Meteorologische Zeitschrift, Vol. **24**, No. 3, 225–242 (published online April 4, 2015)

Article

Swiss and Austrian Foehn revisited: A Lagrangian-based analysis

MICHAEL WÜRSCH[1]* and MICHAEL SPRENGER[2]

[1]Meteorologisches Institut, Ludwig-Maximilians-Universität München, Germany
[2]ETH Zürich, Institute for Atmospheric and Climate Science, Switzerland

(Manuscript received August 18, 2014; in revised form December 19, 2014; accepted January 5, 2015)

Abstract

Two different South Foehn types have been described in the literature: the Swiss Foehn is characterized by significant ascent on the southern side of the Alps, hence fulfilling a requirement of the thermodynamic Foehn theory associated with latent heating. On contrast, the Austrian Foehn is characterized by near-horizontal flow to the south of the Alps, followed by dry-adiabatic descent into the northern Foehn valleys. In this study, we make use of three years (2000–2002) of NWP reanalysis data, based on the COSMO model, and corresponding Foehn observations at a Swiss (Altdorf in the Reuss Valley) and Austrian (Ellbögen in the Wipp Valley) measurement site to address the applicability of this Foehn type classification. First, the methods are introduced in a case study of a strong Foehn case on 2–4 April 2000. The more traditional Eulerian analysis is complemented by trajectory calculations. Forward trajectories started in the Po Valley and backward trajectories started at the two Foehn stations reveal a complex flow situation. For instance, air parcels arriving in Altdorf can be trapped in the easterly, low-level Po Valley jet before ascending and passing over the Alpine crest, thus originating from further east than air parcels arriving in Ellbögen and having experienced less vertical ascent south of the Alps. This highlights the potential of Lagrangian-based flow analysis and concurrently points to the limitations of a pure Eulerian perspective.

The main part of the study considers a climatology of the 3-year backward trajectories started at Altdorf and Ellbögen. Some key findings are: (i) a larger fraction of trajectories arriving in Altdorf experience substantial lifting on the Alpine south side compared to Ellbögen; (ii) both Foehn types can be observed at both stations, i.e., the type naming cannot be taken as an exclusive regional classification; (iii) precipitation traced back is more predominant for Altdorf trajectories than for Ellbögen ones, indicating that the latent heating contributes more to Foehn warming in Altdorf than in Ellbögen. Finally, from a forecasting perspective it is of interest whether the Foehn type can be deduced from a simple measurement alone. To this aim, Milan pseudo-soundings in the Po Valley, essentially south of Altdorf, are considered. Composite soundings are compared for Foehn cases in Altdorf with substantial lifting to those with weak lifting, corresponding to a non-blocked and blocked flow in the Po Valley. The two classes clearly differ in their composite profile; however, the spread prohibits an immediate classification on this sounding alone.

Keywords: Foehn, climatology, Altdorf, Innsbruck, trajectories

1 Introduction

Foehn research has a long history, starting in the late 18th century. Essentially the key questions were already stated by the first scientists (HANN, 1866; KUHN, 1989; SEIBERT, 1990). One of the long-standing questions addresses the warming of the South Foehn air in the northern Alpine valleys. Different mechanisms were proposed, the most prominent being referred to as the thermodynamic warming mechanism (HANN, 1866). Basically it states that the Foehn air rises on the Alpine south side, thereby experiencing condensation and hence following a moist-adiabatic cooling; after crossing the Alpine crest or the north-south transecting passes, the Foehn air descends dry-adiabatically into the Foehn valleys. SEIBERT (1990) has critically reviewed the evolution of this 'theory', although it is since a long time known that it can only partly explain the Foehn warming. Nowadays, blocking of cold air over the Po Valley and subsidence of stable stratified potentially warmer air is believed to be a part of the missing piece (SEIBERT, 1985). SEIBERT (1990) describes a case study where the Foehn air originates from 2000–2500 m asl (above sea level) over the Po Valley and the low level air stays blocked. The typical evolution of a Foehn case is also characterized in SEIBERT (1990). Finally, STEINACKER (2006) and DROBINSKI et al. (2007) provide a good overview on current Foehn research and a comprehensive list of case studies is collected in KUHN (1989).

The basic ingredients of the thermodynamic Foehn theory are (i) that the air parcels ascend from low levels to the pass and Alpine crest heights to finally descend into the Foehn valleys; and (ii) that there must

---

*Corresponding author: Michael Würsch, Meteorologisches Institut, Ludwig-Maximilians-Universität München, Theresienstr. 37, 80333 München, Germany, e-mail: michael.wuersch@lmu.de

DOI 10.1127/metz/2015/0647
Gebrüder Borntraeger Science Publishers, Stuttgart, www.borntraeger-cramer.com

be condensation and precipitation on the Alpine south side. Many of the studies contradicting this argumentation have been done for the Inn and Wipp Valley in the Austrian Alps (Seibert, 1985). It is not clear whether the same line of arguments equally applies to other valleys, in particular to the main Swiss Foehn valleys (Reuss and Rhine Valley). In fact, it was proposed, and is summarized in Steinacker (2006), that two distinct Foehn types should be distinguished: an Austrian one, where only weak ascending air motions are found on the Alpine south side, and a Swiss one which more closely follows the characteristics of the thermodynamic theory. These two Foehn types were already recognized by Hann (1866), who called them Foehn type I and II respectively. Note however that Richner and Hächler (2013) caution to take the geographical annotation too restrictive: an Austrian Foehn type can also be observed in Switzerland and vice versa.

So far it was difficult to clearly quantify the different occurrences because a direct proof needs to compare the air trajectories associated with the two Foehn instances. An Eulerian analysis can only give good indications if the vertical evolution of the air parcels' path differ for the two sites. In order to make a quantitative statement, in this study backward trajectories are calculated from two Alpine Foehn valleys and their history with respect to vertical motion is considered. It will first be shown in a case study (Section 3) that a Lagrangian perspective can indeed shed new light on the complex flow features during Alpine Foehn; then (in Section 4) a climatology of backward trajectories over three years (2000–2002) is established for the two stations and for all observed Foehn instances. This part will then allow to compare the Austrian Foehn with the Swiss one, as discussed and summarized in Sections 5 and 6. In summary, we intend to revisit in this study the long-standing question where the air during Alpine Foehn originates. We do this 'only' for the Alpine Foehn and hence come explicitly back to the distinction between the Austrian Foehn type and the Swiss Foehn type. What we do not intend to do is to make a general statement about the many other Foehn flows around the world. In order to address this question, we make use of a 3-year reanalysis data set based on the 7-km COSMO NWP model (Steppeler et al. 2003; Jenkner et al. 2010), with a 1-hour temporal resolution. It was shown in other studies that meaningful results can be obtained with such a resolution even for orographic flow: Miltenberger et al. (2013); Kljun et al. (2001). However, given the narrow width of the main Foehn valleys (~ 5 km) it is still beyond the reach of this study to see how the air parcels finally descend into the Foehn valleys, which are barely resolved in the model. Hence, consideration is only given to the part of the air trajectories south of the Alpine crest, i.e., in a region (Po Valley) where the trajectories' validity can be assumed to be given.

Of course, trajectories have long been recognized as a potentially powerful 'tool' to answer the basic Foehn questions (Richner and Hächler, 2013). Indeed, a first step in trajectory-based analysis of the origin of Foehn air was taken by Seibert et al. (2000). They calculated ensembles of backward trajectories arriving in Ellbögen in the Inn/Wipp Valley for the Foehn case 4–6 May 1997, based on NWP data with 6 km horizontal resolution. The trajectories showed a lot of variability: some of them passing through the planetary boundary layer in the Po Valley, some crossing the Po bassin at heights between 800 and 750 hPa. No steps were taken to study this complex Lagrangian flow behaviour in a more climatological sense. Most likely because the technical challenges are still nowadays rather big: sufficiently high-resolution NWP model winds must be available to obtain reasonable trajectories. This is also reflected in a recent study by Hächler et al. (2011), where the backward trajectories are started from the Rhine Valley during a single Foehn case. Further Lagrangian studies have been performed for non-Alpine Foehn events, e.g., in Ishizaki and Takayabu (2009) and Takane and Kusaka (2011). There the warming mechanisms over the Toyama Plain (Japan) are analyzed with backward trajectories, indicating that moist and dry adiabatic processes, in addition to sunshine insolation, contribute to the warming. However, it remains unclear to which degree these results apply to the special Alpine setting, where, e.g., the arc-shaped mountain barrier must have an important impact on the flow.

2 Data and methodology

2.1 Foehn climatologies

Altdorf (Switzerland): The Foehn climatology for Altdorf in the Reuss Valley is based on the objective method developed by Dürr (2008; see Richner et al. 2014 for a short summary in English) which yields a yes/no decision for Foehn at several stations in Switzerland. This method relies on 10-min observations at several stations of SwissMetNet, the operational measurement network run by the Swiss National Weather Service (www.meteoswiss.ch) and assigns to a 10-min interval a Foehn event if several characteristics are met. The parameters included in the decision are wind speed and direction, relative humidity and the difference of potential temperature relative to Gütsch (station located close to the Gotthard Pass northeast of Andermatt), a Alpine crest station which is taken as a high-altitude reference. In particular, the criteria for Altdorf are: (i) wind direction between 60–240 deg, (ii) mean wind speed 3.7 m/s, (iii) wind gust 6.2 m/s, (iv) relative humidity $< 54\,\%$, (v) potential temperature difference to Gütsch $< -4\,\mathrm{K}$ and (vi) wind direction at Gütsch between 90–240 deg. Criteria (ii) and (iii) have only to be fulfilled for the onset of Foehn. Note that all meteorological parameters are motivated by the characteristics of a Foehn event, which is clear for (i) to (iv), and relies for criterion (v) on an expected quasi-conservation of potential temperature as the air masses descend from the Alpine passes

Table 1: Seasonal distribution (in %) of Foehn hours in Altdorf and in Ellbögen. The total number of Foehn hours in Altdorf is 1662 h and correspondingly in Ellbögen 6315 h.

	Altdorf	Ellbögen
Spring	46.3	32.2
Summer	11.2	16.4
Autumn	22.0	24.7
Winter	20.5	26.7

down to the Foehn valleys. The thresholds are statistically derived to give an optimal accordance to a manually classified Foehn instance (see Richner et al. 2014 for details). Of course, no automatic Foehn classification can be perfect. Especially in the summer months nearby thunderstorms can mimick the characteristics of Foehn at a singular measurement site. Furthermore, Dimmer Foehn cannot correctly be classified because of its unusual high relative humidity (see Richner and Hächler 2013 for a glossary on Foehn-related terms). Manual tests have yielded that misclassification is rather rare between autumn and spring, i.e., the time period with far higher Foehn occurrences than summer. The method is able to distinguish between cases with pure Foehn and with mixed Foehn air: The latter shows only some of the Foehn characteristics and is a kind of borderline event with a mixture of Foehn and non-Foehn air.

Ellbögen (Austria): For Ellbögen in the Wipp Valley we use a Foehn climatology which is based on a diagnosis presented in the Appendix of Drechsel and Mayr (2008) and developed by Vergeiner (2004). Data is used from three different stations. Two at the crest (Sattelberg and Brenner) and one at Ellbögen. The method was first applied by Föst (2006). The criteria for Ellbögen are (see Drechsel and Mayr 2008 for details): (i) minimum wind speed of 2.0 m/s; (ii) potential temperature offsets of -1.4 K and $+0.3$ K relative to Sattelberg and Brenner; and (iii) wind direction in the range 137 ± 45 deg at Ellbögen. Again, the potential temperature offsets take into account the quasi-conservation of potential temperature as the air crosses the Alpine crest and reaches the downwind location. All in all the method for this Austrian valley is very similar to the one developed by Dürr (2008) for Switzerland.

The time resolution of the Altdorf and Ellbögen Foehn climatologies (10 min) is much higher than the NWP data from the COSMO model (1 h, see next section). Therefore, we reduced the climatologies also to a common time resolution of 1 h. This is done with a simple hourly-based vote: If the number of 10-min time intervals within a hour exceeds or is equal to 3 (30 min), the whole hour is classified as Foehn hour. In total the number of Foehn hours in the time period 2000–2002 is 1662 for Altdorf and 6315 for Ellbögen. The reason for this difference is that Ellbögen lies higher up in the valley and is close to the crest. Indeed, Innsbruck at the 'exit' of the Wipp Valley would be a fairer comparison to Altdorf: there the number of Foehn hours is about a third to a fourth compared to Ellbögen (Föst 2006; Strobl 2009; Ortner 2010). Typically, the Foehn instances occur first in Altdorf, and as the synoptic- and mesoscale weather systems move further east, become also discernible in Ellbögen. Table 1 shows the distribution of Foehn hours in the different seasons. A clear maximum of Foehn occurrence in spring is discernible both for Altdorf and Ellbögen. The seasonality is particularly strong for Altdorf (46 % of Foehn hours in spring), whereas the seasonal distribution is more balanced for Ellbögen. At both stations the minimum is found during summer (11.2 % for Altdorf, 16.4 % for Ellbögen). Finally, it is worthwhile to mention that exceptionally many Foehn hours were recorded in the year 2000. For instance, the station Vaduz in the Rhine Valley recorded about 600 Foehn hours in 2000, but only around 400 during 2000 and 2001. A similar diagram characterizing the Foehn in Altdorf during these three years, compared to a longer climatology, can be seen in, e.g., Gutermann et al. (2012), which presents the long-term time series (more than 100 years). However note that we don't expect the interannual variability to have an important impact on our conclusion: We expect that even in a Foehn-rich year the same meso-scale mechanisms are at work, i.e., in the mean the trajectories to exhibit a similar behavior.

2.2 COSMO re-analysis

The COSMO model is a non-hydrostatic model of the COnsortium for Small scale Modelling which has been known as Lokal Modell (LM) (Steppeler et al. 2003). In this work the COSMO-7 version is used which has a horizontal resolution of 7 km. This leads to the representation of topography as displayed in Fig. 1. The model resolution cannot be expected to give a very detailed reproduction of the alpine topography but the main large-scale effects are captured nonetheless. For completion the real and model heights of the nearest grid point are given here: Altdorf 458 m/638 m; Ellbögen 1070 m/1219 m, Gotthard pass 2106 m/2076 m and Brenner pass 1370 m/1714 m. A large observational dataset is assimilated using a nudging method to keep the model analysis close to reality. Surface measurements like station pressure, 2-m humidity and 10-m wind are used and especially useful in Switzerland where the station network has a resolution of less than 20 km. The boundary conditions come from the operational analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF). In summary, the three-year period (January 2000 to December 2002) is expected to provide a representative sample to investigate the mentioned phenomena and derive climatological implications. A more detailed description of the reanalysis can be found in Jenkner et al. (2010) and Jenkner (2008).

We also compare the COSMO reanalysis with the radio-soundings from Milan to see whether the stratification of the atmosphere is reproduced correctly. In

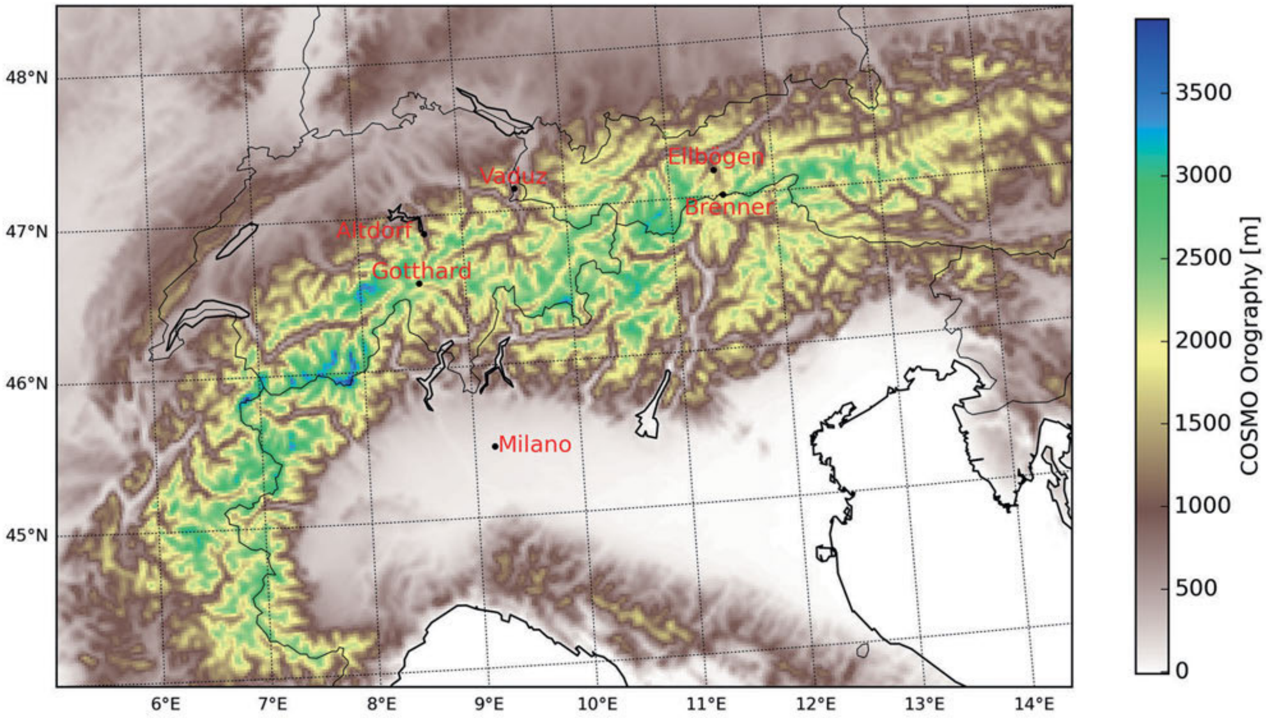

Figure 1: Topography of the COSMO model (in [m], 7 km horizontal resolution).

general the difference between them lies in the tenths of a degree. Inversion layers are not as pronounced as they should be and small-scale features are missing but the reanalysis is never off more than 2 °C, or in other words the location of the inversion in COSMO is never more than 200 m away from the sounding. Of course, the vertical wind field is expected to be sensitive to the strength and position of a potential inversion layer over the Po Valley. In particular, it is possible that air parcels in the COSMO model rise more easily than air parcels in reality if the the model's inversion strength is underestimated. Furthermore, any uncertainty in the height of an inversion layer becomes particularly relevant if it is around pass heights. However, the overall good agreement between Milan pseudo and observational soundings gives us confidence that in an average sense our climatological results are robust. Furthermore, it would be far from obvious how the modeled inversion height could be corrected.

2.3 Trajectory calculations

Lagranto is a software to analyze Lagrangian aspects of atmospheric flow phenomena (Wernli and Davies 1997). As Lagranto was originally designed to be used with ECMWF analyses it is adjusted to work with COSMO output, i.e., handling COSMO's rotated coordinate system and the different vertical grid structure. Several studies used Lagranto trajectories, e.g., Winschall et al. (2012) for severe floodings in the Alps or Roch (2011) to quantify orographic blocking based on a novel Lagrangian method. In a method comparison study, Miltenberger et al. (2013) compare the Lagranto-calculated trajectories with online trajectories within the COSMO model, whereas the later make use of the 20-sec availability of the wind fields during a COSMO forward integration. They find that forward trajectories can differ significantly over complex terrain, but even 2-hour resolved offline trajectories represent the Lagrangian path reliably if no flow bifurcation points are met. Note that the improved quality of online trajectories, as described in Miltenberger et al. (2013), would be of great value to Foehn research; however, in our setting they are not applicable because the analysis relies on backward trajectories whereas only forward trajectories are amenable online. In summary, the backward trajectories started at Altdorf and Ellbögen should not be interpreted too extensively over complex terrain. But away from topography, e.g., over the Po Valley in our case, the trajectories' quality should be okay. Finally note that Lagranto does not include any kind of turbulence parameterisation, i.e., it only relies on 1-hourly available 3D wind fields from the COSMO simulation.

A special treatment was applied if the air parcels intersect the surface topography, a problem which occurs due to imperfect treatment of the lower boundary condition in the model (Stohl et al., 2001). If a trajectory intersects the topography, it is artificially lifted by 10 m above ground and the air parcel is allowed to be advected again by the wind. Especially in a relatively high-resolution model like the COSMO reanalysis, this handling of (unphysical) surface crossings is very reasonable. On physical grounds one might argue that indeed for such near-surface air parcels the assumption of a laminar flow breaks down anyway and that therefore a re-lifting of the air parcels is appropriate. All in all, note that this near-surface handling and the lifting distance of 10 m do not influence the major arguments of this study.

The air parcels were released at several distinct stations and heights. Trajectories were run in backward mode, i.e., elucidating the source region, for: Altdorf in the Reuss Valley (46.87 ° N / 8.63 ° E / 449 m a.s.l), Vaduz in the Rhine Valley (47.14 ° N / 9.52 ° E / 457 m a.s.l) and Ellbögen in the Wipp/Inn Valley (47.1875 ° N / 11.4294 ° E / 1080 m a.s.l). Note that the pressure heights given do correspond to the approximate real height of these stations, not to the one corresponding to the COMSO model topography. Trajectories are started every 100 m in the vertical, starting with the closest one above model topography. Forward trajectories were run from several stations on the south side of the Alps (see Fig. 3). All trajectories were run 12 hours forward or backward in time. Furthermore, trajectories were also started not only at the exact latitude/longitude coordinates given above, but also for ten randomly, horizontally displaced ones. This allows to assess the coherence of the air streams. We decided that the starting points of the trajectories must be located inside a circle of a 8 km radius. If the radius is larger, the coherence of the trajectories gets too low and they lose their connection to the starting station. On the other hand, for a too small radius almost all trajectories have the same path within the time period considered and we lose the averaging effect we would like to have by choosing these different points. Note that complex wind fields, turbulence, deficiencies in topography representation in COSMO and numerical inaccuracies put some uncertainty to any trajectory calculation. For instance, we expect that the trajectories are sensitive to the horizontal and vertical starting positions. However, since we are interested in a climatological assessment of the trajectories we expect that these inaccuracies do not systematically affect the results of this study. In other words: We take single trajectories with some caution, but assume that the average over many Foehn trajectories is meaningful.

3 Case study: 2–4 April 2000

In this section, we consider a strong Foehn event which happened during the period 2–4 April 2000. The synoptic situation is typical for a prefrontal Foehn: a low over the Bay of Biscaya pushes air from the south-west towards the Alps (not shown) and a pressure difference of up to 8 hPa is established over the Alpine region, finally leading to the onset of Foehn winds in the northern Alpine valleys. The aim of the case study is to present and discuss the power of the Lagrangian perspective. It will become apparent that the complexity of the air streams arriving at the Foehn stations can only be captured with great difficulty in a pure Eulerian perspective.

3.1 Foehn observation and Eulerian perspective

In Altdorf Foehn breaks through around 9:30 UTC 2 April 2000 and brings an increase of almost 5 °C within ten minutes (not shown). The temperature stays around 15 °C and the wind direction is almost from south until the Foehn ends on 21 UTC 4 April 2000. With the Foehn breakthrough we can also detect a sharp increase in maximum wind gusts compared to almost no wind during the night before the Foehn, when Altdorf was possibly located in a pool of cold air. Finally there is a drastic decrease of the relative humidity from 70 % to 30 %. In short, all characteristic Foehn signals in wind gusts, temperature and relative humidity are well present for this case. The situation in Ellbögen is not so clear: Foehn breakthrough happens around 10 UTC 2 April 2000. While the Foehn is very stable in Altdorf it shows more transient nature in Ellbögen. The end of the Foehn phase is also clearly visible in Altdorf in a relative humidity increase which is not the case for Ellbögen, where there is more of a steady increase in temperature and wind speed.

The mesoscale Eulerian perspective of this Foehn case is shown in Fig. 2 at 1500 m and 3000 m asl and for two time instances. Note that the low-level wind over the Po Valley is characterised by an easterly jet, a feature which is very common during South Foehn (Bousquet and Smull 2003). This easterly wind is restricted to the lowest 2000 m and is bounded above by an inversion layer. Note that the inversion layer is also discernible in a radiosounding started at Milan, although there it is found at a slightly lower height (not shown). The layer of very stable air is located over the Po Valley (not shown) which is most pronounced on the western end of the valley at approximately 3000 m (Seibert 1990; Reeves and Lin 2006). The Po Valley jet (in the lower levels) is decoupled by this inversion from the free tropospheric flow. The jet is strongest on the eastern edge of the valley in a layer around 500 m to 1500 m and weakens towards the west, supposedly due to orographic blocking. In general, the jet as well as the stable layer dissolve on 4 April 2000, marking the end of the Foehn phase. If the horizontal wind field at Alpine crest height (3000 m, Fig. 2b) is considered, no easterly wind component is discernible anymore: the wind at this level is from south or south-west. Finally, one can note that immediately to the north of the Alps the highest wind speeds can be found, which is the COSMO representation of the Foehn.

From the inspection of the Eulerian wind fields at two time instances it is already clear that the path of actual air parcels to the south of the Alps can be rather complex, and hence cannot be reliably reconstructed. It is also not clear, if and in which way the flow arriving at Ellbögen and Altdorf differs. This aspect requires the calculation of kinematic trajectories.

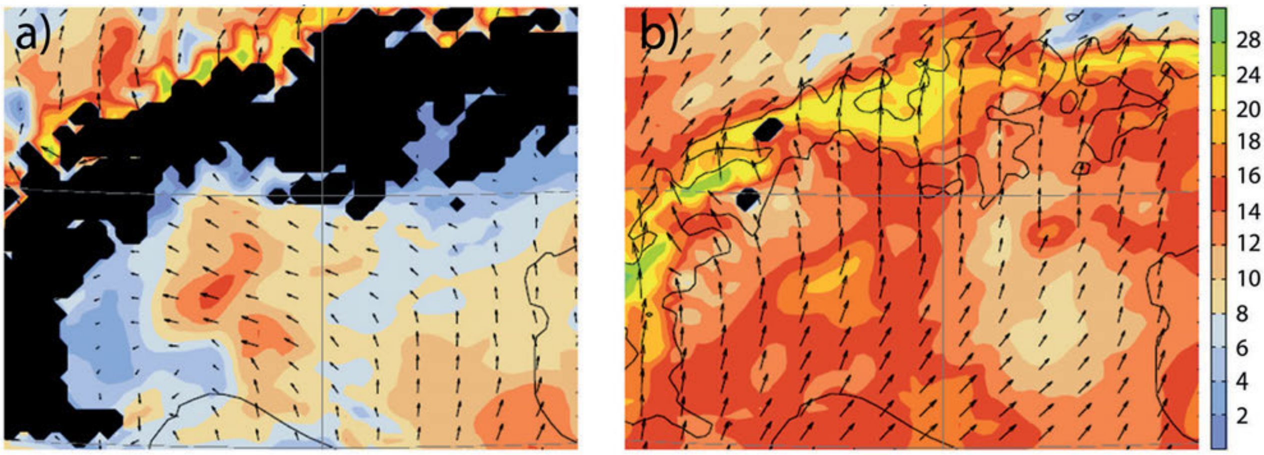

Figure 2: Horizontal wind vectors and wind speed (in [m/s], color shading) at 1500 m (left) and 3000 m (right) above sea level and for 10 UTC 3 April 2000. In the black region the topography is higher than the wind level.

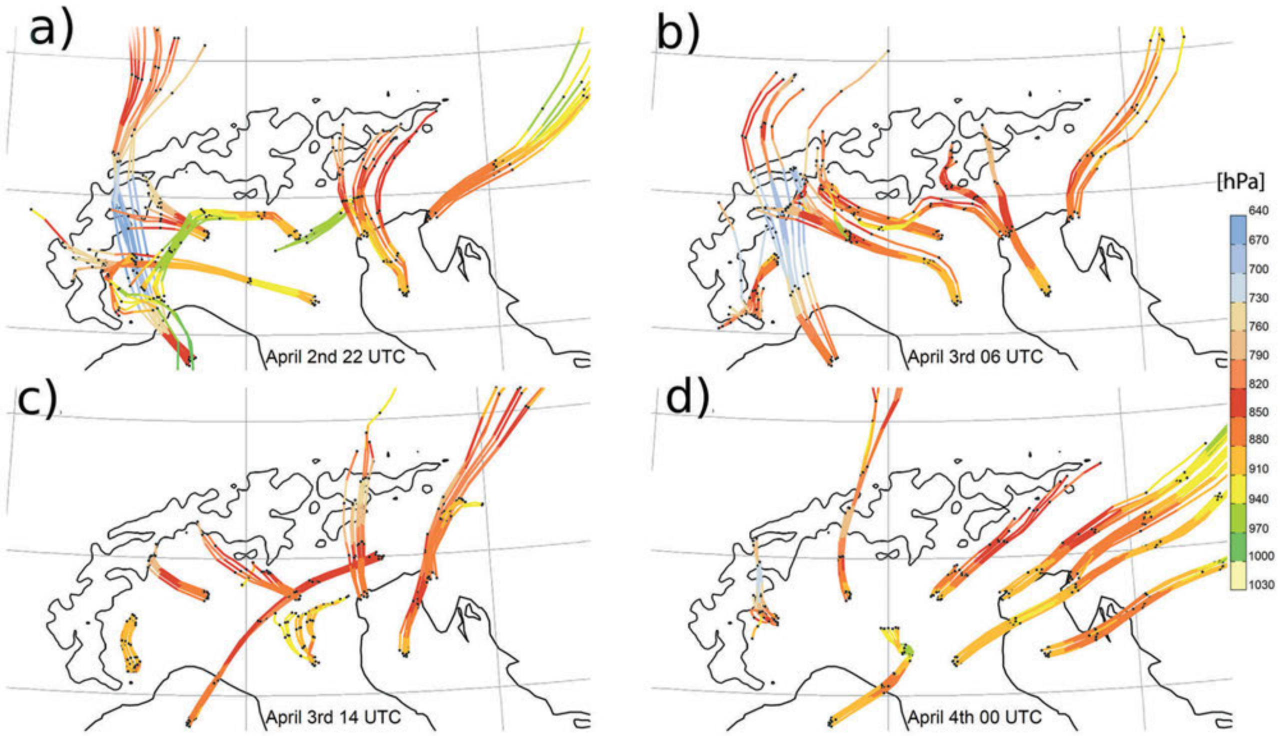

Figure 3: 12-hour forward trajectories beginning on (a) 22 UTC 2 April 2000, (b) 06 UTC 3 April 2000, (c) 14 UTC 3 April 2000, and (d) 00 UTC 4 April 2000. The starting heights are all set to 1000 m above sea level. The pressure (in hPa) of the air parcels is shown in color and the black dots indicate three hour intervals.

3.2 Lagrangian perspective

Fig. 3 shows 12 hours *forward* trajectories starting at 1000 m above sea level for four different dates during the Foehn event. As a first impression the rich variety of air streams can be noted: Depending on where and when the trajectories are started rather different paths emerge. The differences between the different Foehn phases are also clearly visible. During Foehn, a significant number of air parcels in lower levels is moving westward in the Po Valley jet and even turn south-west towards the western end of the Alps. Another large number of trajectories stops somewhere 'in the Alps'. Although this happens due to numerical deficiencies in the computation of the trajectories it clearly shows that these air parcels are not able to move over the topographic barrier. They can only rise up to around 800 or 750 hPa. It is supposed that a stable layer around 3000 m is one of the reasons why these air parcels cannot rise over the Alps (see Section 3.1). In addition, one can also see that air parcels starting at the most western point of the Po Valley have the smallest fraction of parcels rising over the Alps which might be

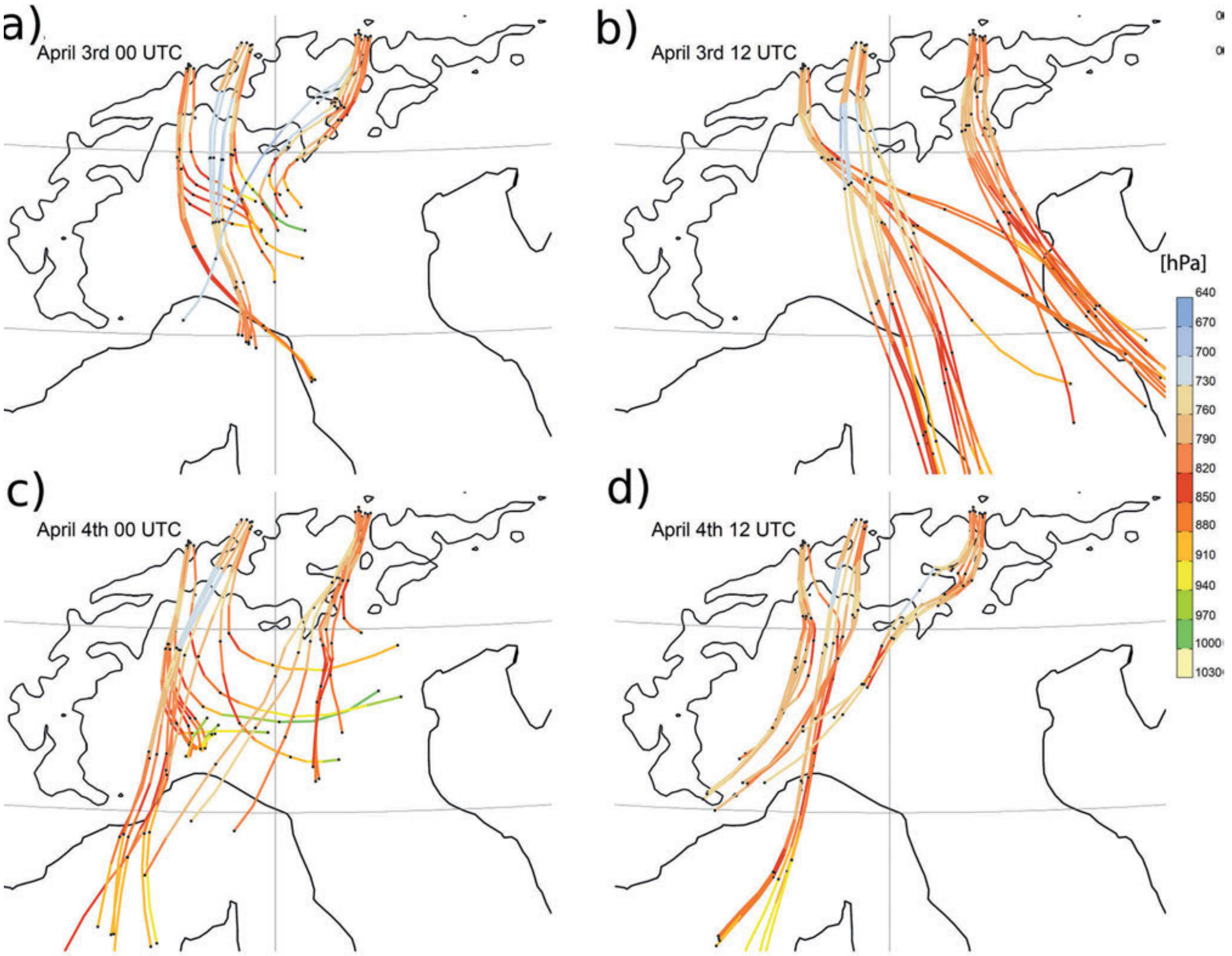

Figure 4: 12-hour backward trajectories starting on 1500 m for (a) 00 UTC 3 April 2000, (b) 12 UTC 3 April 2000, (c) 00 UTC 4 April 2000, and (d) 12 UTC 4 April 2000. The pressure (in hPa) of the air parcels is shown in color and the black dots indicate a three hours interval. The starting position of the backward trajectories are Altdorf, Vaduz and Ellbögen, as listed in Section 2.3 and shown in Fig. 1.

due to the strongest inversion located over this area and the high Alpine crest there. In summary, on the one hand there is blocked air in the lower levels of the Po Valley during the main Foehn event, on the other hand when the Foehn phase is finished one can see that the largest fraction of the air parcels moves together with the large-scale flow. Hence, these parcels seem to have much less problems in overcoming the orographic barrier except for the western end of the Alps.

In Fig. 4 one can see 12-hour *backward* trajectories starting on 1500 m for the three stations in the Foehn valleys (see Section 2.3). At the beginning of the event the air moves only very slowly compared to the later times. Furthermore, the air arriving in Altdorf quite often moves on lower levels than air heading to the other two stations (Vaduz and Ellbögen) and from time to time even passes below other parcels. Therefore, this air seems to be under the strongest influence of the Po Valley jet. Hence the Altdorf air undergoes the strongest ascent while for the other two stations no clear signal is visible. It is also apparent that the air in the Foehn valleys does not originate on the lowest levels on the south side of the Alps. Only a small part of the air originating in the lowest levels above the Po Valley arrives in Altdorf and therefore is rising over the Alps. During the main phase of the Foehn, the air has its source southeast of the stations while towards the end of the Foehn most of the air is coming from higher levels southwest of the Foehn valleys.

4 Climatological assessment

In this section the Lagrangian approach is extended to all Foehn cases in 2000–2002. Focus will only be given to the backward trajectory perspective, as presented in Section 3.2. Hence, the aim is not to show the complexity of the flow in the Alpine south side, but to characterize explicitly the air parcels arriving at the two Foehn stations Altdorf and Ellbögen. There are three different aspects which will be addressed: (i) Where are the Foehn air parcels at distinct time steps?; (ii) What is the vertical

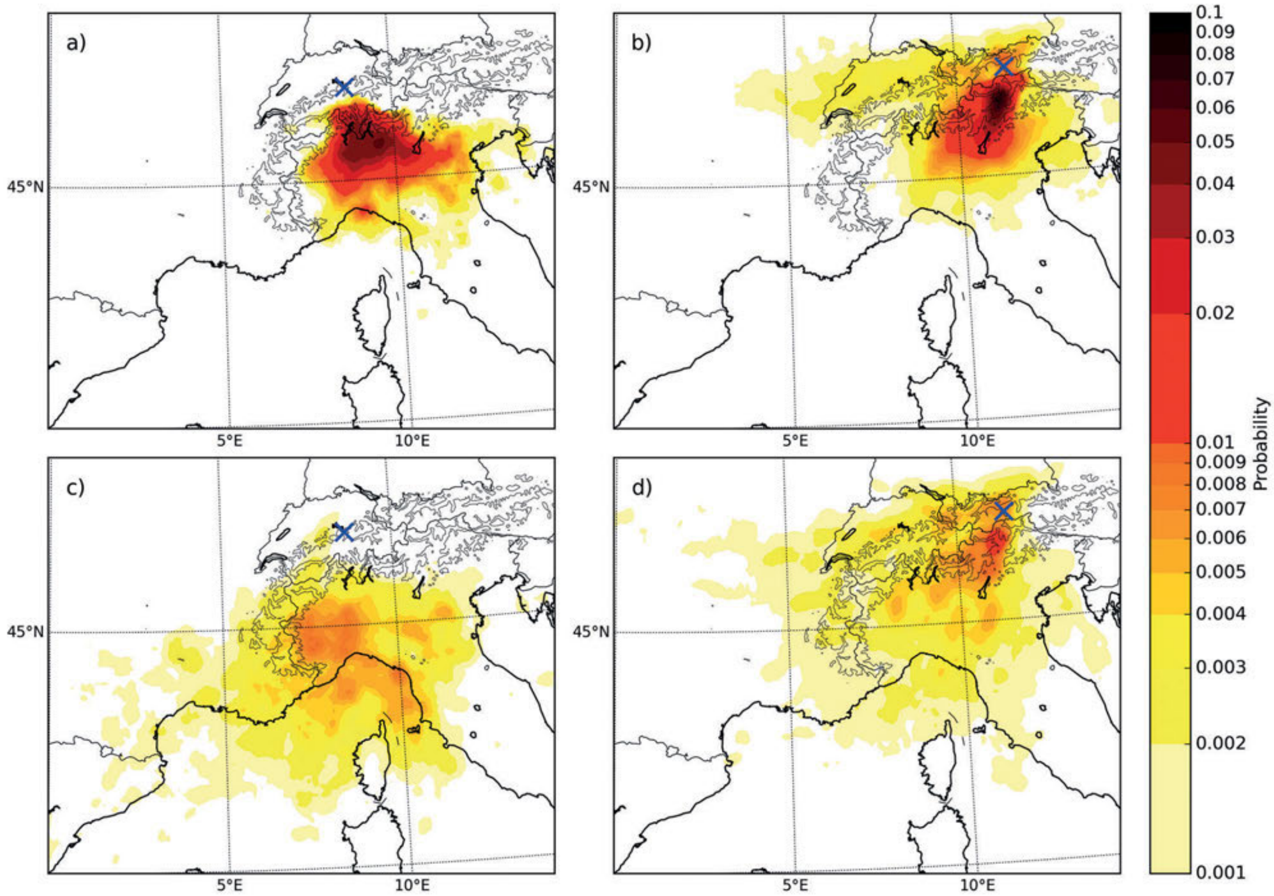

Figure 5: Mean position of the air parcels 12 hours prior to their arrival in Altdorf (left) and in Ellbögen (right). The upper panels correspond to a starting height of 1100 m for Altdorf and 1200 m for Ellbögen, i.e., for a height near the resolved topograph; in the lower two panels the starting height over Altdorf and Ellbögen is taken to be 2000 m. The coloring is nonlinear and displays the probability that a parcel has visited a geographical position (see Section 4.1 for details). The position of Altdorf (left panel) and Ellbögen (right panel) is marked with a blue cross. The contour line of the alps is drawn at 1500 m.

evolution of the air parcels on the Alpine south side?; (iii) Are there indications for different thermodynamic evolutions for the different stations? Note that we do not consider how the air parcels descend into the northern Foehn valleys, and therefore do not contribute to this long-standing question. The limitation with respect to numerics and model resolution forbid such an analysis in this study. All we intend is to characterize the air streams prior to their descending into the Foehn valleys, i.e., when they are still over the Po Valley and to the south of the Alpine crest. With respect to thermodynamics, our analysis can also only be a little step forward in understanding Foehn warming. We only correlate the backward trajectories with relative and specific humidity along the trajectories and with the surface precipitation beneath their path: no detailed analysis of heating mechanisms along the trajectories is undertaken.

4.1 Horizontal and vertical evolution

The horizontal position of the air 12 hours ahead of its arrival in the Foehn valleys gives information about the coherence as well as the velocity of the flow and is displayed in Fig. 5 for Altdorf and Ellbögen on low levels (always 1100 m for Altdorf and 1200 m for Ellbögen) and high levels (2000 m for both stations). The trajectory positions at time 12 h before arrival at Altdorf and Ellbögen are interpolated onto a longitude/latitude grid with 0.1 ° horizontal resolution. The gridding algorithm, described in detail in Škerlak (2014), includes a smoothing parameter of 20 km and the output gives the probability that a longitude/latitude vertex is visited, i.e., the values in Fig. 5 depend on the horizontal resolution of the grid. The sum over all grid points is equal to 1. One can see that for the lower level in Altdorf most of the air originates somewhere over the Po Valley and no preferred direction can be spotted. The air over Ellbögen originates favorably from a narrower band southwest of its destination. This can be seen in orange to red colors which make out the highest percentage of all trajectories (note the nonlinear scale). On 2000 m the geographical distributions for the two places are much more alike (Fig. 5c). However, the Altdorf air still seems to have a larger dispersion compared to the one of Ellbögen. The main difference between the two levels is

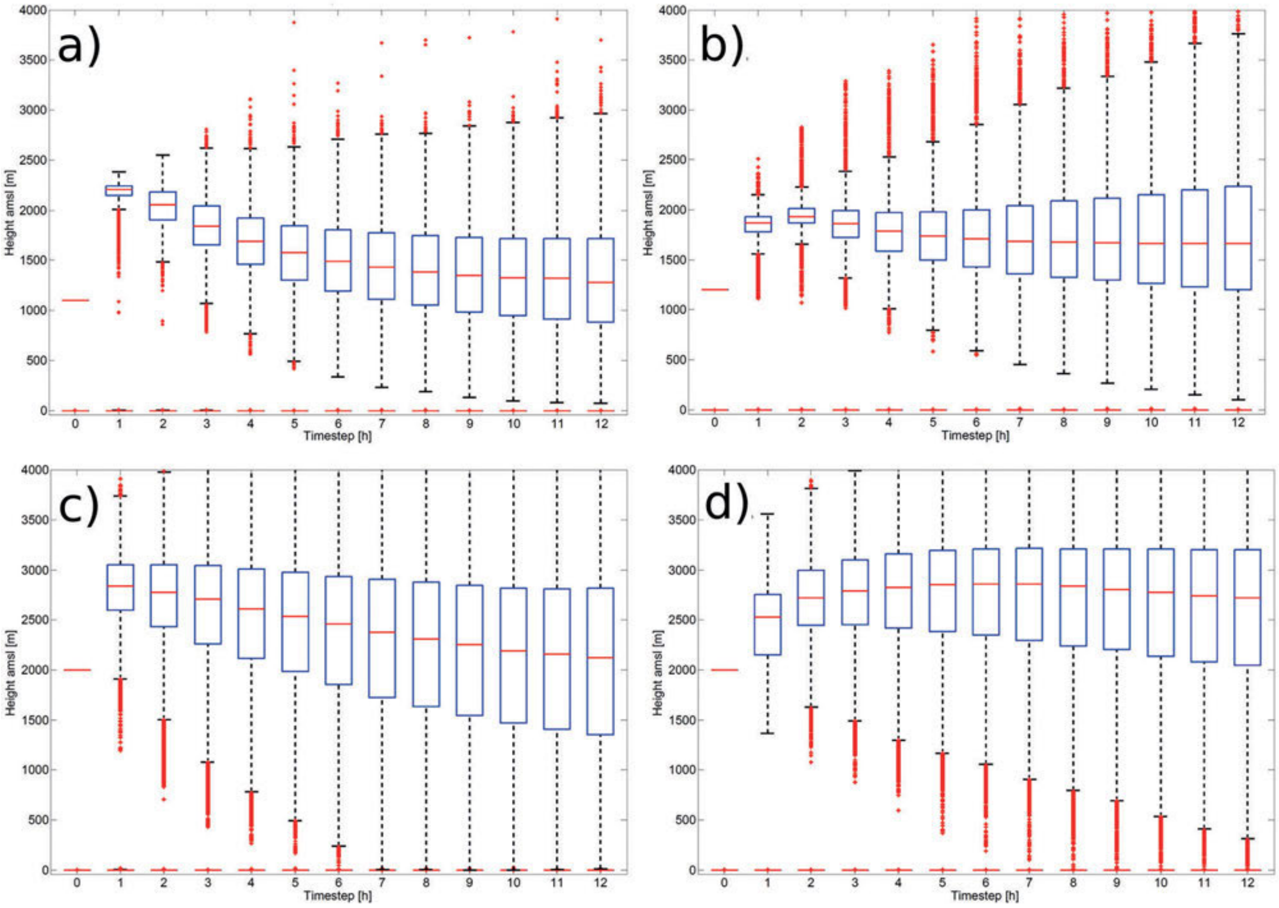

Figure 6: Box plots for the vertical position of the air during the 12-hour backward trajectories starting on 1100 m (a) and 2000 m (c) in Altdorf and on 1200 m (b) and 2000 m (d) in Ellbögen (as in Fig. 5). The horizontal axis gives the time (in [h]) before arrival at the respective Foehn station. The blue box includes, at the specific time, all air parcel heights between the 0.25 and 0.75 quantile, the median is marked as a red line within. Outliers are marked with red stars. At time 0 the box plot reduces to a well-defined height, corresponding to the fixed starting height.

the much larger path the upper-air covers. The obvious reason for this behaviour are the higher wind speeds at 2000 m which differs even more from the lower levels close to topography. Finally note that the probability of finding air parcels north of the stations is non-vanishing 12 h before arriving there. At first thought this is counter-intuitive. However, the percentages are indeed very small (note the nonlinear scale). Furthermore, it is well possible that rapid temporal evolution of the wind field, for instance near the ending stage of a Foehn event, can lead to strongly curved trajectories which originate north of the station. It is also possible that these cases are characteristic for shallow Foehn events (Sprenger and Schär, 2001), when the Foehn flow is restricted to levels below Alpine crest and the flow above is from westerly or even north-westerly direction. An indication for this scenario comes from a simple composite analysis. We looked at the mean geopotential field for all Foehn hours in Ellbögen when the air originates from further north (12 hours earlier). Indeed, it turns out (not shown) that the geopotential field is significantly more zonally oriented compared to a composite in which all Foehn hours are included. Of course, a very small part might also be attributed to wrongly classified Foehn hours in our Foehn climatologies, or simply to the fact that the numerical model does not correctly represent the basic Foehn situation.

Concerning the thermodynamic Foehn theory, the vertical pathway is of much interest. This is best shown in whisker plots of the vertical position of the air parcels at distinct time steps before they arrive at the Foehn station (Fig. 6): the blue box contains the median and the upper and lower quartile. The outliers are marked by red crosses and defined as points lying more than 1.5 times the interquartile range (IQR) lower than the first quartile or 1.5-IQR higher than the third quartile. The IQR is the difference between the first and third quartile. The boxplot in Fig. 6a shows the mean vertical evolution of the air mass arriving on 1100 m in Altdorf and for Ellbögen on 1200 m in Fig. 6b. The descent of the air into the valleys is similar for both stations although it is larger for Altdorf and also shows the ‘ability’ of the model to represent Foehn-like flow. The fundamental difference between the two stations lies in the behaviour of the air

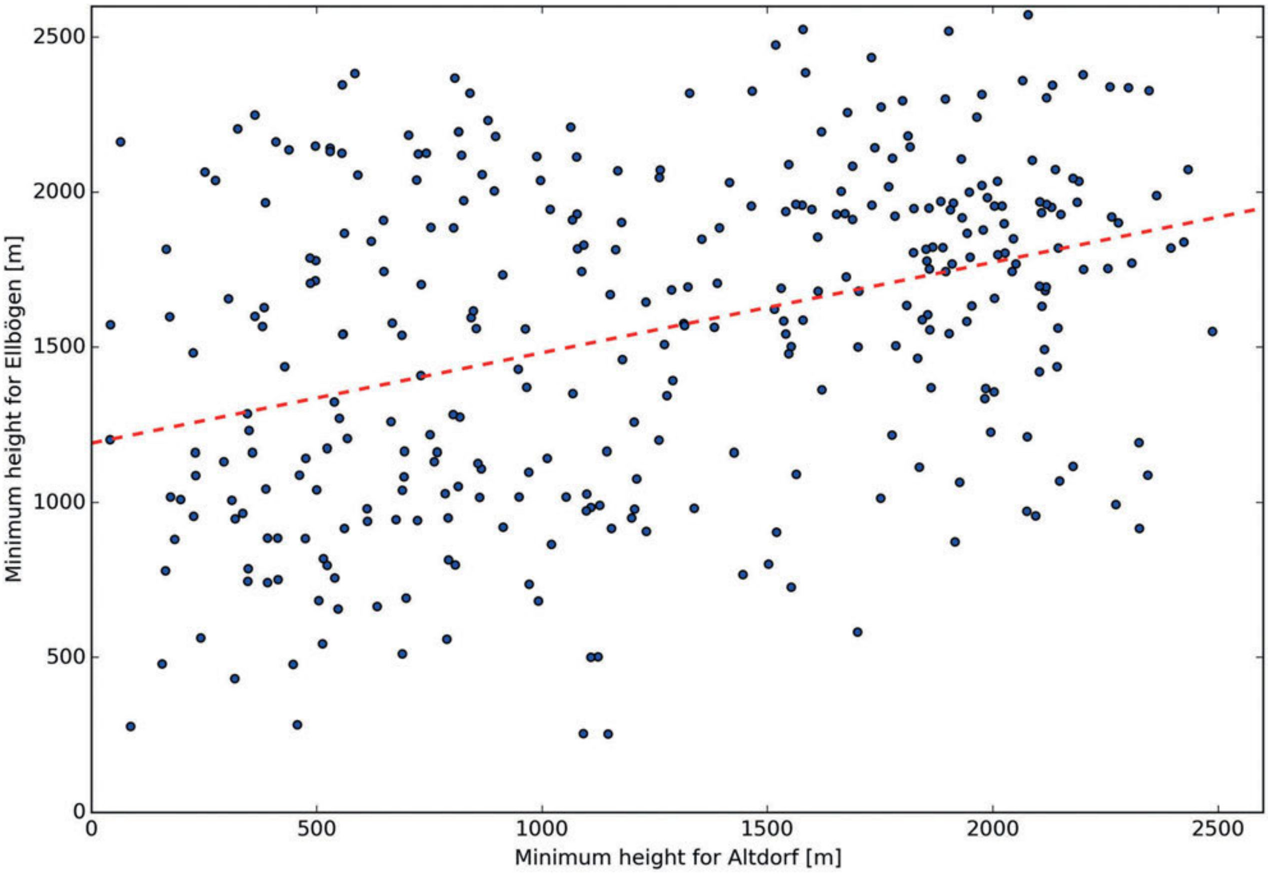

Figure 7: Scatter plot of lowest height the trajectories encounter over the Po Valley. All winter hours are included when both stations recorded Foehn. The average is taken over all trajectories that arrive at the same time on 1100 m (Altdorf) or 1200 m (Ellbögen). The red dashed line showes the result from a linear regression analysis.

mass on the upstream side of the Alps. For Altdorf, on average the air starts at around 1300 m and rises roughly 1000 m to get over the Alps. The results for Ellbögen differ in two ways: (i) The mean ascent is only around 300–400 m and most importantly some of the trajectories do not rise at all. For Altdorf almost all of the trajectories undergo an increase in altitude while for Ellbögen a significant fraction stays at the same level before dropping into the Wipp Valley; (ii) Additionally, the spread is larger for Ellbögen which could be related to the fact that the Foehn climatology contains more hours and therefore averages over a larger sample. Nevertheless, the general picture is clear and the differences between the two Foehn valleys are evident. Looking at the backward trajectories starting on 2000 m (Fig. 6c, d) one can detect similar features as for the lower levels, although with lower amplitudes. Most of the air passing over Ellbögen only rises marginally, while the air over Altdorf typically undergoes a significant ascent of roughly 600 m.

However, the conclusion from the previous paragraph must be taken with caution. In fact, in Fig. 6a the mean over all trajectories exhibit the Swiss-type ascending air motion. But there is also a substantial fraction of trajectories which are located above Gotthard pass height 12 hours before arriving at Altdorf. Hence, these trajectories conform to the Austrian Foehn type. In an analoguos way, the vertical evolution of the Ellbögen trajectories (in Fig. 6b) indicate that a substantial fraction of trajectories is far below Brenner pass height 12 hours before arriving at Ellbögen. Hence, these trajectories undergo significant lifting south of the Alps: a Swiss-type trajecory behavior at the Austrian station. In short, the significant spread of the vertical evolution confirms that both Foehn types can indeed be seen at both stations.

Finally, it is of interest to compare the Foehn trajectories in the two valleys, i.e., to assess if the ascent for the Ellbögen trajectories is correlated to the ascent of the Altdorf trajectories. Such a behavior can be expected if the ascent at both stations is ‘controlled’ by the same thermodynamic structure of the air in the Po Valley. For instance, it is reasonable to expect that both trajectories experience only weak ascent if a strong temperature inversion is present in the Po Valley *and* does not reach above pass heights. To quantify this aspect, Fig. 7 shows a scatter plot of ascent values during times when both stations experience Foehn, where only winter cases are considered. To focus on ascending trajectories, only the ones which ascent over 100 m are shown. The ascent associated with a Foehn trajectory is calculated as the difference between the lowest position of the air upstream of the Alps and the maximum above the Alpine crest. The scatter plot indicates that the two stations are not completely independent; however, all in all from the scatter plot it can be inferred that the correlation is rather weak, i.e., for any given minimal height of the Altdorf trajectories over the Po Valley a wide range of corresponding minimal heights for the Ellbögen trajectories is discernible. The correlation between the two stations is largest in winter with a r-value of 0.39 and a p-value of $2.0 \cdot 10^{-13}$. In spring the correlation is smallest and close to zero. We assume that the Po Valley inversions are strongest during winter, and that therefore the 'coupling' between the two station is strongest during this season. In short, the weak correlations indicate that there is 'no' common control for the minimal height of the two backward trajectories.

4.2 Thermodynamic evolution

Fig. 8 shows the evolution of relative humidity, the amount of precipitation along the backward trajectory and correspondingly the evolution of specific humidity, starting at 1100 m for Altdorf and 1200 m for Ellbögen. For Altdorf, relative humidity continuously increases, followed by an abrupt decrease during the last timestep (Fig. 8a). The magnitude of this decline is in the order of 45 %. The air arriving on 2000 m is around 20 % drier than the low-level air at the beginning of the trajectory but undergoes a steeper increase in relative humidity which makes it only 5 % drier on its arrival in Altdorf (not shown). The relative humidity for the trajectories terminating in Ellbögen (Fig. 8b) behaves as one would expect from the results of Section 4.1. Compared to Altdorf, Ellbögen trajectories experience RH values that are on average 10–20 % lower. In addition, the curve for the relative humidity is flatter and there are no abrupt changes.

The amount of precipitation along the backward trajectories is examined in Fig. 8c, d. While the trajectories for Ellbögen experience almost no rain, significant amounts reach the ground below air parcels two hours ahead of their arrival in Altdorf. Still a small reservation has to be made because it is not known at which model levels the precipitation has formed. However, the relative humidity plots can give a hint about the whereabouts of the rain and show that the air along the Altdorf trajectories reach RH very close to 100 % while the Ellbögen air rarely reaches saturation. Accordingly the specific humidity along the trajectories drops roughly 1 g/kg through hour 4 to hour 1 for Altdorf (Fig. 8e, f) while it stays almost constant for Ellbögen. The average hourly precipitation rates in Fig. 9 confirm the aforementioned conclusions that there is much less rain falling on the southern side of the Alps near Ellbögen than near Altdorf. Along the southwestern edge of the Alps, the mean rainfall reaches values up to 1 mm/h during Foehn in Altdorf. On the eastern part there is significant less rain with only around 0.5 mm/h while there is Foehn in Ellbögen.

5 Discussion

5.1 Lifting mechanims

Having established the stronger lifting for the Altdorf Foehn air compared to the Ellbögen one, the question now arises how this lifting is enforced. There are different aspects which must be taken into account (e.g., Rotunno and Ferreti, 2001): (i) orographic lifting, (ii) low-level convergence and (iii) influence of temperature inversions in the Po Valley. The discussion in this section cannot be exhaustive, but only intends to address some selected topics.

First, the convergence on the southern side of the Alps that the air arriving on 1100 m in Altdorf experiences is significantly stronger than for the air arriving in Ellbögen on 1200 m: Indeed, the mean convergence that the Altdorf trajectories experience is $1 \cdot 10^{-3}\,\mathrm{s}^{-1}$, compared to about $0.25 \cdot 10^{-3}\,\mathrm{s}^{-1}$ for the Ellbögen trajectories (Fig. 10c, d). Note that immediately before the air parcels arrive at their respective site, the divergence signal becomes 'erratic': In particular, the signal at Altdorf changes sign for times 0 and 1 h (from convergent to divergent flow) and attains huge amplitudes (up to $15 \cdot 10^{-3}\,\mathrm{s}^{-1}$). This is most likely associated with substantial gravity-wave activity and must be taken with some caveat. For the trajectories starting at 2000 m, the divergence/convergence is almost zero (not shown). The geographical pattern of divergence shows a clearly convergent flow in the western part of the Po Valley (not shown). This is particularly apparent at 500 m above sea level, and matches well with the mean vertical wind speed at 1000 m (Fig. 10a). At 2000 m height, the predominance of ascending air in the western Po Valley is even more pronounced (Fig. 10b), however the direct correlation to divergence gets lost. In summary, we expect low-level convergence to be more important as a lifting mechanism for Altdorf than for Ellbögen.

Quantifying the impact of orographic lifting is more challenging. Typically, the inverse Froude number is used to determine whether atmospheric flow passes over or around a mountain (Reinecke and Durran, 2008 and references therein). It is based upon the vertical stratification N, average mountain height (H, 3000 m for the main Alpine crest) and impinging flow velocity (U), and is then calculated as $Fr = N \cdot H/U$. The larger Fr, the stronger the blocking tendency of the flow due to the mountain. We calculate this quantity for different points in the region of the Po Valley at 1500 m height and only account for trajectories that are approaching with a maximum angle of 60 degrees between the direction of the trajectory and the Alpine crestline. The results show a region with lowest values of Fr in a band with width 50 km west of Milan. The values are as small as 2 with most of them around 4. West of this region the number is larger because the flow is not directed towards the Alps and east of the region it is larger because of the higher stability. On average there are Froude numbers of 15 to 20 or even higher in these other regions

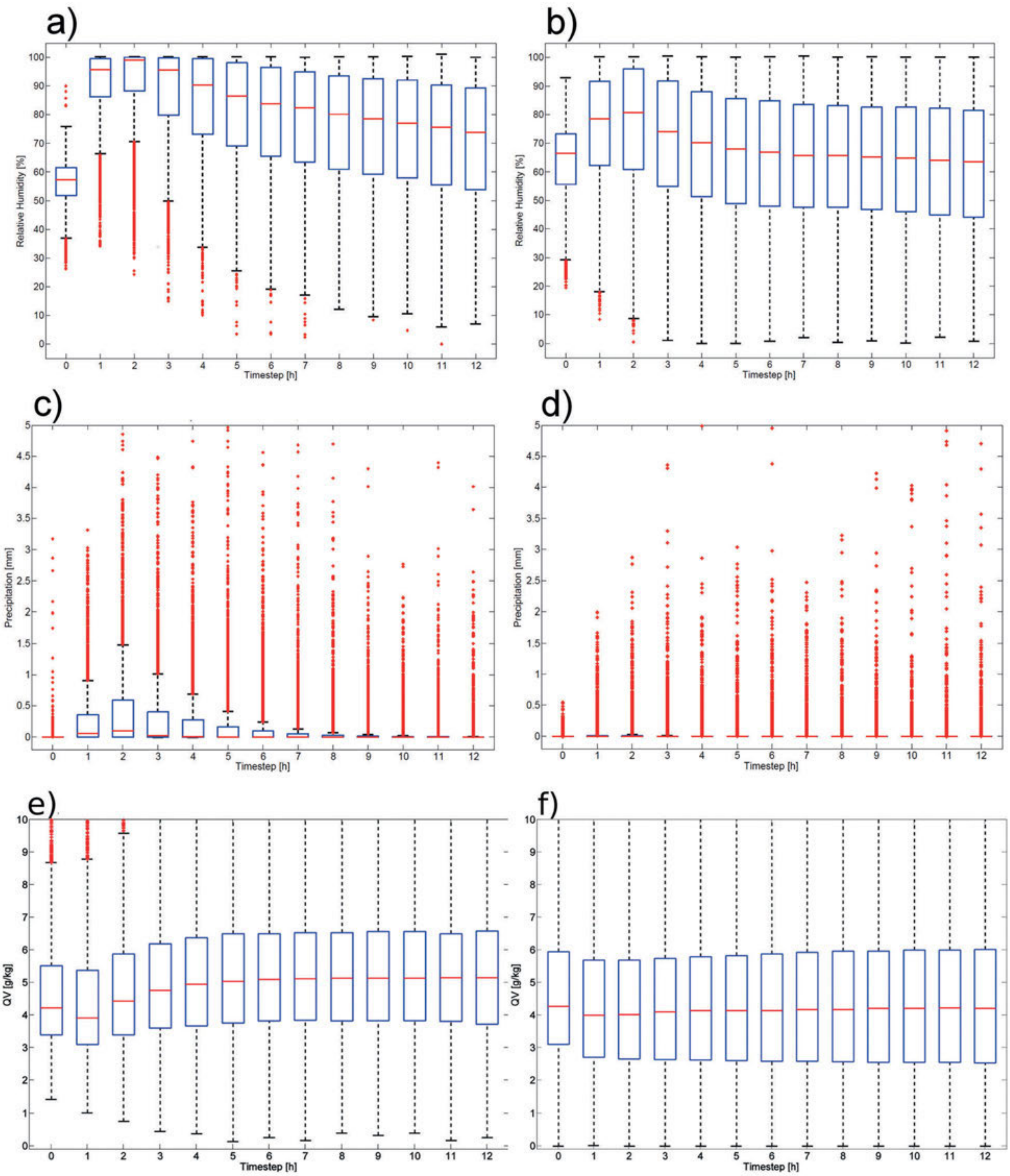

Figure 8: Box plots as in Fig. 6, however showing the evolution of relative humidity (in [%], upper row), 1-h accumulated precipitation (in [mm], middle row) and specific humidity (in [g/kg], lower row), all taken from the COSMO model. The starting heights of the backward trajectories are the same as in Fig. 6, i.e., 1100 m for Altdorf (left) and 1200 m for Ellbögen.

while in the band mentioned they very rarely exceed 10. Also, south of Ellbögen on 2000 m a significant part of the movement is towards the east and not northward. In summary rising from close to the ground seems to happen mainly in a band with north-south extension and a width of approximately 50 km west of Milan. These results are also confirmed by looking at the vertical motions averaged over all the Foehn hours (Fig. 10a, b). They easily reach 0.1 m/s in this region while outside it rarely exceeds 0.05 m/s. Note that the use of the inverse Froude number as a measure of flow blocking is associated with many difficulties, and therefore can only be

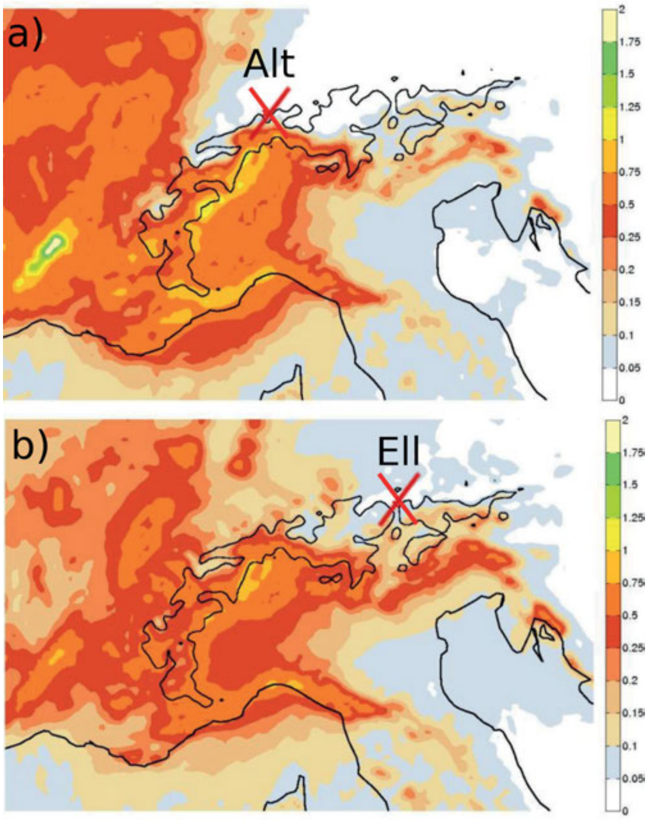

Figure 9: Total hourly precipitation rate [mm/h] averaged for all Foehn hours in Altdorf (a) and Ellbögen (b). As in Fig. 6 precipitation is taken from the COSMO model. The 1500-m height contour (thin black line) for the Alps is shown to better relate the precipitation field with the Alpine barrier.

taken as a first rough measure. For instance, the Eulerian inverse Froude number cannot reasonably take into account the case of a complex vertical stability profile, e.g., a temperature inversion. Furthermore, a more refined analysis would have to consider moisture effects on the stability. Here we restrict from doing so because we expect the uncertainty of any Eulerian blocking analysis to be too large.

Finally, the low-level flow in the Po Valley is often decoupled from the mid-tropospheric flow by a pronounced temperature inversion. It is clear that this inversion strongly influences the vertical displacement of the air and any difference in inversion strength and height might show up in Altdorf/Ellbögen differences. The squared Brunt-Väisälä frequency is around $2 \cdot 10^{-4}\,\mathrm{s}^2$ for both low level trajectories. It rises only a little during the last hours ahead of the crest for Altdorf and goes up to $3.3 \cdot 10^{-4}\,\mathrm{s}^2$ for Ellbögen. To get an idea of the location of the inversion on the southern side of the Alps we choose a location for each of the Foehn stations where the air is 3–4 hours prior to its arrival. Then, we calculate the height where the squared Brunt-Väisälä frequency is largest between 1300 and 4000 m – the first height chosen not too close to the ground and hence not being dominated by night-time inversions and the second one to reach levels above the main Alpine crest. South of Altdorf the most stable layers lie around 2700 m with a smaller maximum around 1700 m. For Ellbögen the inversions are found at lower levels, between 1700 m and 2300 m almost 50 % of the time. These heights must be compared to the heights of the south-north transecting mountain passes in the model, i.e., to the Gotthard pass (2076 m) for Altdorf and the Brenner pass (1714 m) for Ellbögen. The lower gap of the Brenner is very narrow in reality while that the upper gap (2300 m–2800 m) has a very significant influence on the flow both upstream and downstream (Armi and Mayr 2007). This steep topography is the reason why the Brenner is much higher in the model and it can be expected that the model does not reproduce the narrow lower gap.

5.2 A potential Foehn type predictor

In Section 4 the Austrian and the Swiss Foehn types were shown to be predominant in the respective countries. On the other hand, an Austrian Foehn type will also be observed in Switzerland and vice versa. In short, the geographical connotation of the two types must not hide that there is in fact a continuous spectrum of Foehn types, of which the Austrian and Swiss types are only the most extreme ones. Here, we try to define a parameter which might help the forecaster to decide which of the two types is found and/or to which degree they apply. The suggested parameter relies on the the presence of orographic blocking in the Po Valley. In fact, Richner and Hächler (2013) suggest that the blocking of air in the Po Valley, due to a capping inversion or a strongly stratified air layer, is directly related to the ascent or its absence of air parcel trajectories (their Figure 4.5 and Section 5.1). This motivated us to split our Altdorf climatology into different distinct classes: one extreme class is characterized by strong vertical ascent of the trajectories arriving in Altdorf, the other by the lack of it. More specifically, for each Foehn hour we consider the ensemble of backward trajectories starting at 1100 m a.s.l above Altdorf (see Section 2.3). We then find the maximum height $z_{\max}$ of all these trajectories within the preceding 12 h and north of 44 °N (taken as simple southern boundary of the Po Valley). Typically this maximum height is attained as the air parcels surmount the Alpine crest (see Fig. 6 at time -1 h). During the time before this maximum height, the minimum height $z_{\min}$ of the trajectories north of 44 °N is determined, literally interpreted as the minimum height of the trajectories over the Po Valley. Finally, the mean of all minimum heights is taken and attributed to the specific Foehn hour. This procedure then allows a physically meaningful separation between blocked and unblocked flow situation in the Po Valley. Here, we consider three distinct categories, corresponding to large ascent, medium ascent and no ascent over the Po Valley: (i) $z_{\min} < 500$ m; (ii) $1000\,\mathrm{m} < z_{\min} < 1500$ m; and (iii) $z_{\min} > 2000$ m. All these heights have to be compared to the Gotthard pass height of $\sim$ 2100 m. The

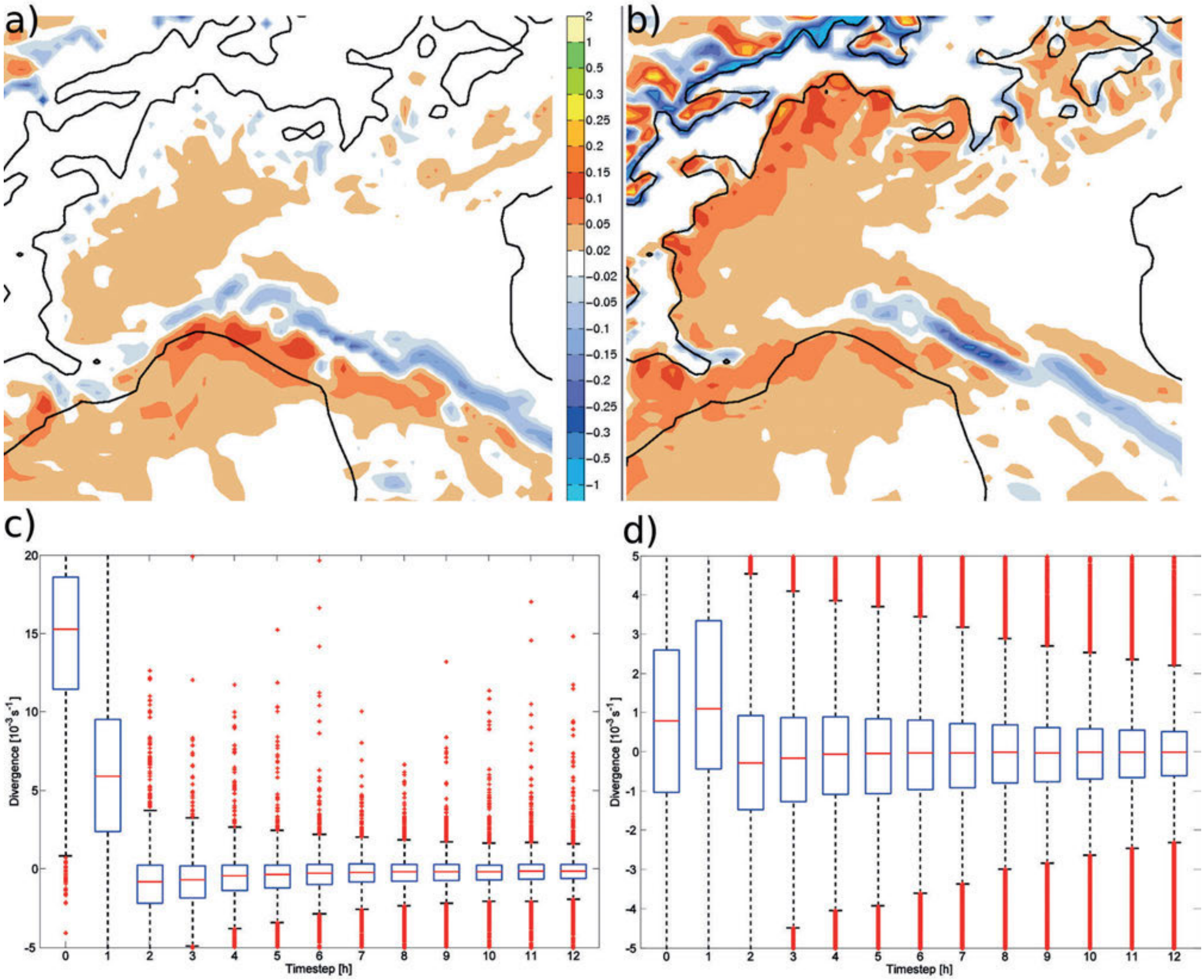

Figure 10: Averaged vertical wind speed (in [m/s]) in the Po Valley at (a) 1000 m and (b) 2000 m above sea level. The average is taken over all hours with Foehn in Altdorf. In the lower panels, horizontal wind divergence (in $[10^{-3}\,\mathrm{s}^{-1}]$) is traced along the backward trajectories: (c) for air parcels arriving in Altdorf and (c) air parcels arriving in Ellbögen (d). Note the different axis range for panels (c) and (d).

distribution of $z_{\min}$ is shown in Fig. 11 for all Foehn hours in Altdorf: $z_{\min} < 500\,\mathrm{m}$ is quite common, peak values are around 1000 m and fully blocked flows with $z_{\min} > 2000\,\mathrm{m}$ do also occur.

Based on the classification described above we compiled composite pseudo-soundings at Milan, which is located essentially to the south of Altdorf and in the 'middle' of the Po Valley. We expect this sounding to be representative for the flow approaching the Swiss Alps during Foehn, and wonder whether the Foehn classification is also discernible in the Milan pseudo-sounding. If so, there might be the potential to reverse the argument and take the Milan sounding itself as a predictor of the Foehn type. The composite soundings for winter are shown in Fig. 12 a and b, including (equivalent) potential temperature and wind speed. Starting with potential temperature, we see that the blocked situation (green) is characterized by a near-surface cold pool and steeply increasing potential temperature (strong stratification) there. The difference between potential temperature at pass height ($\sim$ 785 hPa) and surface is about 10 K. At pass height, the air is slightly warmer than for e.g. the unblocked situation (blue), indicating an overall more stable stratification in the air column. This agrees with expectation: In fact, a cold stable layer is prerequisite for blocking and therefore cooler potential temperature can be found in the Po Valley. An interesting S-like structure is discernible for the case with largest ascent (blue): Below $\sim$ 850 hPa the potential temperature profile closely matches with the blocked curve, but then it only weakly increases further with height. This indicates a two-layer structure over the Po Valley, where the lower layer is more strongly stratified than the layer above. Fig. 12b shows the zonal and meridional wind speeds for the different classes. For all classes a westward wind maximum is discernible: It is particularly clear ($\sim 7\,\mathrm{m}/s$ at 950 hPa) for the unblocked class (blue), indicating the presence of a well-established low-level Po Valley jet. In the case of intermediate ascent (red) the westward jet is weaker and more uniformly spread between 950 and

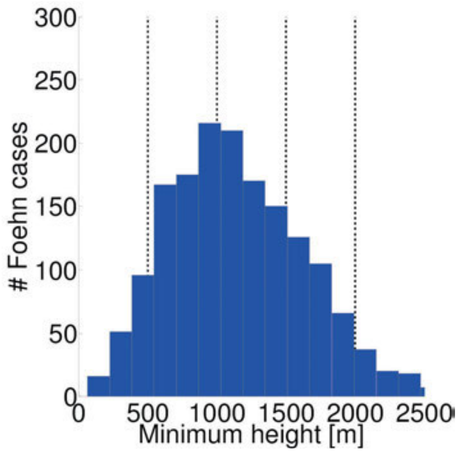

Figure 11: Histogram of minimum heights of trajectories over the Po Valley, including all Foehn trajectories arriving at 1100 m a.s.l. in Altdorf (see Section 5.2 for details). The three different categories discussed in Fig. 12 are defined as $z_{\mathrm{min}} < 500$ m; 1000 m $< z_{\mathrm{min}} <$ 1500 m; and $z_{\mathrm{min}} > 2000$ m.

900 hPa. Finally, in the case of blocked flow (green), still weaker westward wind speeds are found. This applies also to the meridional wind speed which is weaker in this case compared to the two categories with ascending air.

The discussion so far was restricted to winter. A comparison to the other seasons, except for summer due to its infrequent Foehn cases (see Table 1), is mandatory and also shown in Fig. 12. In spring (panels c, d) the profiles of potential temperature show some differences compared to the ones in winter. Overall the structure of the potential temperature profile is characterized by weaker stratification in the lower levels (smaller increase with height) and somewhat enlarged stratification above ~ 800 hPa. The overall difference of ~ 5 K between potential temperature at pass height and surface is considerably smaller than in winter (~ 10 K). The three wind profiles are rather similar, quite in contrast to winter (panel b). A flat westward wind maximum (~ 4 m/s) can be seen between 900 and 850 hPa for all three categories. Finally, in autumn (panels e, f) the profiles of potential temperature and wind speed becomes again more reminiscent of winter profiles. The potential temperature difference between pass height and surface is similar to winter (~ 10 K), but the two ascending categories (blue and red) do not differ as much as in winter; again, the unblocked situation (blue) exhibits a two-layer structure with a transition at ~ 825 hPa. The similarity between the two ascending classes is also reflected in the wind speed profiles, which again exhibit a clear near-surface (~ 950 hPa) westward wind maximum for the two ascending categories. On the other hand, the blocked category (green) stands out with substantially weaker wind speeds.

The occurrence of a clear Po valley jet is consistent with the potential temperature profile, as discussed before. For instance, a two-layer structure goes along with a well-established low-level jet. However, there are also features in Fig. 12 which are counter-intuitive and cannot easily be explained. In Fig. 12c the difference in potential temperature between pass height and surface is larger for the intermediate category (red) than for the blocked one (green). Similarly, in autumn the blocked category (green) exhibits the weakest stratification and the unblocked one (blue) is most stably stratified below 850 hPa. It's difficult from the composite pseudo-soundings of potential temperature alone to decide how this can be the case. An indication comes from the consideration of equivalent potential temperature (θ_e) profiles, which are also shown in Fig. 12 (dashed lines). In winter (Fig. 12a), θ_e profiles are stable, with a slight unstable situation for blocked situation at ~ 850 hPa; the θ_e profiles in spring are much more neutral, except for a weak unstable θ_e profile around ~ 850 hPa. Finally, in autumn the unblocked situation (blue) has the steepest θ_e profile below ~ 850 hPa, followed by the intermediate situation (red). The blocked situation (green), on the other hand, has an essentially neutral θ_e profile. In short, moist stability can differ substantially for the different categories and also for the different seasons. This becomes particularly relevant considering the high relative humidities experienced by the air parcels (see Fig. 8). Finally, it is also well possible that the composite analysis is not sharp enough to capture the relevant features of the stability profile! For instance, it is well known that temperature inversions are very important for Foehn dynamics, and exactly these narrow inversion layers at different heights might be smeared out by the composite analysis.

Coming back to the initial question – whether the Milan sounding can be used to distinguish blocked from unblocked flow situations – it can be stated that there are distinct differences between the categories, but that these differences are not large enough to unambiguously reverse the argumentation.

6 Conclusions

Using a three-year (2000–2002) Foehn climatology at Altdorf (Switzerland) and Ellbögen (Austria) and NWP reanalysis data based on the COSMO model, a Lagrangian based analysis of air flow has been presented. In a detailed case study, it was clearly shown that the flow during Foehn on the Alpine South side can be rather complicated and it is far from simple to determine the source of air parcels arriving at a Foehn station from pure Eulerian fields. Two complicating factors are: (i) non-stationarity of the flow; (ii) decoupling of low-level easterly flow in the Po Valley from the upper-level south to south-westerly flow. The Lagrangian approach circumvents this difficulty by directly following the air parcels on their way. The analysis of the Lagrangian backward trajectories for almost 8000 Foehn hours in total builds the main focus of this study. The key results are summarized as follows:

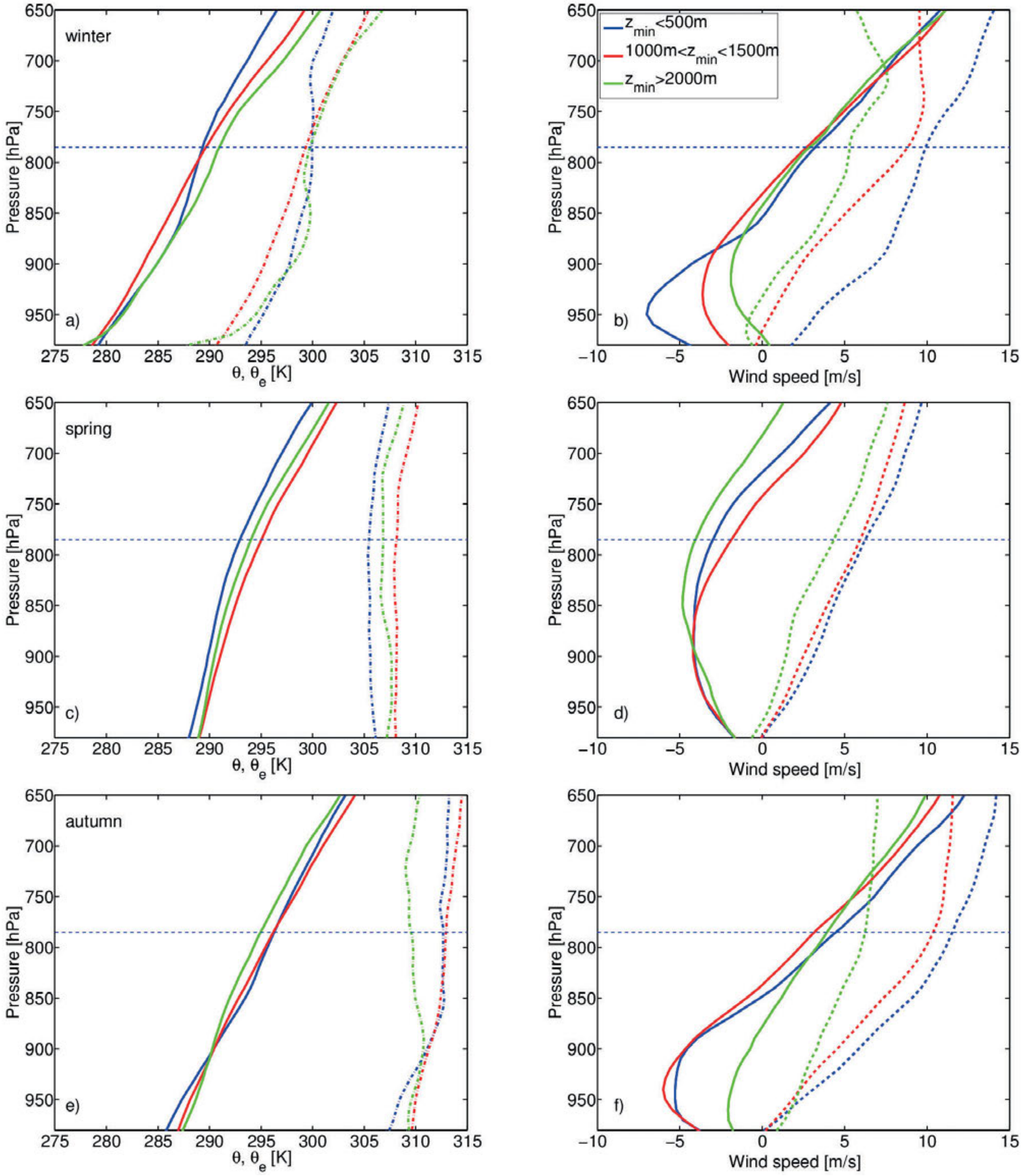

Figure 12: Composite of COSMO pseudo-sounding at Milan for Foehn hours at Altdorf separated according to the minimum height of the backward trajectory over the Po Valley (see Section 5.2 for details): $z_{\mathrm{min}} < 500$ m (blue), $1000\,\mathrm{m} < z_{\mathrm{min}} < 1500$ m (red) and $z_{\mathrm{min}} > 2000$ m (green). The dashed blue line (at 785 hPa) corresponds to the approximate height of the Gotthard pass which is the main ‘feeder’ for Foehn air in Altdorf. Left panels show potential temperature (in K) for the three main Foehn seasons, the right panels correspondingly the wind speed components (in m/s) in west-east (solid) and south-north (dashed) direction. The three rows are for winter, spring and autumn.

- It was shown that for Altdorf, a significant part of the air parcels originates at low levels over the Po Valley, then ascends to the height of the Gotthard pass before steeply descending into the northern Reuss Valley. In contrast, for Ellbögen in the Wipp Valley, the ascent on the Alpine southside is weaker and hence the air originates mostly from higher levels. This is a first climatological differentiation between specific Foehn valleys and in general, the results confirm the existence of two distinct Foehn types: a Swiss one with significant lifting on the Alpine south side and an Austrian one with near-horizontal flow on the south (as described in Steinacker, 1983). Seibert (1990) asks about the difference of the Foehn behaviour between the western and eastern Alps and the easterly flow in the Po Valley. Our study is a first hint at how this difference looks like. Foehn air moving over the Gotthard pass undergoes much larger changes in height and originates on lower levels over the Po Valley compared to air arriving in more eastern valleys.

- By tracing the precipitation and relative humidity of the air parcels, we conclude that although the air parcels are quite humid, rainfall is no requirement at all during Foehn. In particular, compared to Ellbögen the Foehn air arriving in Altdorf experiences larger values of relative humidity and is more often associated with precipitation. This agrees well with cloud specific humidity traced along the backward trajectories, which remains more stationary for Ellbögen. This hints to distinctive processes contributing to Foehn air warming: the Swiss Foehn appears to follow more closely the evolution proposed by the thermodynamic Foehn theory. The available data did not allow for the calculation of latent heating caused by condensation, this might be question for a future study.
- All Foehn cases in Altdorf were split into three distinct classes, depending on the minimum height attained by the backward trajectories over the Po Valley. Composite pseudo-profiles are then separately calculated at Milan, which is located south of Altdorf. Clear differences between the classes are discernible with respect to the profile of potential temperature and wind. For instance, during winter the profile of potential temperature takes a two-layer structure (S-like) for largest ascent (originating below 500 m a.s.l in the Po Valley). This is also reflected by a pronounced westward low-level jet over the Po Valley around 950 hPa. In the case of intermediate ascent, originating from levels between 1000–1500 m over the Po Valley, or nearly lack of any ascent (above 2000 m over Po Valley), the low level-jet is less well established. A clear difference is also discernible between the spring and autumn composites: The westward jet is much more pronounced, at lower levels and focused near surface, in autumn. In spring, the jet maximum is situated at considerably higher levels, which coincides with a correspondingly smaller stratification over the Po Valley.

The presented results hint to a distinction between a Swiss Foehn type and an Austrian one, whereas the former more closely fulfills the vertical evolution envisioned in the thermodynamic Foehn theory. However, it must be kept in mind that the denomination of the Foehn as 'Austrian' or 'Swiss' is also misleading: Both types of Foehn occur at both Foehn stations. Our study only shows that the Swiss type is predominant at Altdorf (Switzerland), and correspondingly the Austrian type is more frequent at Ellbögen (Austria). Furthermore, the analysis of Milan soundings indicates that, at least in winter, the Foehn type is also discernible from this sounding alone. However, it remains unclear whether the differences are 'sharp' enough to reverse the line of argumentation and use the Milan sounding as an unambiguous predictor of Foehn type in Altdorf. Further studies in this direction will be necessary.

Beside these little steps toward a better understanding of Alpine Foehn, the study highlights a complementary methodological step toward Foehn research and mountain meteorology in general. In fact, Lagrangian methods for the Alpine Foehn were neglected compared to Eulerian studies in the past due to the complexity of orographic flows. Here, we showed that well-defined research questions are in the reach of Lagrangian methods, i.e., if the trajectories are not over-interpreted where the temporal and spatial resolution of the NWP models clearly do not suffice, e.g., within the narrow Foehn valleys of the Alps. On the other hand, novel possibilities become available if the realm of offline trajectories is left and online trajectories are used, where the full temporal resolution of NWP winds is used. Recent progress in this direction was reported by Miltenberger et al. (2013) for a north Foehn case, and we intend to adopt this new research tool to better understand the warming of Foehn air as it descends into the valleys.

7 Acknowlegdgements

We would like to thank Georg Mayr and Susanne Drechsel for providing the Foehn climatology at Ellbögen; the Altdorf Foehn climatology was provided by Bruno Dürr and the Arbeitsgemeinschaft Foehnforschung Rheintal (AGF, www.agf.ch). Finally, thanks to the national Swiss Meteorological Service (MeteoSwiss) for help with the COSMO reanalysis data set.

References

Armi, L., G.J. Mayr, 2007: Continuously stratified flow across an Alpine crest with a pass: Shallow and deep föhn. – Quart. J. Roy. Meteor. Soc. **133**, 459–477.

Bousquet, O., B.F. Smull, 2003: Observations and impacts of upstream blocking during a widespread orographic precipitation event. – Quart. J. Roy. Meteor. Soc. **129**, 391–409.

Drechsel, S., G.J. Mayr, 2008: Objective forecasting of foehn winds for a subgridscale alpine valley. – Wea. Forecast. **2**, 205218.

Drobinski, P., R. Steinacker, H. Richner, K. Baumann-Stanzer, G. Beffrey, N. Benech, H. Berger, B. Chimani, A. Dabas, M. Dorninger, B. Dürr, C. Flamant, M. Frioud, M. Furger, I. Gröhn, S. Gubser, T. Gutermann, C. Häberli, E. Häller-Scharnhost, G. Jaubert, M. Lothon, V. Mitev, U. Pechinger, M. Piringer, M. Ratheiser, D. Ruffieux, G. Seiz, M. Spatzierer, S. Tschannett, S. Vogt, R. Werner, G. Zängl, 2007: Föhn in the Rhine Valley during MAP: A review of its multiscale dynamics in complex valley geometry. – Quart. J. Roy. Meteor. Soc. **133**, 897–916.

Dürr, B., 2008: Automatisiertes Verfahren zur Bestimmung von Föhn in Alpentälern. – Arbeitsbericht **223**, MeteoSchweiz, 22 pp., available at www.meteoswiss.ch

Föst, F., 2006: Eine objektive Föhnklimatologie für das Wipp- und Inntal. – M.S. thesis, University of Berlin, Germany.

Gutermann, T., B. Dürr, H. Richner, S. Bader, 2012: Föhnklimatologie Altdorf: die lange Reihe (1864–2008) und ihre Weiterführung, Vergleich mit anderen Stationen. – Fachbericht MeteoSchweiz **241**, 53 pp., available at www.meteoswiss.ch.

Hächler, P., K. Burri, B. Dürr, T. Gutermann, A. Neururer, H. Richner, R. Werner, 2011: Der Föhnfall vom 8. Dezember 2006. – Eine Fallstudie. Arbeitsbericht **234**, MeteoSchweiz, 52 pp., available at www.meteoswiss.ch

Hann, J., 1866: Zur Frage über den Ursprung des Föhns. – Zeitschrift der österreichischen Gesellschaft für Meteorologie, 257–263, in German.

Ishizaki, N., I. Takayabu, 2009: On the warming events over Toyama Plain by using NHRCM. SOLA, **5**, 129–132. DOI:10.2151/sola.2009-033

Jenkner, J., 2008: Stratified verifications of quantitative precipitation forecasts over Switzerland. – PhD thesis ETH Zürich, Nr. 17782.

Jenkner, J., M. Sprenger, I. Schwenk, C. Schwierz, S. Dierer, D. Leuenberger, 2010: Detection and climatology of fronts in a highresolution model reanalysis over the Alps. – Meteor. A pp. **17**, 1–18.

Kljun, N., M. Sprenger, C. Schär, 2001: Frontal modification and lee cyclogenesis in the Alps: A case case study using the ALPEX reanalysis data set. – Meteor. Atmos. Phys. **78**, 89105.

Kuhn, M. (Ed.), 1989:. Föhnstudien. – Wissenschaftliche Buchgesellschaft, Darmstadt, 504 pp., in German.

Miltenberger, A.K., S. Pfahl, H. Wernli, 2013: An online trajectory module (version 1.0) for the non-hydrostatic numerical weather prediction model COSMO. – Geosci. Model Develop. **6**, 1223–1257.

Ortner, A., 2010: Detaillierte Statistik des Südföhns in Innsbruck: Einfluss des Südföhns auf die Temperatur. – Diplomarbeit am Institut der Meteorologie und Geophysik, Leopold Franzens Universität Innsbruck.

Reeves, H.D., Y.L. Lin, 2006: Effect of stable layer formation over the Po Valley on the development of convection during MAP IOP-8. – J. Atmos. Sci. **63**, 2567–2584.

Reinecke, P.A., D.R. Durran, 2008: Estimating Topographic Blocking Using a Froude Number When the Static Stability Is Nonuniform. – J. Atmos. Sci. **65**, 1035–1048.

Richner, H., P. Hächler, 2013: Understanding and Forecasting Alpine Foehn. – In: Chow, K.F., S.F.J. De Wekker, B. Snyder (Eds.): Mountain Weather Research and Forecasting. – Springer Atmos. Sci. **219**, 260 pp.

Richner, H., B. Dürr, T. Gutermann, S. Bader, 2014: The use of automatic station data for continuing the long time series (1864 to 2008) of foehn in Altdorf. – Meteorol. Z. **23**, 159–166.

Roch, A., 2011: Orographic blocking in the Alps: A climatologic Lagrangian study. Master thesis ETH Zurich, 46 pp., available at www.iac.ethz.ch/groups/wernli/

Rotunno, R., R. Ferretti, 2001: Mechanisms of Intense Alpine Rainfall. – J. Atmos. Sci. **58**, 1732–1749.

Seibert, P., 1985: Fallstudien und statistische Untersuchungen zum Südföhn im Raum Tirol – PhD thesis University of Innsbruck, 369 pp., in German.

Seibert, P., 1990: South Foehn Studies Since the ALPEX Experiment. – Meteror. Atmos. Phys. **43**, 91–103.

Seibert, P., H. Feldmann, B. Neininger, M. Bäumle, T. Trickl, 2000: South Foehn and ozone in the Eastern Alps – case study and climatological aspects. – Atmos. Env. **34**, 1379–1394.

Škerlak, B., 2014: Climatology and process studies of tropopause folds, cross-tropopause exchange, and transport into the boundary layer. – ETH Zürich, DOI: 10.3929/ethz-a-010256937

Sprenger, M., C. Schär, 2001: Rotational aspects of stratified gap flows and shallow föhn. – Quart. J. Roy. Meteor. Soc. **127**, 161–187.

Steinacker, R., 1983: Fallstudie eines Süd- und eines Nordföhns über den Alpen. – Aero-Revue **8**, 141–144, in German.

Steinacker, R., 2006: Alpiner Föhn – eine neue Strophe zu einem alten Lied. – promet **32**, 3–10, in German.

Steppeler, J., G. Doms, U. Schattler, H. Bitzer, A. Gassmann, U. Damrath, G. Gregoric, 2003: Meso-gamma scale forecasts using the nonhydrostatic model LM. – Meteror. Atmos. Phys. **82**, 75–96.

Stohl, A., L. Haimberger, M.P. Scheele, H. Wernli, 2001: An intercomparison of results from three trajectory models. – Meteor. Appl. **8**, 127–135.

Strobl, A., 2009: Eine Südföhn-Statistik für das Oberinntal und ein Vergleich mit dem Wipptal. –Diplomarbeit am Institut der Meteorologie und Geophysik, Leopold Franzens Universität Innsbruck.

Takane, Y., H. Kusaka, 2011: Formation mechanisms of the extreme high surface air temperature of 40.9 °C observed in the Tokyo Metropolitan Area: Considerations of dynamic foehn and foehnlike wind. – J. Appl. Meteor. Climatol. **50**, 1827–1841, DOI:10.1175/JAMC-D-10-05032.1

Vergeiner, J., 2004: South foehn studies and a new foehn classification scheme in the Wipp and Inn valley. – Ph.D. thesis, University of Innsbruck, 111 pp.

Wernli, H., H.C. Davies, 1997: A Lagrangianbased analysis of extratropical cyclones. I: the method and some applications. – Quart. J. Roy. Meteor. Soc. **123**, 467–489.

Winschall, A., S. Pfahl, H. Sodemann, H. Wernli, 2012: Impact of North Atlantic evaporation hot spots on southern Alpine heavy precipitation events. – Quart. J. Roy. Meteor. Soc. **138**, 1245–1258.