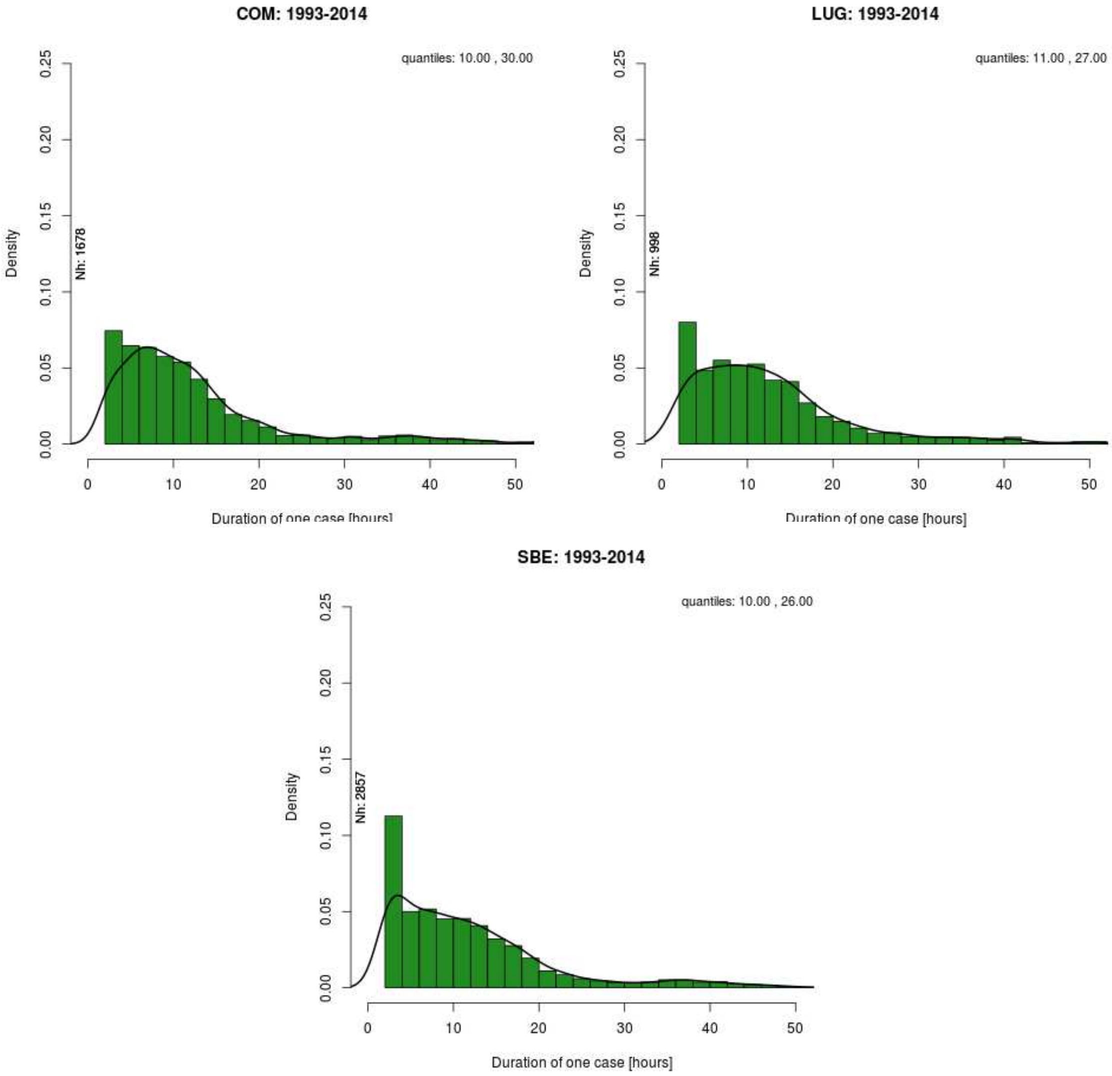


Figure 21: Distribution of foehn cases duration for stations Comprovasco, Lugano and San Bernardino considering the period from 01.01.1993 to 31.08.2014. Quantiles: 50-percentile, 90-percentile.

90-percentile of the duration is, on the other hand, higher for COM (30 h), while SBE has the smallest value amounting to 26 h.

By looking at figure 22, we can compare again the two situations in Magadino (MAE and MAW). It is visible that MAW has many short cases. On the contrary, the graph for station MAE is very similar to that of station SBE and they also have the same mean value (10 h). In table 4 the ten longest cases considering stations COM, LUG, MAE, MAW and SBE from 1993 to 2014 are listed. SBE and COM are the stations which have the highest number of long lasting cases in the list with respectively 5 and 4 cases among 10. This can be a further reason to think that stations located closer to the Alpine crest show long lasting cases.

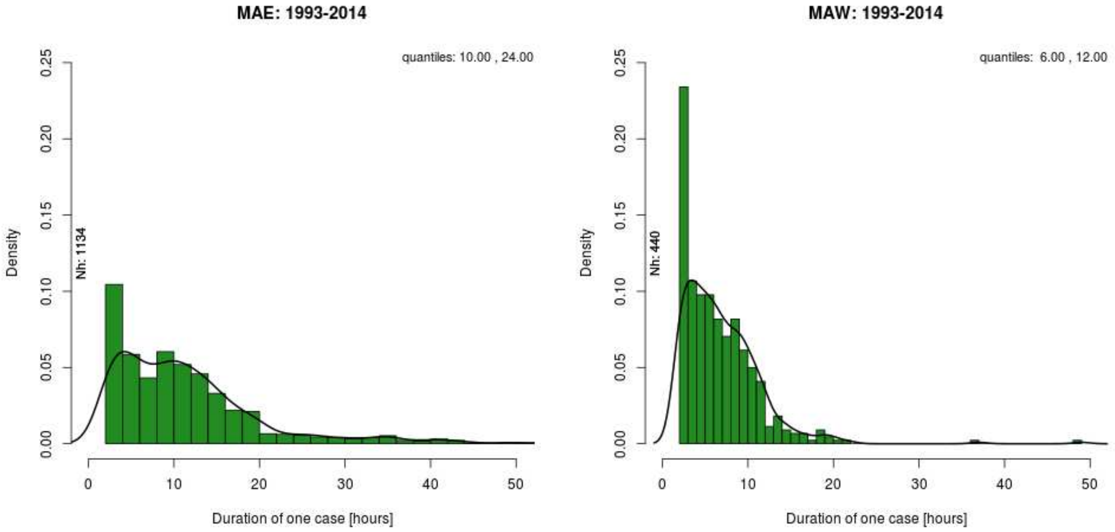
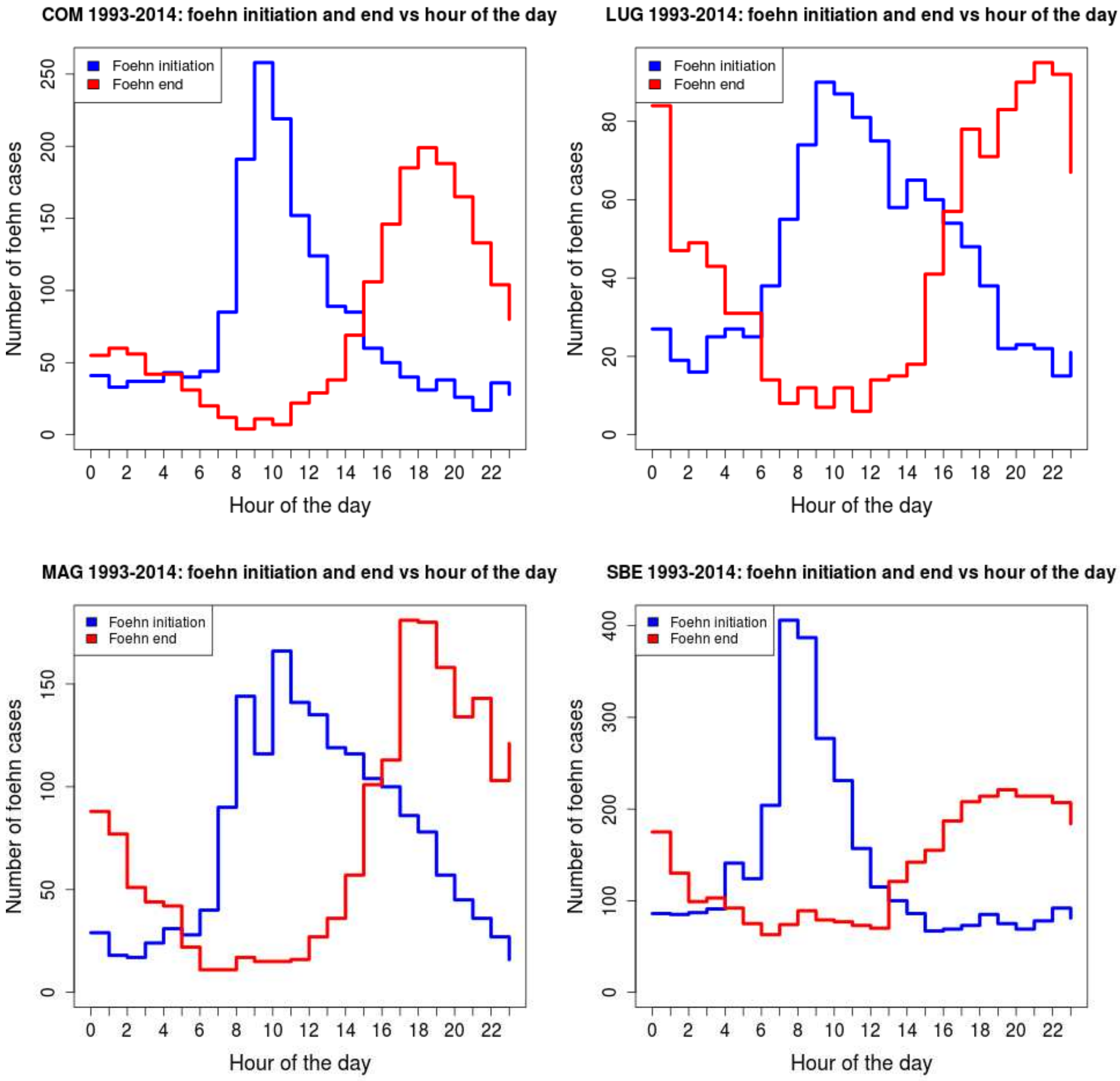


Figure 22: Comparison of the distribution of north foehn cases duration between station Magadino when the wind comes from the east sector (MAE) and when the wind comes from the west sector (MAW) considering the period from 01.01.1993 to 31.08.2014. Quantiles: 50-percentile, 90-percentile.

Table 4: The ten longest foehn cases from 01.01.1993 to 31.08.2014 considering stations Comprovasco, Lugano, Magadino with wind from east (MAE) and with wind from west (MAW) and San Bernardino

Station	Start date	End date	Duration [h]
SBE	13.05.2014 07:00	17.05.2014 21:00	111
SBE	13.02.2012 08:00	17.02.2012 14:00	103
COM	24.03.1993 19:00	29.03.1993 01:00	102
LUG	25.03.1993 00:00	29.03.1993 03:00	99
COM	06.11.1999 18:00	10.11.1999 16:00	95
SBE	13.02.2005 10:00	17.02.2005 08:00	95
SBE	19.02.2005 20:00	23.02.2005 18:00	95
COM	11.04.2001 00:00	14.04.2001 20:00	93
SBE	09.09.2001 06:00	12.09.2001 23:00	90
COM	13.05.2014 08:00	16.05.2014 23:00	88

Another important aspect to be discussed is the diurnal variation of foehn initiation and foehn end, represented in figure 23. In average, a north foehn case can start between 8am and 4pm, with the exception of station SBE where the foehn cases usually start between 6am and 11am. Initiation and stop of foehn cases have a relatively good anticorrelation which indicates that north foehn cases typically stop between 4pm and 4am. The maximum of foehn initiation lies for stations COM and LUG at 9am, while at MAG the highest number of foehn cases start at 10am. In addition, at SBE the highest number of foehn cases start at 7am. On the other hand, the soonest maximum amount of foehn ends occurs at MAG at 5pm while the latest in the afternoon at LUG at 9pm. The maximum of foehn end at COM and SBE lie in the middle respectively at 6pm and 7pm.


COM 1993-2014: foehn initiation and end vs hour of the day

LUG 1993-2014: foehn initiation and end vs hour of the day

MAG 1993-2014: foehn initiation and end vs hour of the day

SBE 1993-2014: foehn initiation and end vs hour of the day

Figure 23: Number of initiations and number of ends of foehn cases which occurred in the period from 01.01.1993 to 31.08.2014 for stations Comprovasco, Lugano, Magadino and San Bernardino.

4.2.1 Interannual variability of foehn cases

Figure 24 illustrates the annual number of north foehn cases from January 1993 to August 2014 for each station. It may seem that the annual number of foehn cases is decreasing in the last 20 years, but in reality, it is very heterogeneous and there is no clear correlation between the stations. There is however a large variation among years with the largest number of cases, for example 2004 for COM, 2009 for LUG, 1995 for MAE and 2007 for SBE. Anyhow, neglecting year 2014 which is not complete, 2011 was a year with the fewest north foehn cases for three out of the four stations. In conclusion, a trend in the last 20 years is not recognizable but the number of north foehn cases varies significantly from year to year.

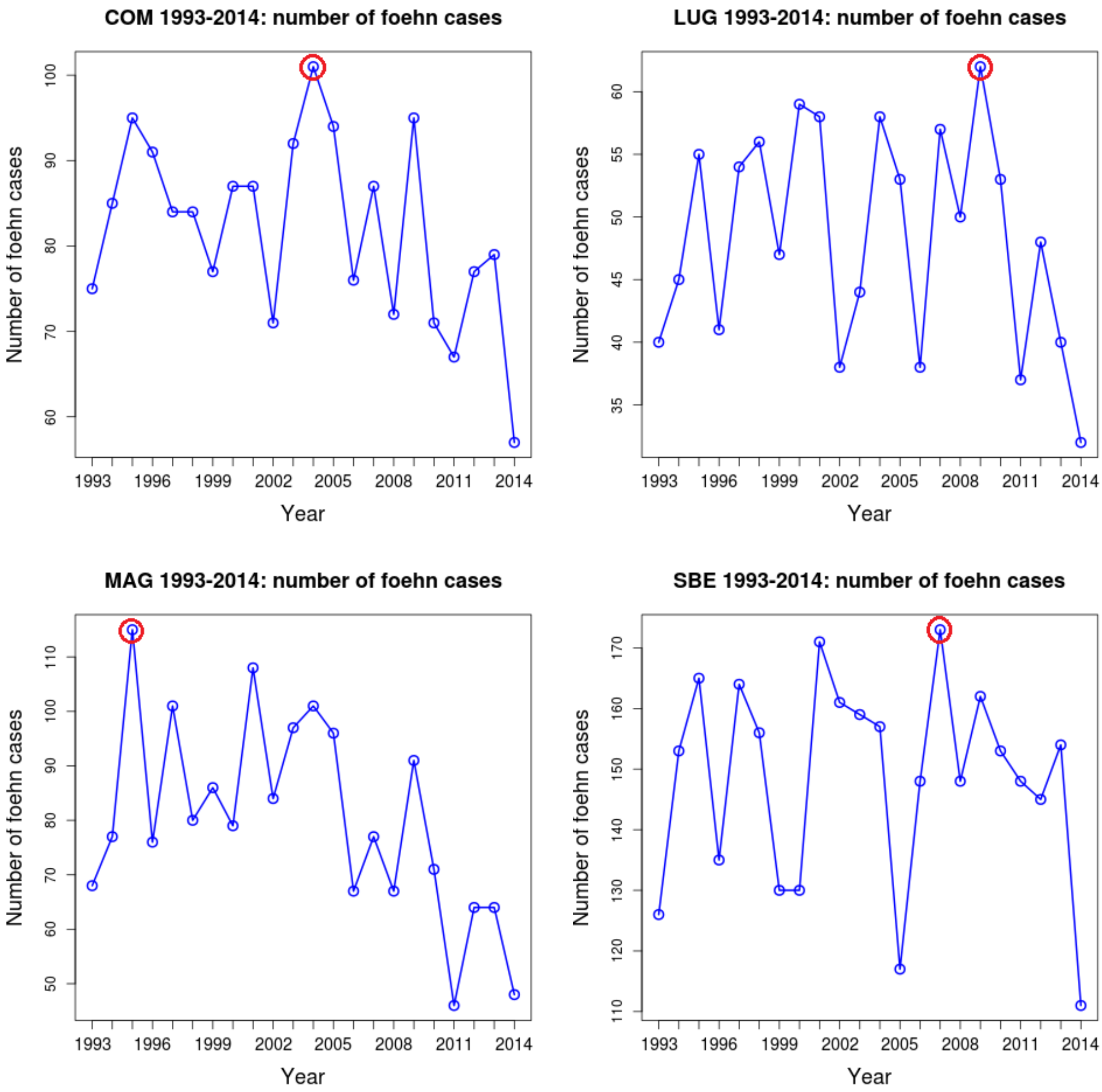


Figure 24: Number of north foehn cases for stations Comprovasco, Lugano, Magadino and San Bernardino from 01.01.1993 to 31.08.2014.

4.3 Intensity of foehn events

In this section, some aspects about wind speed and wind gusts are discussed. If we look at the boxplot for FF and FFF (figure 25) we do not see a seasonality. There is no clear seasonal cycle which means that a strong north foehn event can occur in summer as well as in winter or in any other season. This particular pattern is visible in all stations. In addition, the boxplots generally have a large scatter. The largest spread is found in September with a wind velocity that varies between 0 and 14 m/s and wind gusts that vary between 0 and 28 m/s. Remarkable are the wind gust values which are very similar in variation and scatter to the wind speed. The only difference lies in the values which are about twice as high. As it can be seen in figures 39 and 40 in appendix A.3, the discussed features about the intensity are recognizable for all the discussed stations (LUG, SBE and MAG). In table 5, the strongest case for each station singly from 1993 to 2014 is listed. The strongest case happened at SBE from the 15th until the 17th of February 2005. The case lasted 94 hours and in this time frame the hourly mean wind velocity of 14.5 m/s was reached. On the other hand, the strongest wind gusts were reached at station LUG between the 8th and the 9th of April 1995 with a hourly mean value of 24.9 m/s.

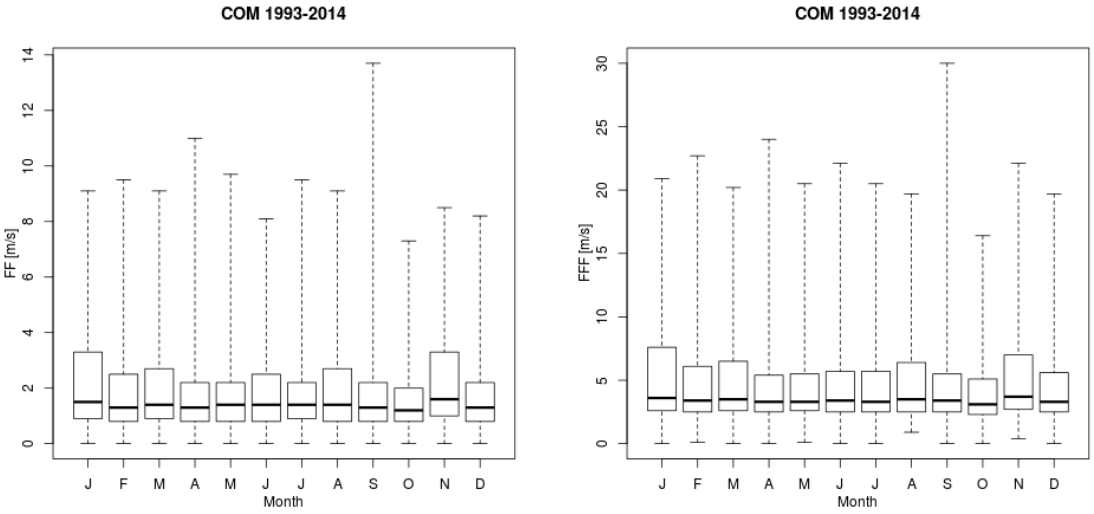


Figure 25: Distribution of wind speed (left) and wind gusts (right) for station Comprovasco for the period from 01.01.1993 to 31.08.2014.

Table 5: The strongest foehn case from 01.01.1993 to 31.08.2014 for each station. Wind velocity (FF) and wind gusts (FFF) correspond to the maximum hurly mean value reached at least once in the time frame of the foehn case.

[h!] height**Station**	**Start date**	**End date**	**FF [m/s]**	**FFF [m/s]**
COM	13.03.2013 20:00	15.03.2013 22:00	13.5	21.1
LUG	08.04.1995 03:00	09.04.1995 03:00	13.2	24.9
MAE	22.01.2008 18:00	23.01.2008 04:00	13.1	21.3
MAW	28.03.1997 15:00	28.03.1997 19:00	11.0	20.8
SBE	13.02.2005 10:00	17.02.2005 08:00	14.5	23.9

4.4 Geographical variability and comparison between stations

As it was already mentioned, the topography, the geographical position and the altitude of the station strongly influence the occurrence of north foehn. By looking at figure 26 we were able to investigate the geographical variation of the parameters FF, FFF, monthly frequency and maximum duration of north foehn considering the period from the January 1993 to August 2014. If we look at the maps in detail, we see that the wind gusts have the same spatial distribution as the wind speed but with higher values, which is consistent with what it can be seen in figure 25. Station PIO is the only exception. However, it is known that Piotta is a very difficult station to be analized because of its small distance to the Alpine ridge and the east-to-west orientation of the valley, which prevents the wind gusts from reaching high velocity.

COM, LUG and SBO are aligned in a north-to-south axis. We see that FF and FFF have higher valuest at station LUG. This is due to the fact that the air flow has the time and the space to intensify itself. Stations OTL and MAG are located in the Magadino Plain which has an east-to-west orientation; hence, the flowing air can penetrate into the valley with difficulty and this results into lower velocities which decrease with increasing distance covered by the air. As general pattern, all the four parameters are more intense near the Alpine crest and where the valley has a north-to-south orientation. These two factors are those that most influence the duration and the frequency of foehn. This aspect was further investigated by looking at figure 27. The comparison between the total frequency of foehn events and the maximum duration of foehn cases with the altitude and the distance from the Alpine ridge of the station is crucial in order to better understand the variation of the phenomenon between the stations. Figure 27 shows on the left the dependency of the maxmum duration and the total frequency with the altitude of the stations. A positive correlation is clearly visible: the higher the station, the longer the north foehn cases and the higher the frequency of the events. On the other hand, the images on the right show that with increasing distance from the Alpine ridge the duration and the frequency of north foehn cases decreases. We can conclude that stations located near the Alpine ridge at a higher altitude are more inclined to frequent and long lasting north foehn cases. On the contrary, a smaller number of north foehn events and shorter north foehn cases can be detected at stations located further south and at a lower altitude.

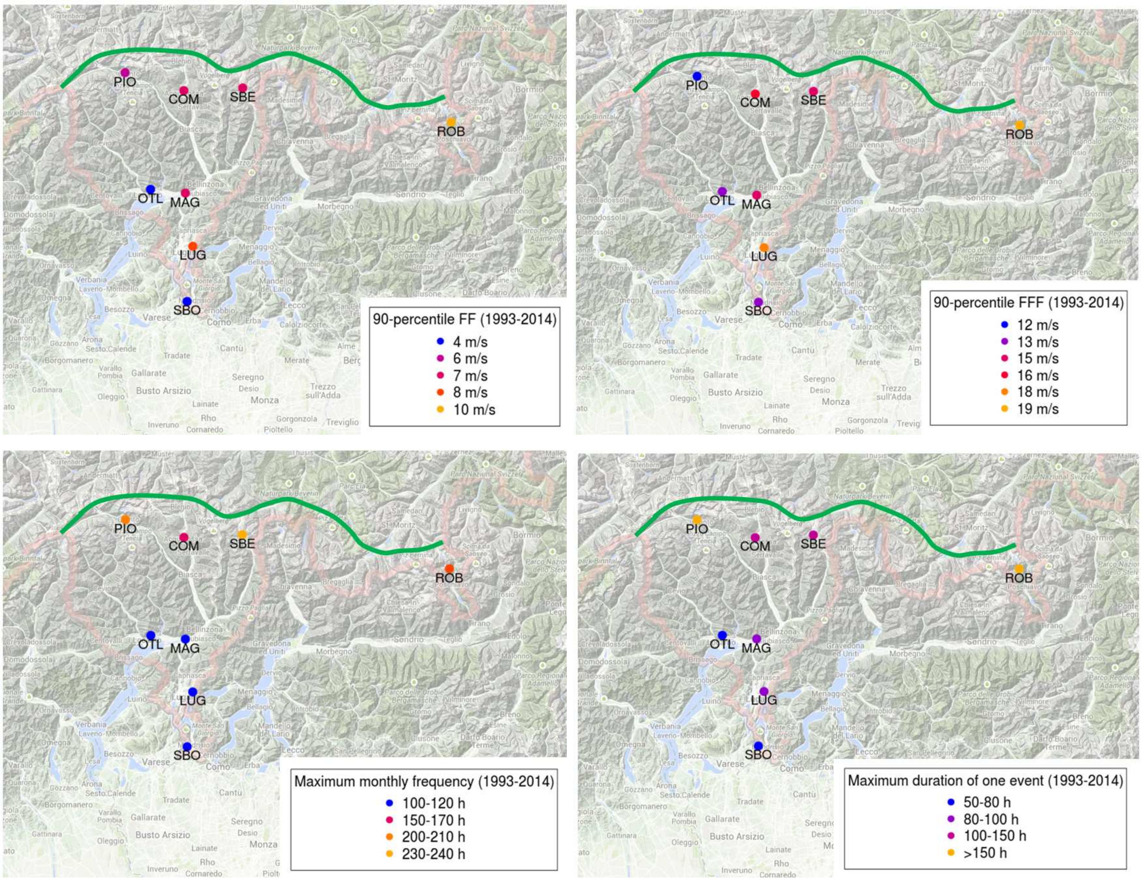


Figure 26: Geographical distribution of wind speed, wind gusts, maximum monthly frequency and maximum duration of north foehn. Green line: approximative Alpine ridge

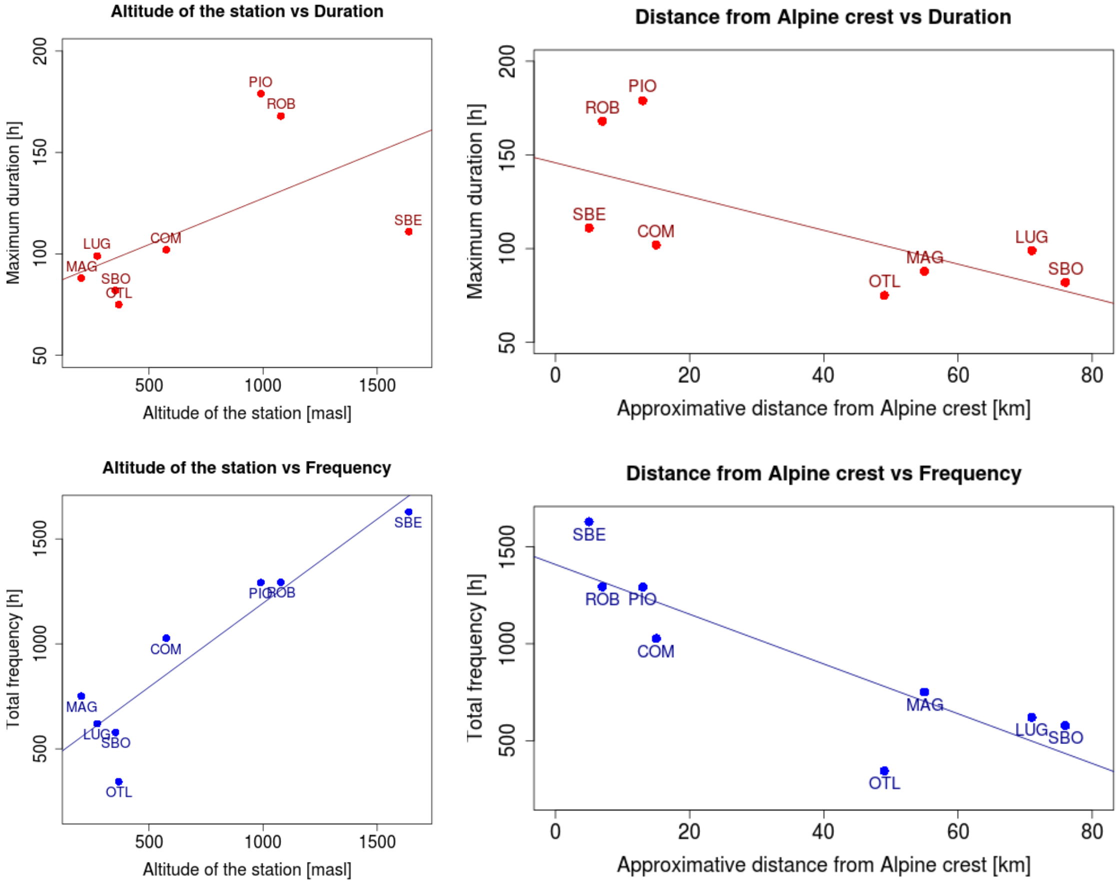


Figure 27: Dependency of total frequency and maximum duration of north foehn with altitude and distance from the Alpine ridge of various stations of the SwissMetNet from 01.01.1993 to 31.08.2014. The distance from the Alpine crest was determined by defining some points on the Alpine crest and calculating the distance between the coordinates of the stations and the coordinates of the reference points, then the minimum distance was used.

4.4.1 Category assignment to all the stations of the study region

The last step of the climatology was to assign a category to all the analyzed stations in the study region. In order to do so, we compared the distributions of the total frequency of all the stations with the reference stations (COM, LUG and MAG). We focused on the seasonal and diurnal cycle and we then assigned a category by finding the most similar distribution with regard of the hour of the day and month were we have the maximum peak. Hence, we were able to assign the stations that were not discussed in this report to the following categories, also visible in figure 28:

- stations resembling COM: BIG, CAG, CAS, CBM, CRE, GRO*, MOL, PIO, ROB, SBE, SBO, VIO*
- stations resembling LUG: AGN*, BEL, CAR, CHI, COL, CRO, DAN, LEC, LOP, LUD*, MEZ, POC, SOD*, VIL
- stations resembling MAG: OTL
- stations without category: BRU*, CAM*, CEV*, DOG*, MER*, SON*.

The stations without category do not show a clear pattern in the distribution and therefore, it was impossible to find similarities with the reference. In addition, it should be mentioned that for some stations (marked with *) the data set was shorter that 5 years and, although some similarities could be visible, the classification was not simple and can contain inaccuracies.

A cross check between stations located nearby was performed by looking at the identification of north foehn events (e.g. figure 13) for some randomly chosen months. The result of the cross check clearly indicates that nearby stations show the same pattern. The same foehn events were identified with only slight differences in duration, initiation or end of the foehn case.

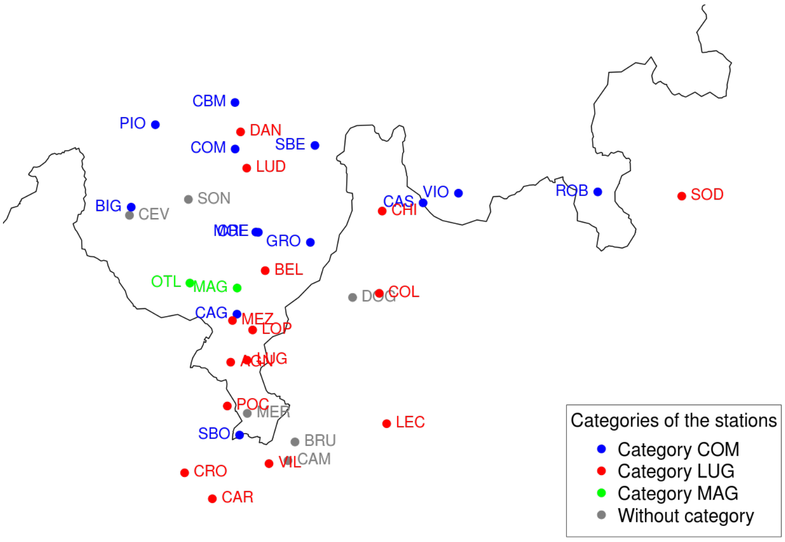


Figure 28: Categories assigned to all the analized stations by comparing the distributions of the total frequency with the reference stations.

5 Quality of the results

The automatic identification of north foehn is based on the definition of the foehn index specific for each station. It was already mentioned that the definition of foehn event and the definition of foehn index can be problematic and depends on the choice of the scientist (section 2.2.2). As a consequence, it can happen that a few falsely classified foehn events influenced the results, but this influence is not expected to be significant. Furthermore, other events may not have been identified.

The time interval of foehn duration was fixed at 1 hour, since we worked with hourly values. It is obvious that shorter events were not taken into account and, therefore, some information was lost.

If we take figure 29 as an example, some difficulties in the identification of north foehn can be seen. The timing of foehn initiation is not perfect and there can be a shift (day 54 in the figure). This is caused by the quite restrictive condition that all the parameters have to be overcome for foehn start. The end of the event on the contrary is only dependent on the relative humidity and on the difference in potential temperature and therefore, it is less constricting. In addition, at day 38 and 43, a short event

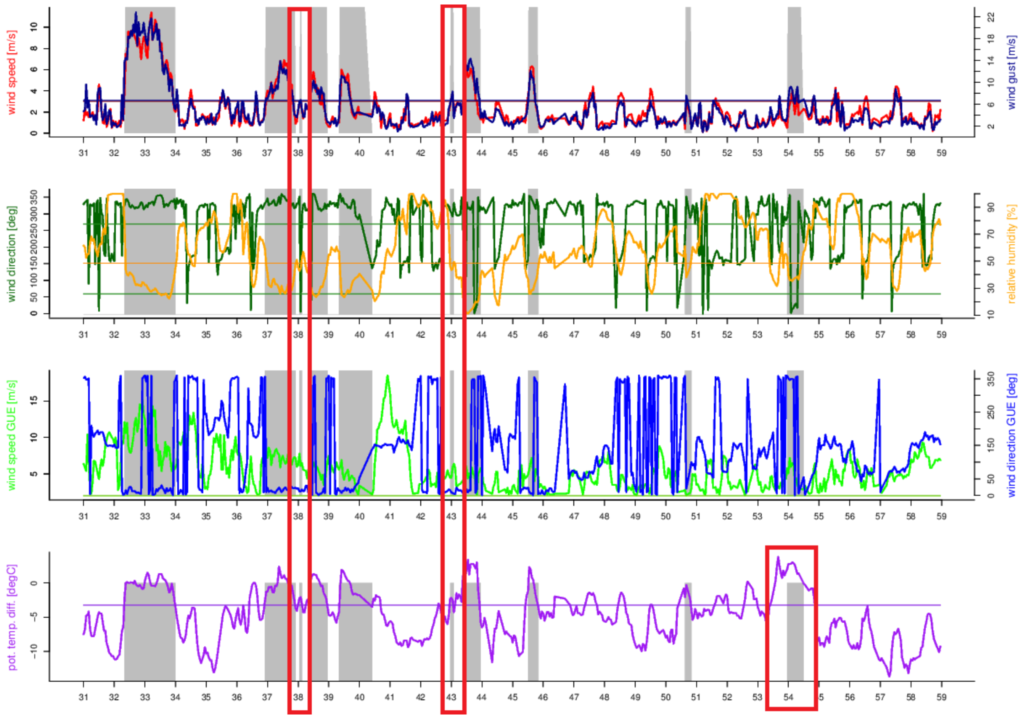


Figure 29: Example of results visualization for the automatic identification of the north foehn for station Comprovasco from the 1st to the 28th of February 2013. Coloured lines: parameters; Coloured horizontal lines: thresholds; Grey boxes: north foehn events (foehn index = 1); Red boxes: inaccuracies in the identification of the north foehn event.

is identified. The interruptions can have as consequence the identification of several shorter events instead of one longer event.

5.1 Sensitivity study

The sensitivity study is necessary to test the robustness of the results and the uncertainty of the applied method. In addition, the sensitivity study allows us to analize the impact of the different parameters on the foehn identification and can be used to ascertain which input parameter accounts for most of the output variance (*Saltelli et al.*, 2000). In order to test this variance, we modified the thresholds, one by one, by adding and subtracting 10-20% and then we looked at the variation of the number of events that are detected by the automatic selection of north foehn.
Table 6 illustrates the results of the sensitivity study. The thresholds of FF, FFF, RH and TPOTDIFF were made vary one at the time of plus or minus 10-20%. Afterwards, the total frequency of north foehn was calculated and the difference in percent is shown in table 6. There is a strong correlation between the influence of the thresholds on the foehn identification and the density plots described in chapter 3, since the density plots were used to determine the thresholds.

The wind speed and the wind gusts are the parameters that, when varied, have the smallest impact on the automatic foehn identification. FF is the least sensitive parameter with a variation of the total frequency that does not exceed -1.4% when adding 20% to the threshold and +2.8% when removing 20%, while the wind gusts have a slight stronger impact with a maximum variation of about -1.6% and +4.0%. The potential temperature difference has a slightly higher importance with a maximum variation of +/-6.7%. The strongest influence on the automatic identification of north foehn is given by the relative humidity. By varying the threshold of +/-10% we can have until +25.5% and -27.7% of identified foehn events. The most sensitive stations in general are MAG, with wind coming from the western sector (MAW) and SBE. Regarding MAW, the density plot of RH has two peaks which indicates that two different phenomena are detected. The peak at around 50% is not considered as foehn, but it probably belongs to valley breezes. Therefore when choosing a higher value, we probably identify several breezes that could compromise the results of the climatology. As previously explained, SBE is a station which is very sensitive to the relative humidity because of the short distance to the Alpine ridge and the high altitude. As an alternative approach, to identify RH-threshold, we assume that the method proposed by *Dürr* (2008) could be applied, although it was not tested with our station. The 95-percentile of the distributions of FF, FFF and TPOTDIFF are used for the automatic identification so that foehn can be identified without using the threshold of the relative humidity. Finally, from the determined foehn events the 99-percentile for RH can be later determined and used as RH-threshold for the foehn index definition. This method can be effective for automatically identifying the thresholds of RH when considering stations located at a high altitude such as SBE. In the case of MAW, we have an overlap of phenomena (foehn and valley breezes). Therefore, the RH-threshold has to be sufficiently low not to identify breezes. Unfortunately, this adjustment can only be done after a manual verification and it is influenced by the subjective choices.

Table 6: Summary of the differences in foehn identification when varying a threshold

Modified threshold	Station	Frequency before [h]	Frequency after [h]	Difference [%]
+20% FF	COM	1027	1024	-0.3
	LUG	620	620	0.0
	MAE	628	625	-0.5
	MAW	141	139	-1.4
	SBE	1629	1625	-0.2
-20% FF	COM	1027	1034	+0.7
	LUG	620	621	+0.2
	MAE	628	635	+1.1
	MAW	141	143	+1.4
	SBE	1629	1643	+2.8
+20% FFF	COM	1027	1011	-1.6
	LUG	620	618	-0.3
	MAE	628	607	-3.3
	MAW	141	136	-3.5
	SBE	1629	1585	-2.7
-20% FFF	COM	1027	1044	+1.7
	LUG	620	622	+0.3
	MAE	628	653	+4.0
	MAW	141	145	+2.8
	SBE	1629	1670	+2.5
+10% RH	COM	1027	1068	+4.0
	LUG	620	640	+3.2
	MAE	628	693	+10.4
	MAW	141	2019	+25.5
	SBE	1629	797	+23.9
-10% RH	COM	1027	958	-6.7
	LUG	620	590	-4.8
	MAE	628	552	-12.1
	MAW	141	102	-27.7
	SBE	1629	1205	-26.0
+20% TPOTDIFF	COM	1027	1055	+2.7
	LUG	620	638	+2.9
	MAE	628	643	+2.4
	MAW	141	141	+0.0
	SBE	1629	1738	+6.7
-20% TPOTDIFF	COM	1027	984	-4.2
	LUG	620	599	-3.4
	MAE	628	604	-3.8
	MAW	141	140	-0.7
	SBE	1629	1520	-6.7

6 Conclusion and Outlook

6.1 Conclusions

Thanks to the automatic identification of north foehn events, north foehn characteristics were identified based on data taken from 36 stations in the southern part of the Alps. The climatology for the stations discussed in chapter 4 was performed on a data set covering the period from January 1993 to August 2014. The first important step when performing a climatology of foehn is the definition of the thresholds, which are essential for the automatic identification of foehn events. By applying a similar methodology as the one used by *Dürr* (2008), thresholds for TPOTDIFF, FF, FFF and RH could be found. However, a crucial first step, was the identification of the typical wind direction sector during north foehn for each station. Stations with multiple main foehn directions should be treated separately for each main wind direction.

From the climatolgical study the following conclusions can be drawn:

- an interannual variability of the north foehn events and number of foehn cases exists but no clear trend is recognizable for the analyzed time period
- north foehn frequency exhibits a seasonal and diurnal cycle
- the average foehn initiation and foehn end are anticorrelated in time, in fact, north foehn case usually starts between 8am and 4pm and stop between 4pm and 4am
- topography, altitude of the station and distance from the Alpine ridge influence the occurrence of north foehn.

The results of the climatology show that when considering the temporal variability, neither for the foehn frequency nor for the number of foehn cases a trend was found, although it was noticed that spring and especially the May months are gaining importance (increase of about 4% of the monthly frequency at COM and SBE). On the other hand, seasonal and diurnal cycles are clearly visible. March is the month with the highest average total frequency (150 h at 2pm) and the north foehn occurs more often in the afternoon.

Another important factor influencing the north foehn is the topography of the region. By comparing nearby stations we saw that their behavior did not change. On the other hand, the distance of the station from the Alpine crest and the orientation of the valley are the main influencing factors. The wind speed, the wind gusts, the monthly frequency and the maximum duration of north foehn events are more intense near the Alpine crest (SBE, PIO, ROB) and where the valley has a north-to-south orientation (SBE, COM, LUG).

The sensitivity study indicates that special attention should be given to the choice of the RH-threshold.

In fact, relative humidity is the most sensitive parameter when applying the automatic identification of foehn. In connection with the results of the sensitivity study, the main limitation of the method occurs when considering stations located at a high altitude and close to the Alpine crest. In fact, in the case of station SBE, the definition of the RH-threshold was difficult a more subjective approach was be used.
To summarize, the applied method which is based on the use of automatic measurement stations, is very powerful. Few small improvements could still be achieved for stations with short time series. The only other way to improve the identification of foehn is by checking through subjective and manual verification each single foehn event. However, this process is very time consuming.

6.2 Outlook

This Master's thesis project was a first attempt to partly fill the lack of climatological studies about foehn in the southern Alpine region. The main goal of the research has been reached but the phenomenon can be further investigated. The SwissMetNet and the other networks used to obtain the needed data show a high potential for the automatic foehn identification. In general, the automatic measurements have enormous potential, especially because they can be used for determining the presence of the north foehn in the study region in real time. Unfortunately, the main limiting factor for a more precise climatology is the length of the data set. For many stations the data are only available for less than 5 years and this involves considerable difficulties in the interpretation of the results. Furthermore, in other cases, not all the necessary parameters were available and therefore, we could not consider these stations for our analysis. Surely, the increase of measuring stations and the availability of more data will help in the study of the foehn.
Besides this climatology, the study of large scale flow is equally essential for understanding the starting mechanism of the formation of north foehn. The study of the large scale flow during north foehn can also be used in order to understand what is special about March namely, why this is the prevailing month. In addition, regarding the climatology, relations between stations and the geographical feature need further investigation. The creation of a physically consistent map (2D-interpolation) of the climatology results obtained at each single station can definitely help the interpretation of the phenomenon.

Abbreviations

CML	Centro Meteo Lombardo
CT	Canton Ticino
MG	Meteo Group
SMN	SwissMetNet

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7 Appendix

7.1 Monthly frequency distributions of all the 36 stations of the study region

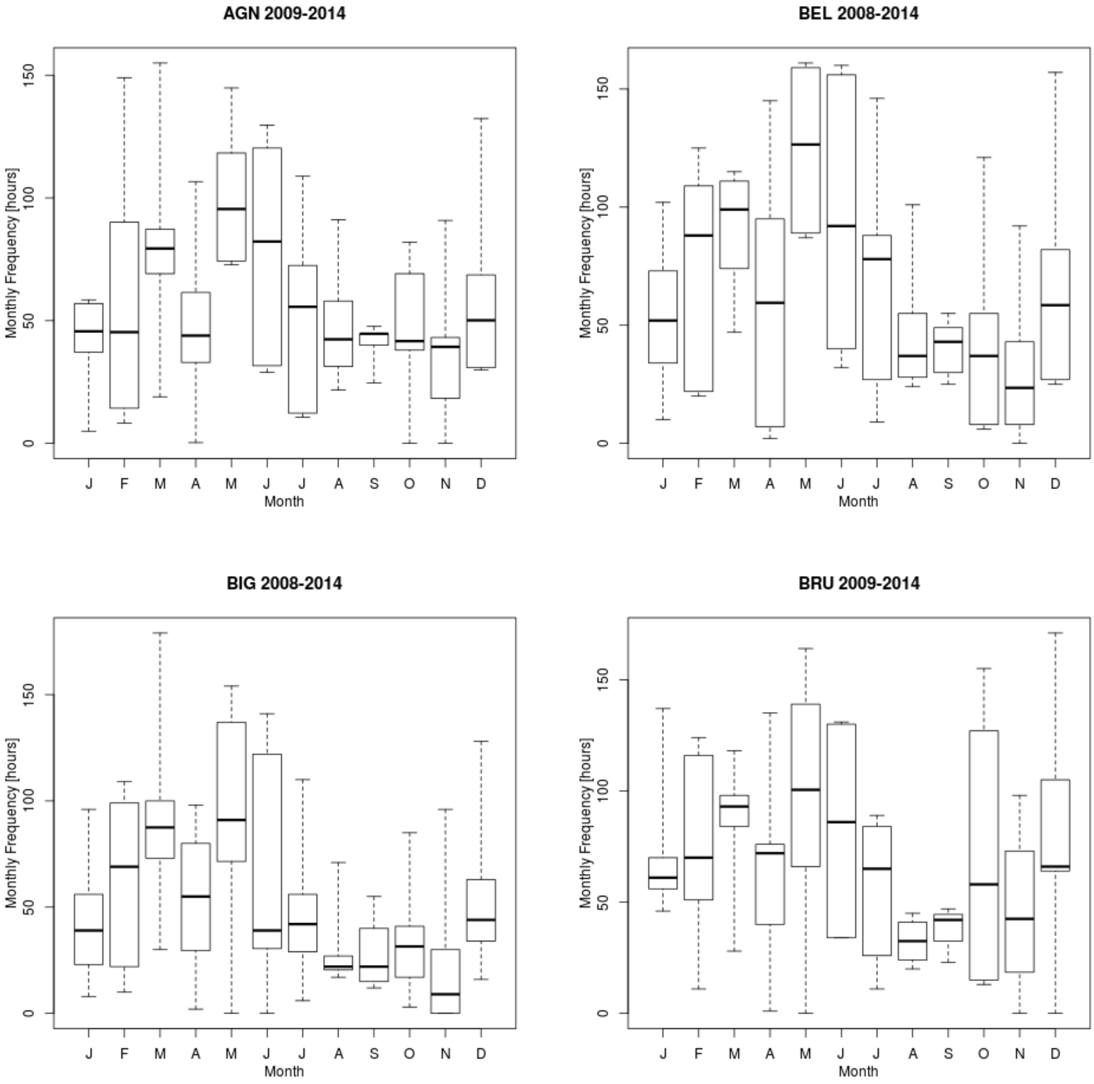

Figure 30: Monthly frequency distribution: stations AGN, BEL, BIG and BRU

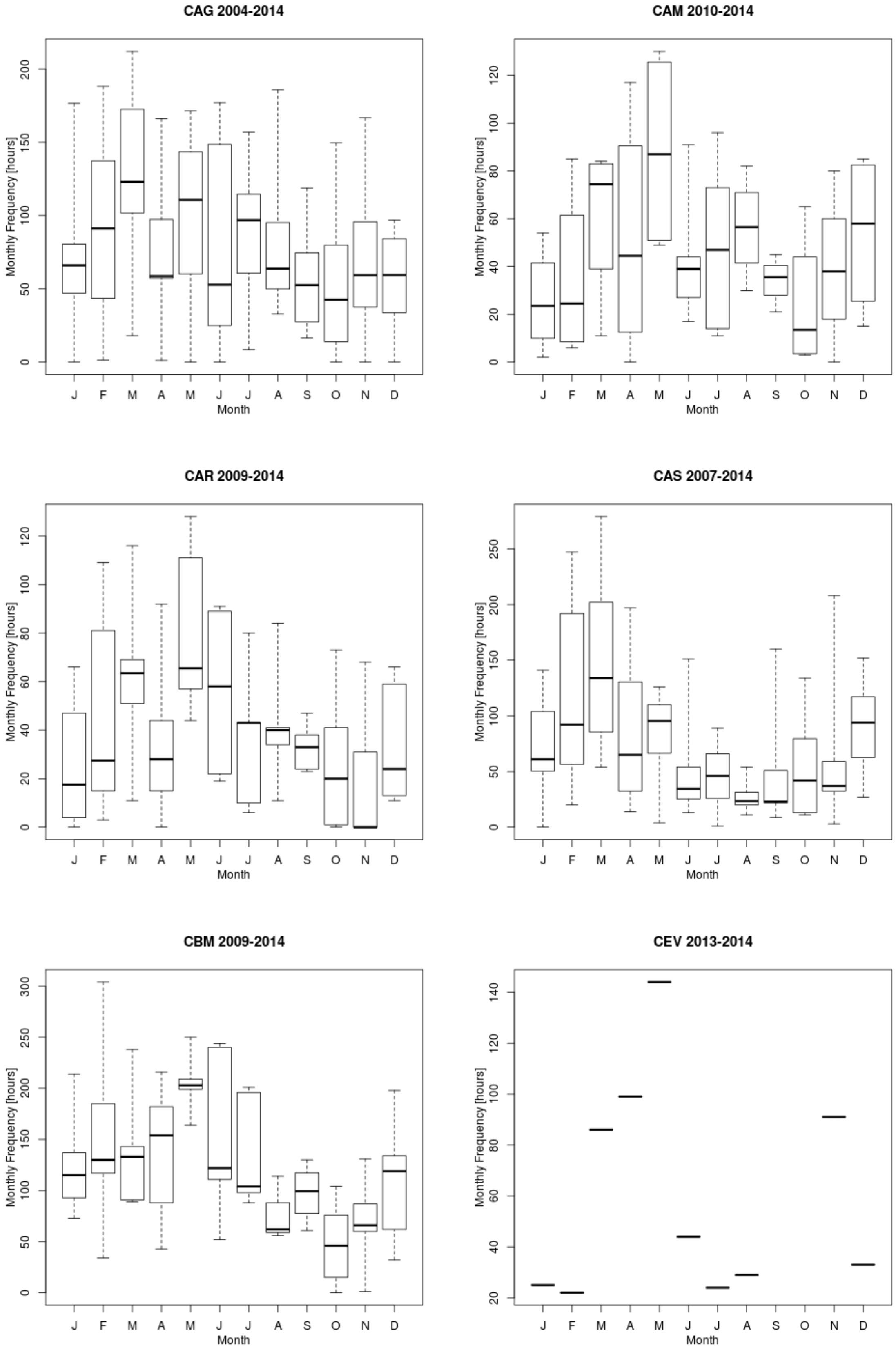

Figure 31: Monthly frequency distribution: stations CAG, CAM, CAR, CAS, CBM and CEV

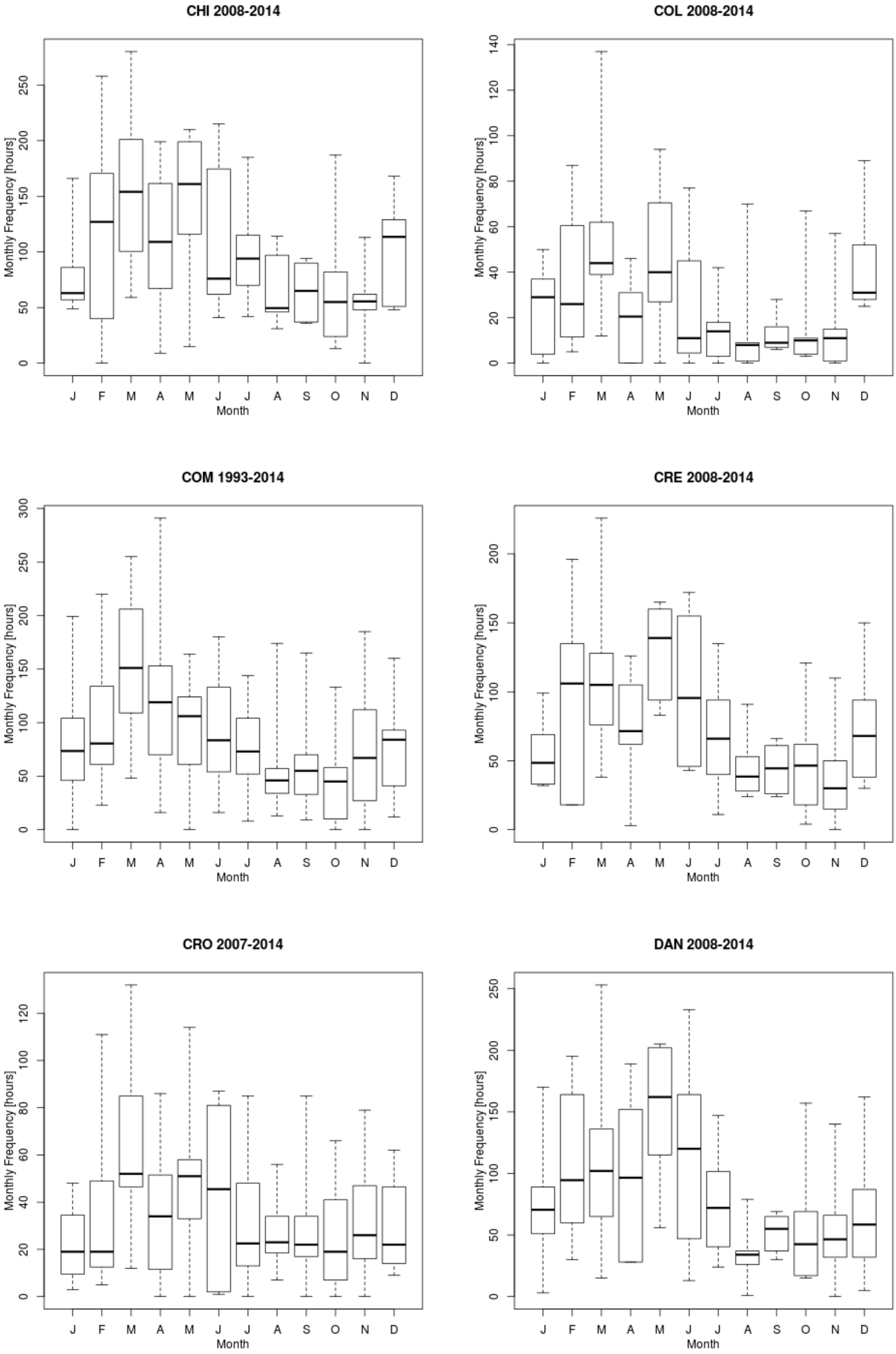

Figure 32: Monthly frequency distribution: stations CHI, COL, COM, CRE, CRO and DAN

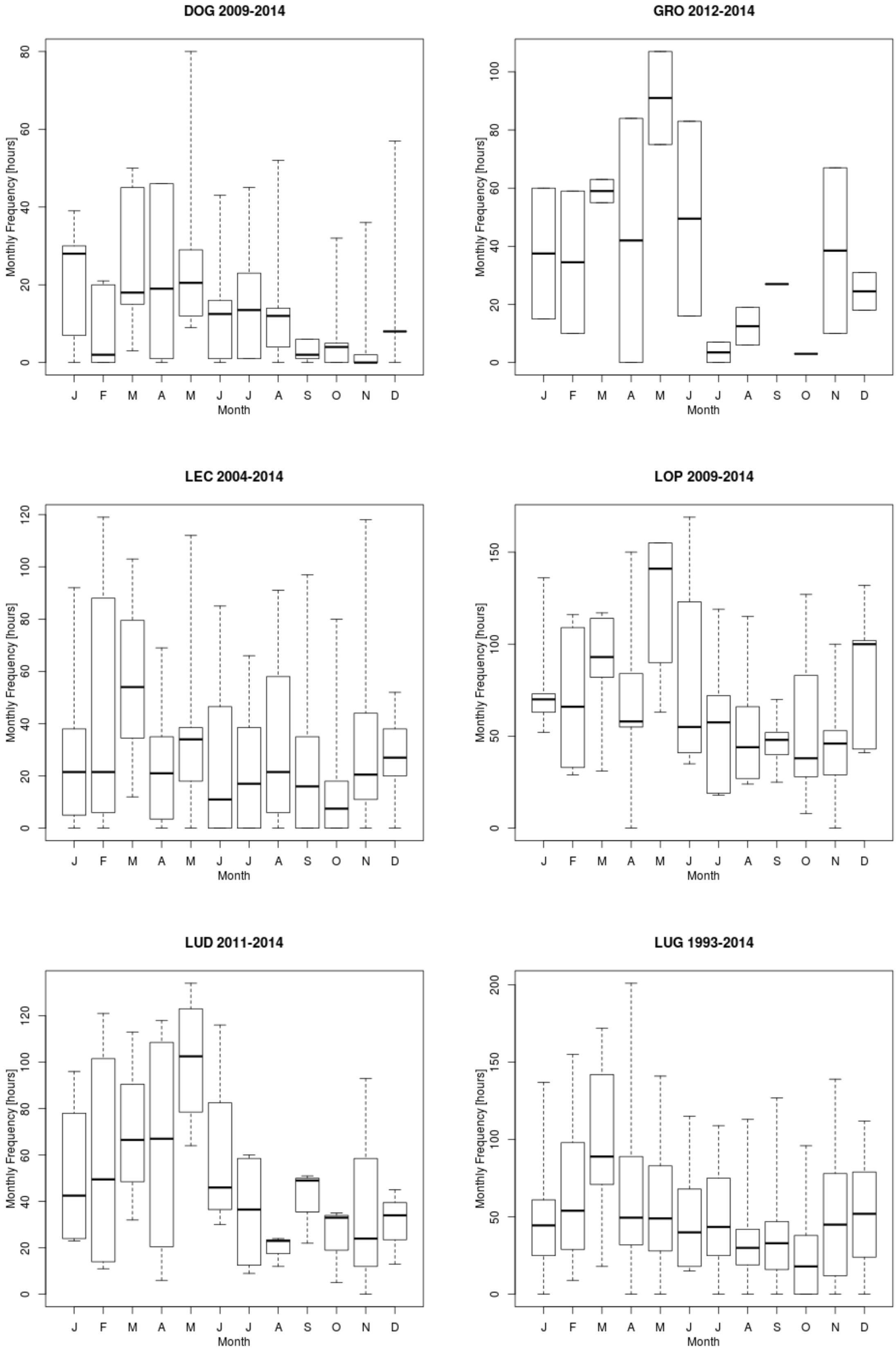

Figure 33: Monthly frequency distribution: stations DOG, GRO, LEC, LOP, LUD and LUG

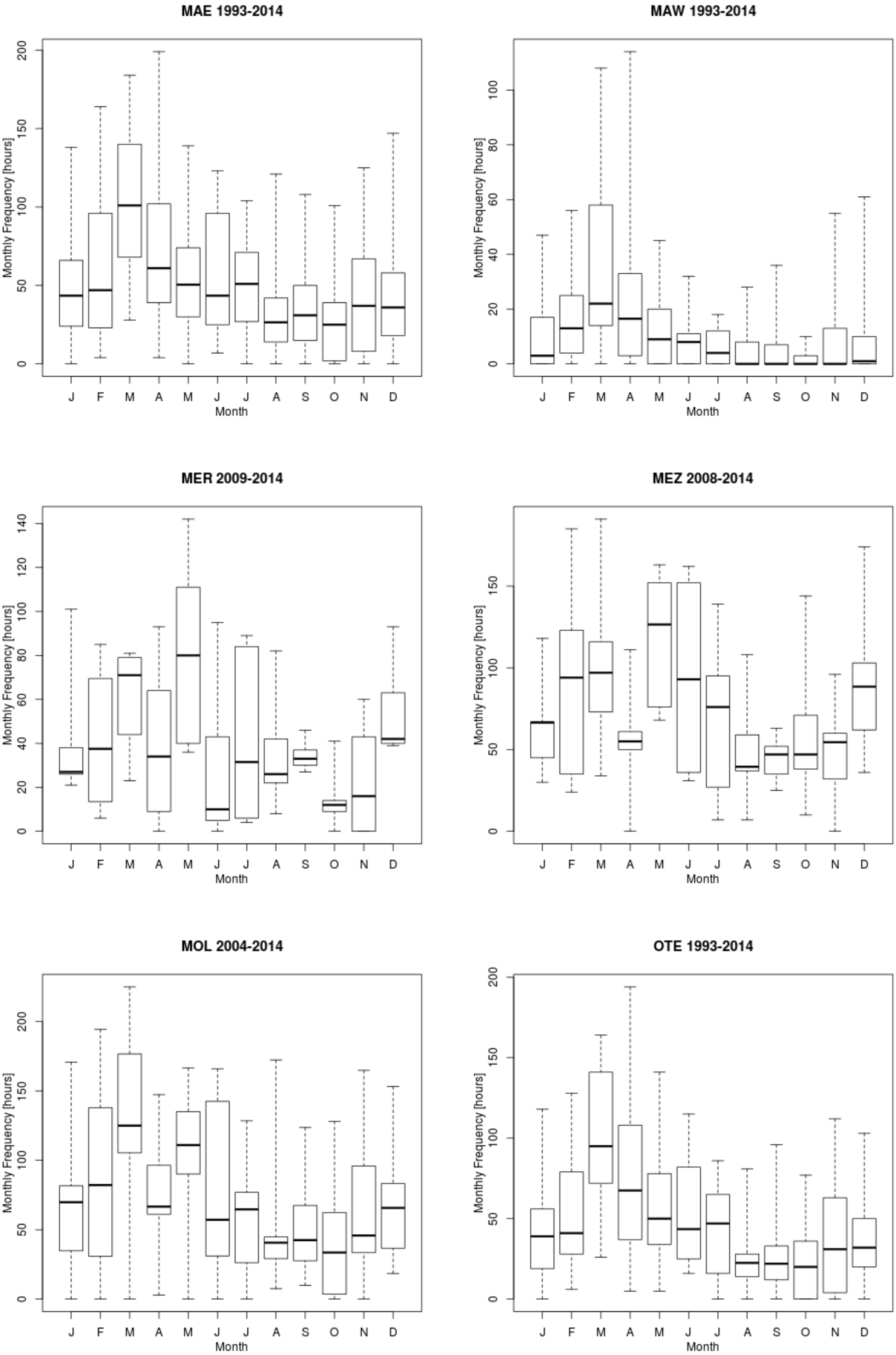

Figure 34: Monthly frequency distribution: stations MAE, MAW, MER, MEZ, MOL and OTE

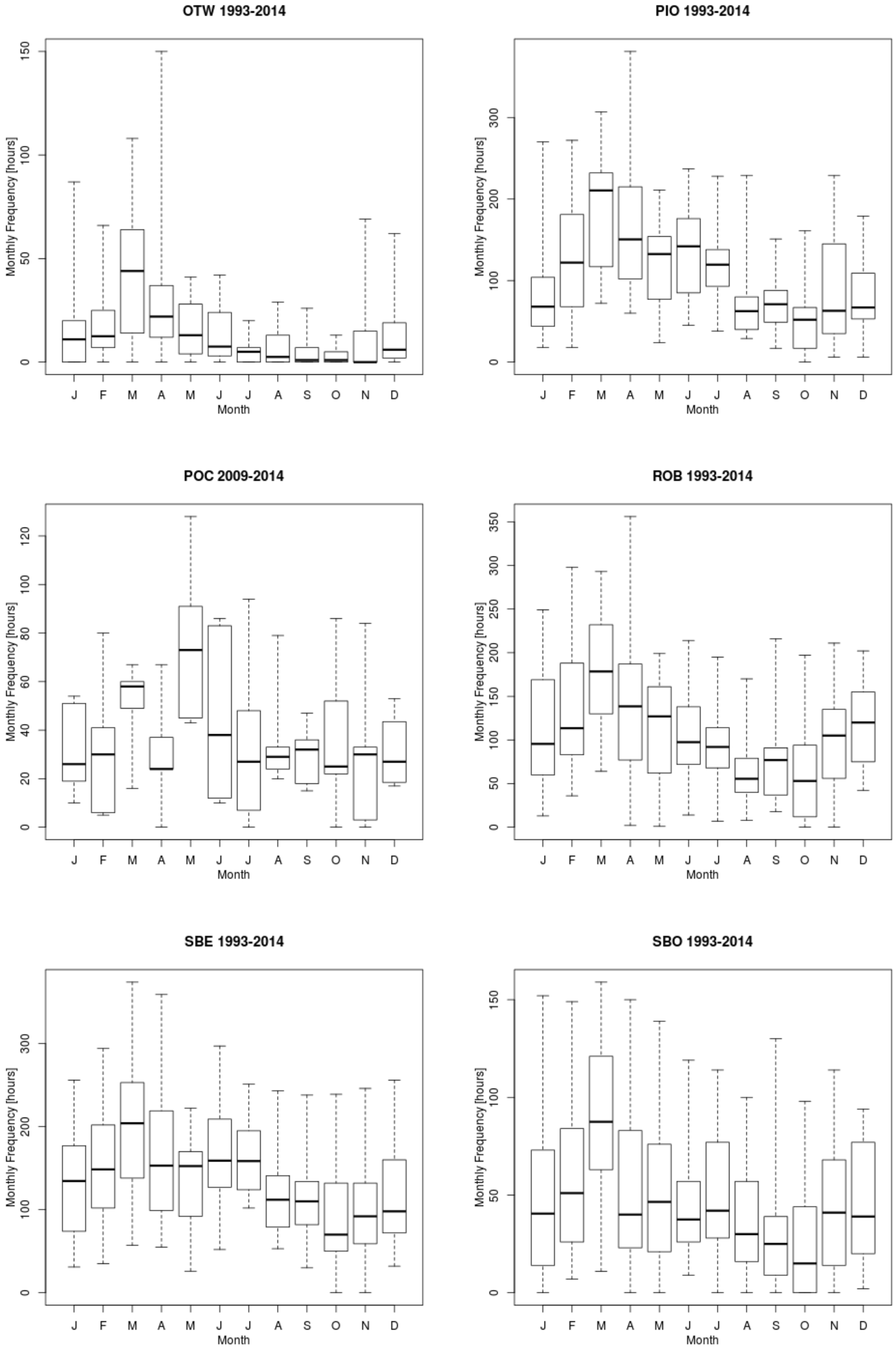

Figure 35: Monthly frequency distribution: stations OTW, PIO, POC, ROB, SBE and SBO

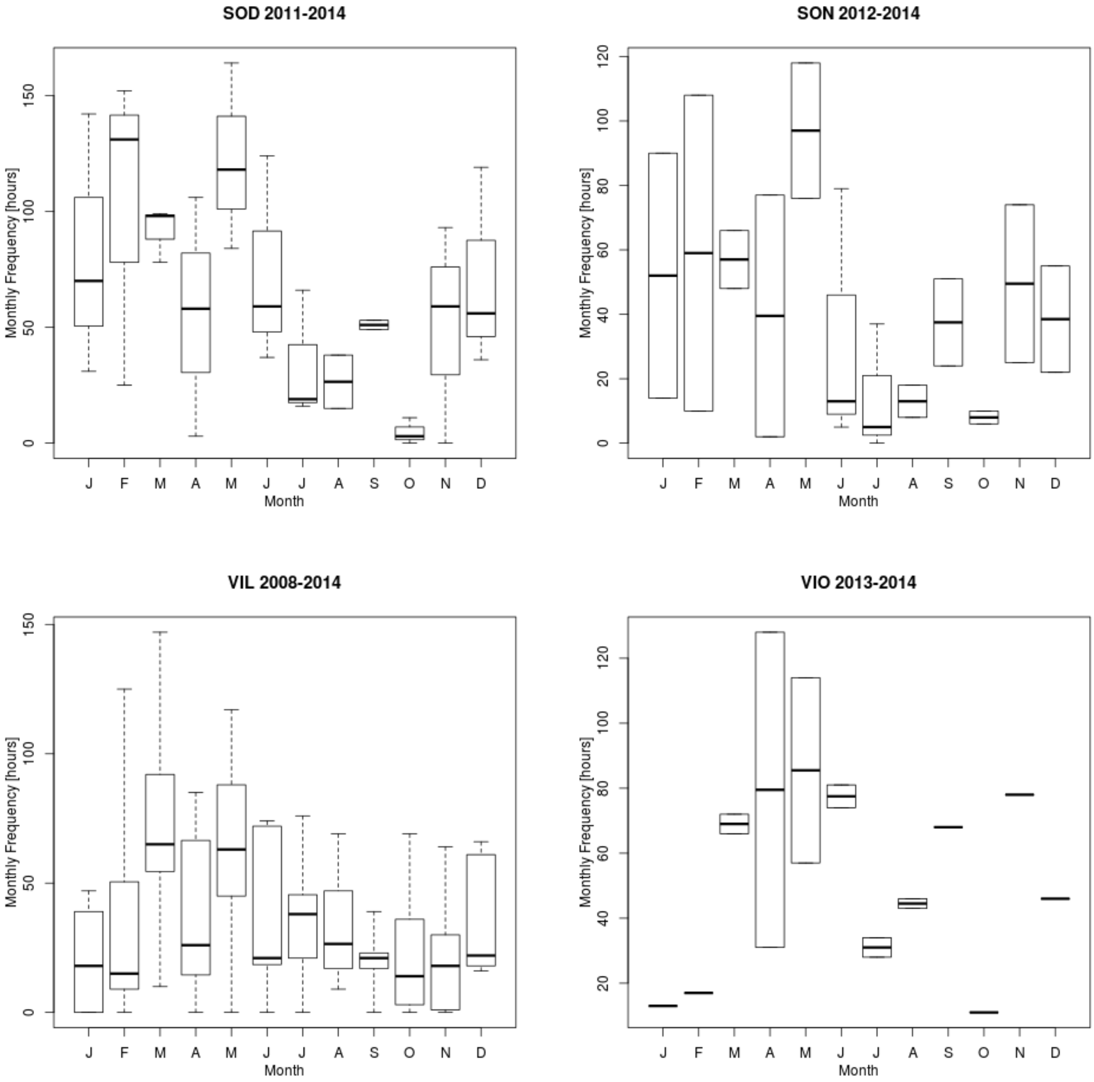

Figure 36: Monthly frequency distribution: stations VIL and VIO

7.2 Comparison of the monthly frequency distributions between the periods 1993-2003 and 2004-2014

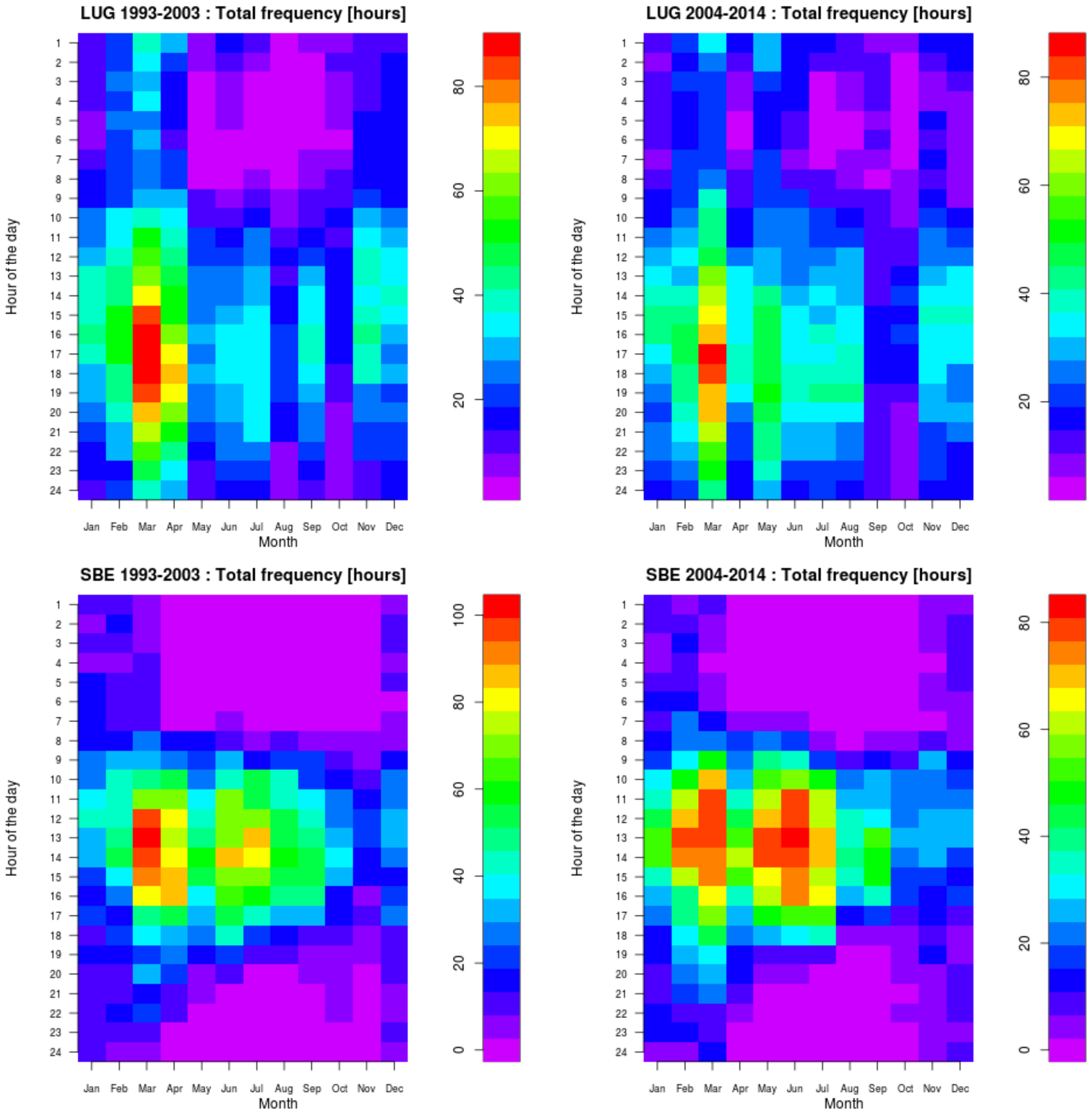

Figure 37: Monthly frequency distribution for stations Lugano and San Bernardino. Comparison between the period 1993-2003 and 2004-2014 (year 2014 is not complete).

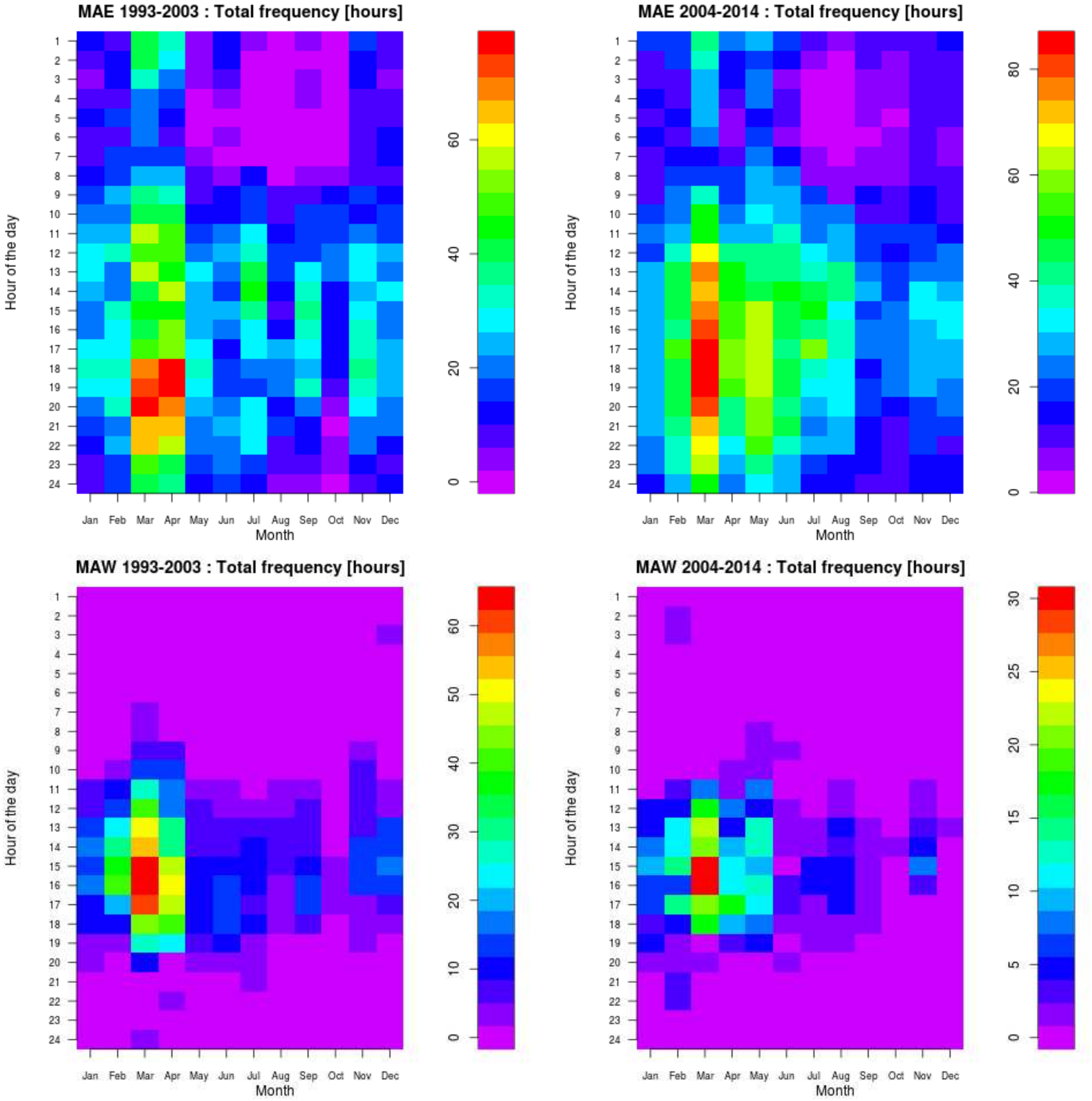

Figure 38: Monthly frequency distribution for station Magadino when the wind is coming from the east (MAE) and when the wind is coming from the west (MAW). Comparison between the period 1993-2003 and 2004-2014 (year 2014 is not complete).

7.3 Monthly distributions of wind speed and wind gusts

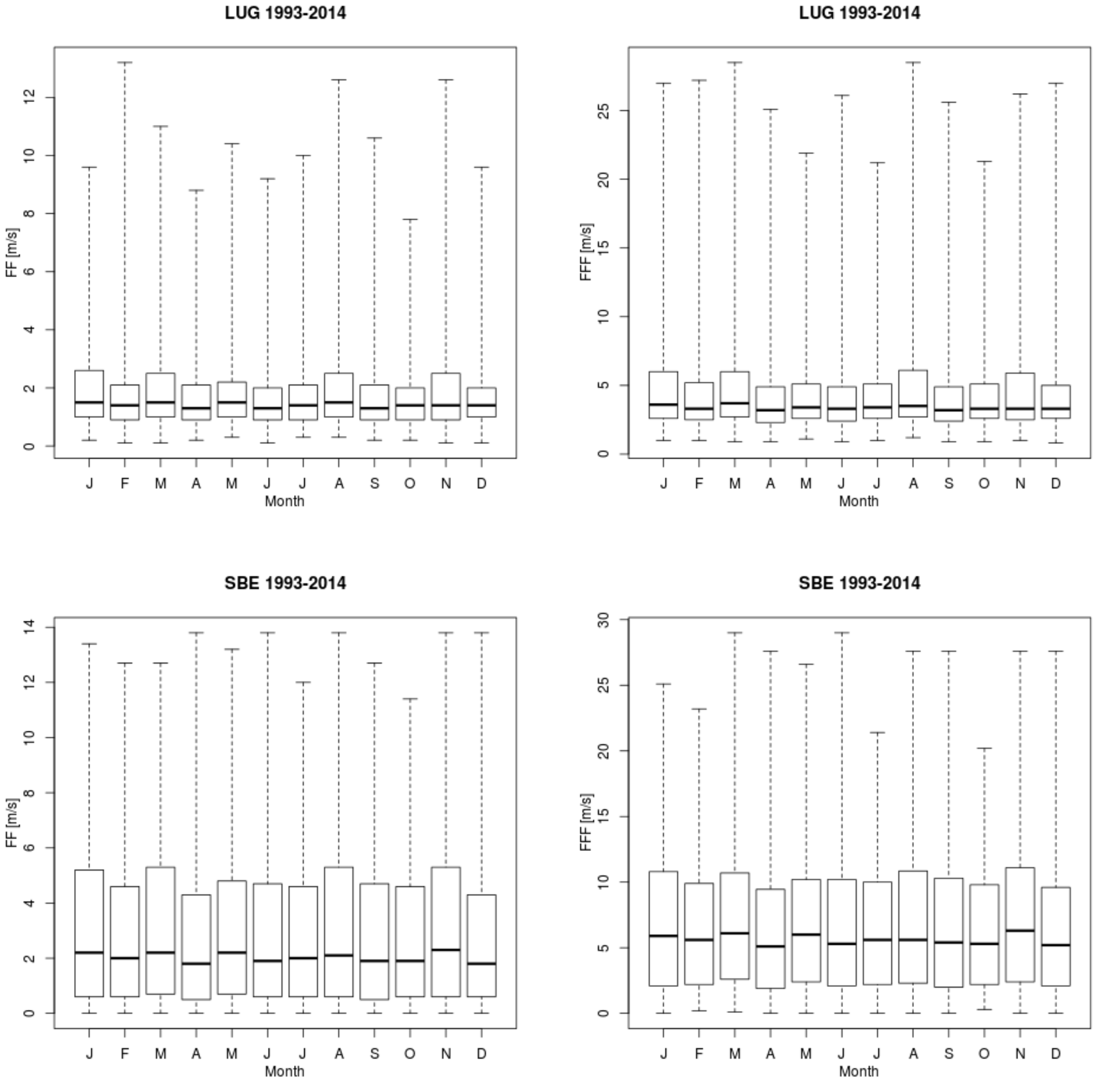

Figure 39: Distribution of wind speed (left) and wind gusts (right) for stations Lugano and San Bernardino for the period from 01.01.1993 to 31.08.2014.

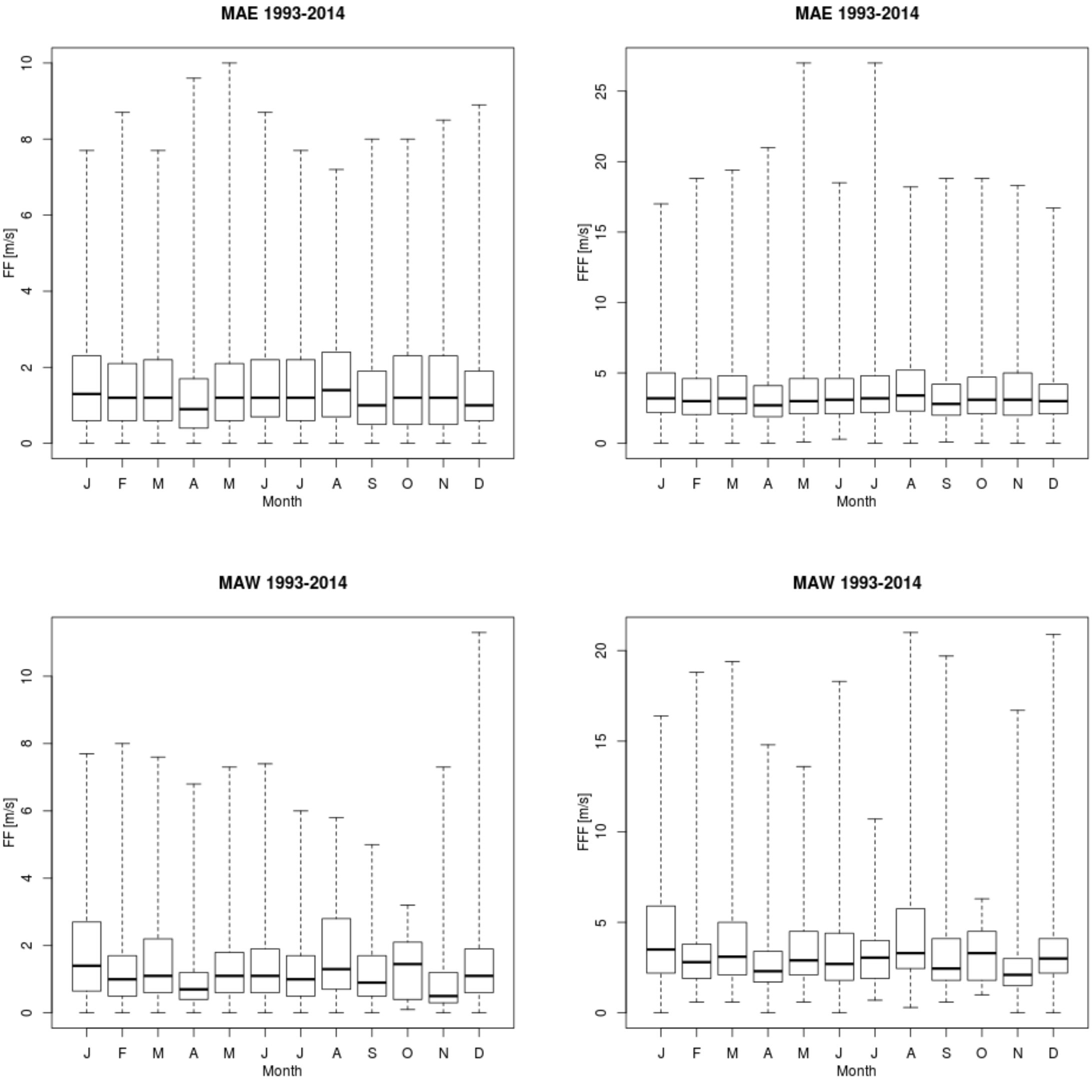

Figure 40: Distribution of wind speed (left) and wind gusts (right) for stations Magadino when the wind is coming from the east (MAE) and when the wind is coming from the west (MAW)for the period from 01.01.1993 to 31.08.2014.

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