10A.1 UNDERSTANDING AND FORECASTING ALPINE FOEHN - WHAT DO WE KNOW ABOUT IT TODAY?

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1. INTRODUCTION

The talk centers on recent results of the Mesoscale Alpine Program (MAP) and on ongoing research activities mainly in Switzerland, but touches also on activities in Austria and France. The overview encompasses statistical analyses of foehn occurrence in different Alpine regions, on the interaction of foehn flow and the cold pool, and on current techniques for forecasting foehn-related windstorms.

Foehn is a generic term for a downslope wind that is strong, warm, and very dry; WMO (1992) defines foehn wind as a "wind [which is] warmed and dried by descent, in general on the lee side of a mountain."

While the term foehn originated in the Alpine area, foehn winds occur all over the world where there are extended mountain ranges. Here they might have a different name such as, e.g., Chinook (North America) or Helm wind (UK). The rapid temperature rise and the very dry air of foehn type winds have led to numerous local, descriptive names such as "snow eater," "grape cooker," etc.

2. HISTORY OF FOEHN RESEARCH

For many decades, foehn was the outstanding example to explain thermodynamic processes and the role of latent heat in the atmosphere. Hence, nearly every textbook contains a graph similar to Fig 1. Driven by the synoptic scale pressure field, humid air is forced towards a mountain range. As it ascends by forced convection, it cools dry-adiabatically until reaching saturation. From now on, the rise is wet-adiabatically until the air reaches the crest of the mountain range; clouds are formed and precipitation occurs. As the air descends in the lee of the mountain, it is heated dry-adiabatically; as consequence, the air becomes very dry and reaches temperatures that - at equal elevation - are higher than the original temperature on the windward side. Because of the very clean and dry air on the lee side, visibility is outstanding (foehn window), and over the crest, the piled-up clouds can be seen as the foehn wall (Fig. 1).

As beautiful as this example is, in reality foehn winds often do not follow this classical textbook theory that is attributed to Hann (19th century). Anyhow, Seibert (2005) proves that Hann's original description of the foehn mechanism was somewhat different (see Fig. 2), and he concludes that Hann's explanation was seriously distorted in the first half of the 20th century. Particularly Austrian researchers repeatedly questioned the validity of the textbook approach. But it was Scorer (1978) who really pitched into the textbook theory: His book "Environmental Aerodynamics" contains a chapter entitled "Foehn Fallacy" which gives at least two explanations for the warming of air masses which do not require the heat of condensation in the luff of the mountain ridge: Mechanical stirring of a stably stratified air mass, and - more important - blocking. In the first case, the lower part becomes warmer and the upper part cools because the mixing produces a constant potential temperature, in the second case, potentially warmer air subsides in the lee.

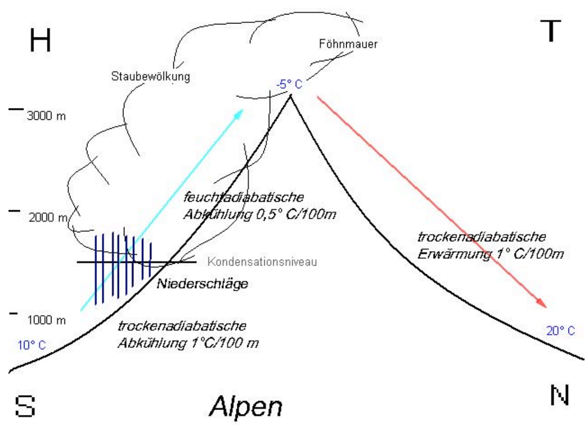

Figure 1: "Textbook theory" of foehn. (German Wikipedia)

Figure 2: The "proof" that Hann did not invent the textbook foehn theory: Illustration depicting Hann's original foehn theory in Ficker (1920). (Note that north-south is reversed with respect to Figure 1.)

It is a little disturbing, that not only popular publications but also modern textbooks often present only the theory depicted in Fig. 1 without discussing alternate foehn schemes.

Analyses of data collected during and after the Alpine Experiment ALPEX clearly confirmed that - at least in the Brenner cross-section - there was blocked air during most foehn cases. This is even true for the

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"century foehn" of November 8, 1982. In the Ticino, i.e., south of the Gotthard, however, there was some but not heavy precipitation towards the end of this extreme foehn event (hourly mean winds up to 35 m/s and gusts over 50 m/s at the station Gütsch, see Fig. 5).

3. CHARACTERISTICS OF FOEHN

Southfoehn occurs in the Alpine region when a synoptic pressure field according to Fig. 3 exists. (There is also northfoehn, however, for simplicity the discussions here are restricted to southfoehn). Nowadays it is widely accepted that foehn winds can and do occur without precipitation. The lower the crest height, the more likely it is that advected air simply crosses the mountain ridge and, subsequently, descends, as already debated by Hann, Ficker and others and as depicted in Fig. 2. Trajectory analyses as well as tracer studies with ozone confirm this mechanism (Baumann et al., 2001).

The fact that much foehn research was and still is being done along the rather flat Brenner cross-section, explains why in Austria the textbook theory was more fiercely queried than, e.g., in Switzerland.

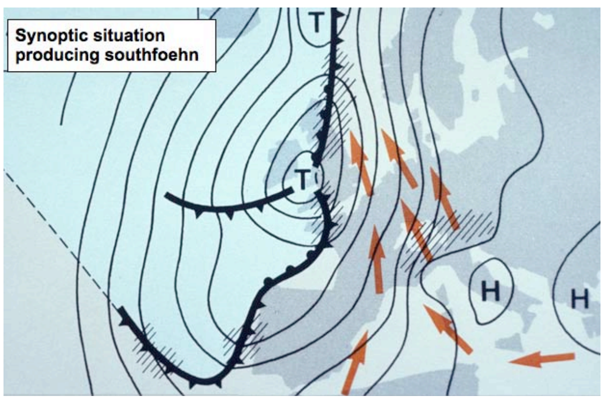


Figure 3: Synoptic pressure field producing foehn in the Alps.

There are at least two reported cases when foehn winds were observed simultaneously on both sides of the same mountain range (Frey, 1986). This can only be explained by assuming subsidence of significant air masses over the ridge. On the north, south winds were in excess of 40 m/s!

On the other hand, it would be wrong to dismiss textbook theory completely. Observations clearly prove that heavy precipitation does occur quite frequently on the windward side of high mountain complexes during foehn. There are indications that this is more often the case south of the (higher) Gotthard than south of the (lower) Brenner massive. Although this suspicion has been brought up repeatedly after ALPEX, there are no statistical analyses that would prove this, and no firm statement can be made.

Fig. 4 shows how foehn manifests itself in one of Switzerland's important foehn valleys, the Reuss Valley which is part of the so-called Gotthard cross-section (Fig. 5). The rise of temperature, the drop in relative humidity, the onset of high winds, and the constant wind direction occur simultaneously within minutes. Consequently, the onset and the breakdown of foehn can easily be determined. This is true for almost any foehn station that is located in the center of a foehn valley.

Fig. 6 shows a foehn occurrence which proves that there are cases which indeed follow the textbook theory. There is significant precipitation and south wind on the upwind side. Table 1 shows that on the top of the ridge the potential temperature is markedly higher than on the upwind side (for the location of the stations see Fig. 5). This alone is not sufficient proof for the textbook theory, however, when considering that the wind south of the ridge is towards the north, one has to conclude that there is strongly forced advection present.

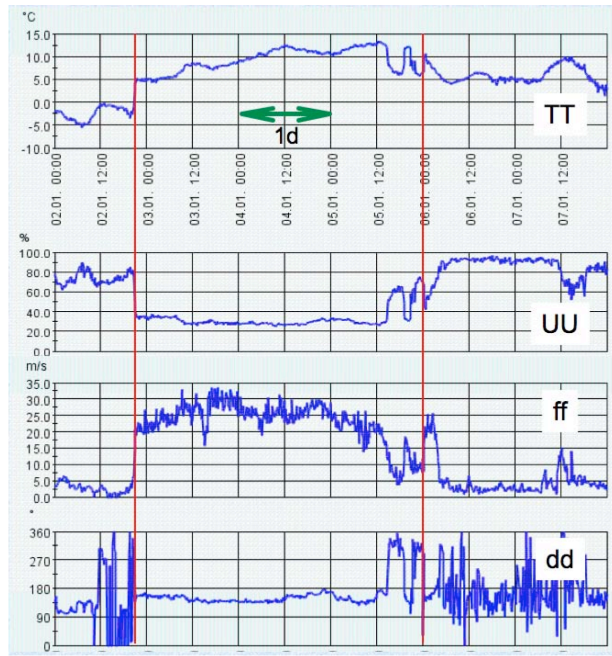


Figure 4: Example of foehn in Altdorf. Note how clearly foehn can be identified.

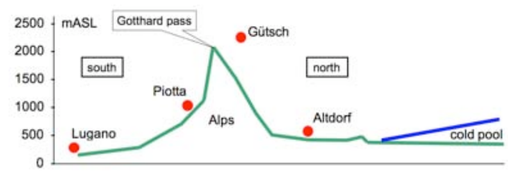


Figure 5: The so-called Gotthard cross-section, the only south-north profile with only one ridge and valleys practically perpendicular to it. In the south is the Leventina, in the north the Reuss Valley.

For the Mesoscale Alpine Program MAP, special efforts were made to densely instrument an area for foehn studies in the Rhine Valley (Richner et al., 2005). For some foehn cases, detailed investigations of the 3-dimensional structure of foehn were made (Drobinski et al., 2003). In these, the distinction between "shallow foehn" and "deep foehn" that had evolved during the last decades was clearly found in the life cycle of the foehn episode. As expected, compared to simple mountain cross-sections (like the aforementioned Gotthard cross-section), complex topographical features cause significantly higher complexity of foehn flow; a glance at the topography shown in Fig. 7 makes this statement understandable.

Model runs for a MAP foehn case concluded that the simulation outputs essentially confirm the observed foehn dynamics (Jaubert and Stein, 2003). However, it is also realized that the role of passes and valleys is not fully understood yet. At any rate, for a reliable foehn forecast, today's mesoscale models are not yet sufficiently accurate, this despite the fact that they do produce realistic flow and temperature fields. Turbulence, on the other hand, is very poorly reproduced in model runs. Computed turbulent kinetic energy (TKE) values were orders of magnitudes lower than those observed by aircraft (Fig. 8).

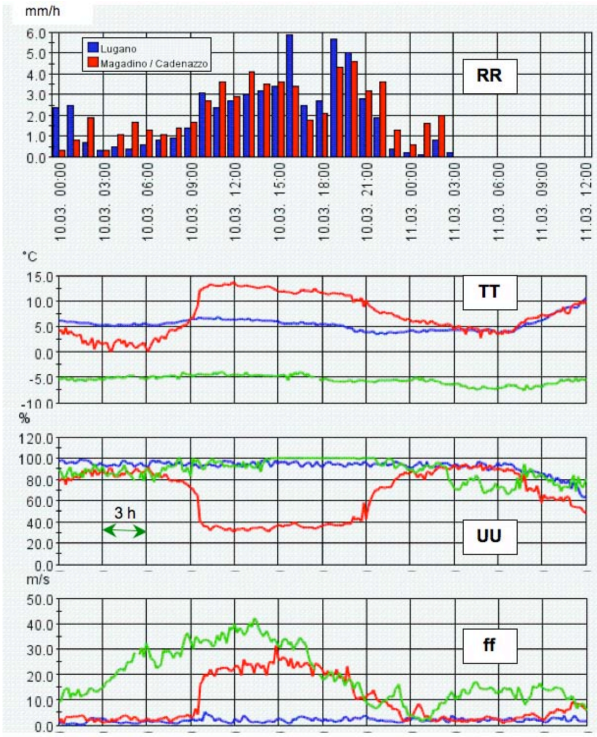


Figure 6: A foehn case with precipitation on the upwind side. Red: Altdorf, blue: Lugano, green: Guetsch (except in top frame).

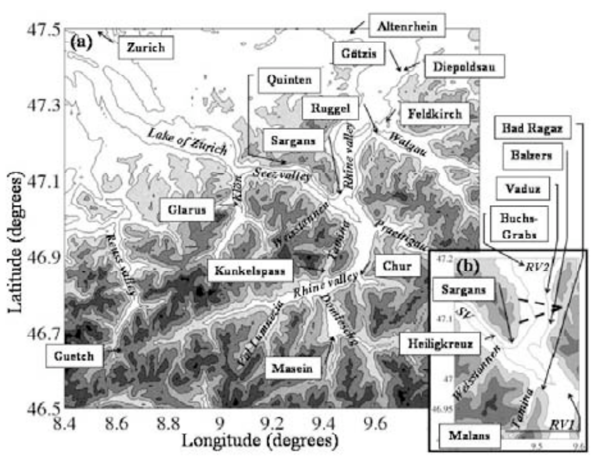


Figure 7: Topography around the Rhine Valley where foehn studies during MAP were conducted. (Drobinski, 2003)

Table 1: Characteristic parameters for stations on the upstream side, the ridge, and the lee side. (March 10, 2008, 1200 UTC, data courtesy MeteoSwiss)

param	***Lugano***	***Piotta***	***Gütsch***	***Altdorf***
z (m)	273	1007	2287	449
p (hPa)	970.0	887.1	752.8	943.1
T (ºC)	6.5	2.3	-4.5	13.1
θ (ºC)	**8.9**	**11.9**	**18.1**	**17.9**

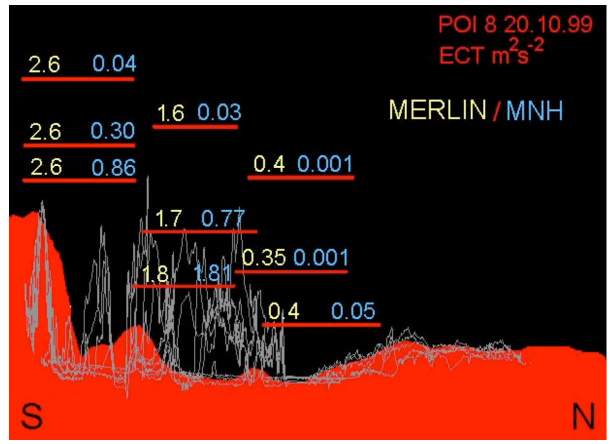


Figure 8: TKE values in the lee of the Alps during foehn. Yellow: values measured by aircraft, blue: model values. (Dissertation M. Lothon)

4. FOEHN DYNAMICS

4.1. Leeside motion

Probably the least understood mechanism in the flow dynamics is the behavior of the air masses after passing the mountain ridge. Why does the air descend and not simply continue at the same height level? This question is even more justified by the fact that its potential temperature is in most cases higher, i.e., that a stable stratification is present!

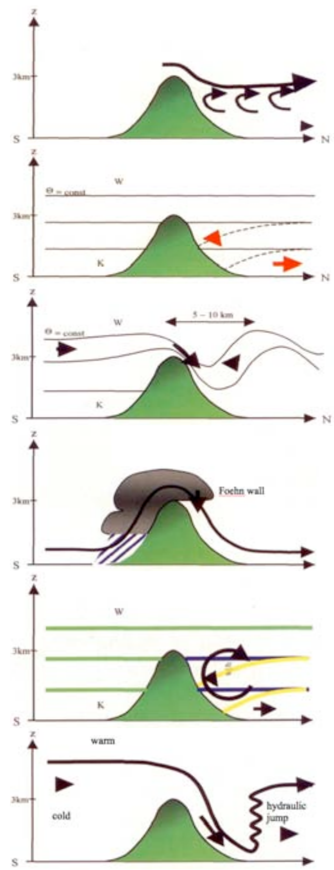
Steinacker (2006) has compiled the different theories that have emerged over the last century. The six theories are summarized in Tab. 2, for details see Steinacker (2006).

It seems that there is no generally applicable theory. In their often-referenced paper, Klemp and Lilly (1975) provide a detailed analysis of a strong downslope wind induced by lee waves (mechanism (c) in Table 2) such as it can occur with foehn. They state that the observed amplification can occur only "if the upstream wind and stability profiles lie within sharply limited but plausible ranges." Hence, depending on temperature, humidity, and wind profile, different mechanisms may be responsible for the downslope flow. Meteorologists may have to live with the fact that an entire range of physical mechanisms is needed to explain the same phenomenon, but occurring under different conditions.

When there are extreme pressure differences across the Alpine ridge, precipitating clouds may be drawn over the ridge, far into the lee-side valleys. Behind the ridge, the air is quite calm and rainy, the foehn flow reaches the ground only after many kilometers. However, when it does touch ground, severe storms are the rule. This type of foehn is called dimmerfoehn ("dimmerig" meaning hazy, obscure). It was first described in the first half of last century by Swiss researchers and prompted a fierce and not always very scientific dispute between Austrian and Swiss meteorologists. The reservation Austrians had against this foehn type may be explained with the fact that dimmerfoehn is very rare; there are years without any such case, and it seems that this foehn type occurs even more rarely in Austria.

A dimmerfoehn is always a deep foehn with very high wind speeds. Often, a dimmerfoehn is connected with the deposition of Sahara dust in the Alpine region.

Table 2: Different theories for the lee-side descending of foehn air. (After Steinacker, 2006).



a) vertical aspiration theory (Streiff-Becker)

b) horizontal aspiration theory (von Ficker und Billwiller)

c) forced downslope motion caused by lee waves (Lyra and Queney)

d) "waterfall" theory (Rossmann)

e) solenoid theory (Frey)

f) hydraulic jump theory (Schweizer)

4.2. Interaction with cold pool

When foehn winds descend in the lee of a mountain ridge, they clash into much cooler, stagnant air. If topography allows, this cold pool is usually flushed away, typically within hours. However, there are cases where topography prevents the outflow of the cold pool; the Wipp and Inn Valley in Austria (with the Nordkette as downstream obstacle), and the Reuss Valley in Switzerland (with the Jura Mountains as obstacles) are prominent examples for this constellation. In addition, mere bends in the main valley axis can prevent the cold pool from being flushed out rapidly.

On the Swiss Plateau, i.e., the area between the Alps in the south and the Jura Mountains in the north, often a cold pool of a few hundred meters depth remains while foehn flows over it. Such a situation can persist for up to several days. The cold pool has a wedge-like form, the angle is typically 2 degrees. Of course, air in the cold pool remains calm, while the line where the foehn flow leaves the ground to flow over the cold air is very gusty. Over water, this border is easily seen by a spray line and by the haze usually present in the cold air.

As the strength of foehn flow increases, it works its way downstream, gradually forcing the cold pool back. This can occur by three possible mechanisms or any combination thereof: (i) heating by convection, (ii) erosion of the top by mixing and entrainment, and (iii) static and dynamic displacement.

During MAP, an attempt was made to directly measure the heat flux near the internal boundary between foehn and cold air by a small aircraft. The daily mean found was about 15 W/m^2, almost exactly the same value that was measured at the ground. Hence, heating by convection and mixing at the top of the cold pool seem to be of similar importance for cold pool removal.

4.3. Waves

Very often, foehn produces waves. There are mainly two types, which must be distinguished:

(i) Lee waves or simply mountain waves, i.e., standing waves with a wavelength of the order of the mean width of the mountain range. Due to the adiabatic expansion, lens-shaped clouds may appear at the wave crests (cumulus lenticularis or altocumulus lenticularis, see Fig. 9).

Figure 9: Lenticularis over the Alps. (Courtesy Andreas Fuchs)

(ii) At the interface between the foehn flow and the cold air mass, the shear produces gravity waves on the top of the cold pool, i.e., at the interface between the two air masses. The mechanism is analogous to the one by which wind produces waves on a lake. The waves are very rarely seen, only when strong haze or fog is found in the cold air mass (Fig. 10), however, they can be made visible indirectly, e.g., with sodar, RASS or lidar (Fig. 11). These waves produce small fluctuations in surface pressure (0.1…1 hPa); depending on the vertical profile of temperature and wind, their period is somewhat longer than the Brunt-Vaisala period (of the order of 10…20 min.).

Figure 10: Waves on cold pool in the Rhine Valley, looking SE. Foehn is from right to left, notice the weak counter flow in the cold air mass. (Courtesy Andreas Walker)

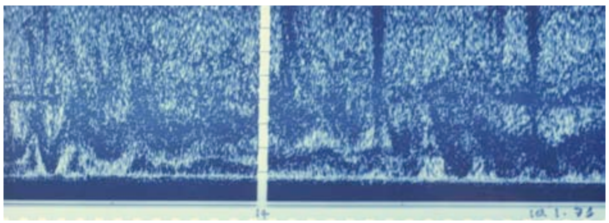


Figure 11: Waves on the cold pool seen by a sodar. In this time-height diagram, the height covered is 900 m, the total recording time about 2 h. (Courtesy Werner Nater)

5. FOEHN CLIMATOLOGY

Statistical analyses show that foehn occurrence is highly variable, and that no trend in the last 140 years is discernible (Fig. 12; Richner and Gutermann, 2007). In addition, the regional and seasonal variability is considerable. Figs. 13 and 14 give some ideas about the variability. Observations are made three times a day, morning, noon, and evening; the numbers refer to the number of such observations.

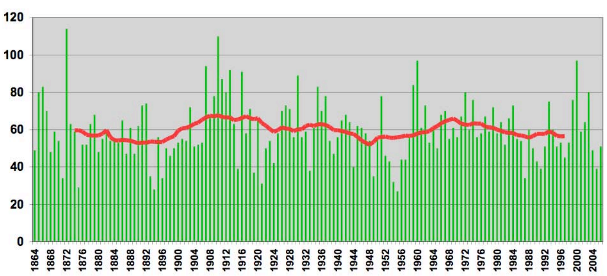


Figure 12: Year-to-year variation of foehn occurrence at the station Altdorf. The heavy line represents the 20-year running mean.

Seasonal variations in foehn frequency (upper frame of Fig. 14) are caused by the changing general circulation pattern and, subsequently, by the resulting synoptic situations. The changes in the diurnal distribution of foehn activity (lower frame of Fig. 14) are the result of interactions of foehn flow with thermally driven local wind systems, i.e., mountain/valley winds. Note that the relative frequency of foehn at noon remains the same throughout the year.

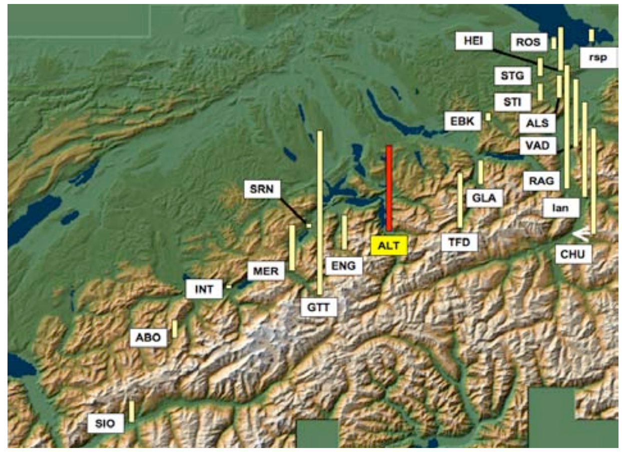


Figure 13: Comparison of the yearly foehn occurrence at different Swiss stations. Values represent the mean yearly sum for the period 1973 to 1982. The value for Altdorf (ALT) for this period is 62.2.

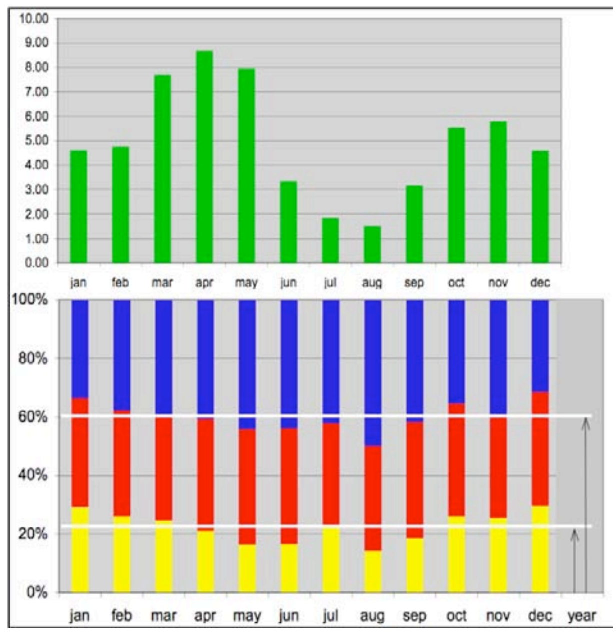


Figure 14: Seasonal variation of total foehn occurrences per month (left) and relative frequencies of occurrence at the three observing times. Yellow: morning, red: noon, blue: evening observations.

6. FORECASTING PROBLEMS

Foehn forecasting rests on three pillars: (i) probabilistic methods based on a few observed or forecasted parameters, (ii) on model output, and (iii) (still very important!) on the skill of experienced forecasters.

6.1. Probabilistic methods

Forecasting foehn means predicting a mesoscale phenomenon based on a synoptic situation. Such forecasts are primarily based on the pressure field. Depending on the orientation of the isobars, foehn might develop in one valley and not in another, hence, different locations would require specific forecasting procedures.

In Switzerland, Widmer developed in the sixties a "foehn test" that was refined by Courvoisier and Gutermann (1971); it remains the operational tool until today. Two pressure gradients across the Alps plus the trend of one of these are used to compute an index. If the index is below a certain, season-dependent threshold value, the probability of foehn at Altdorf within the next 36 hours is over 70 percent. The index allows also predicting the breakdown of foehn with even a slightly higher success rate. Figs. 15 and 16 give an example of the Widmer Index and its potential for forecasting a foehn case in January 2008.

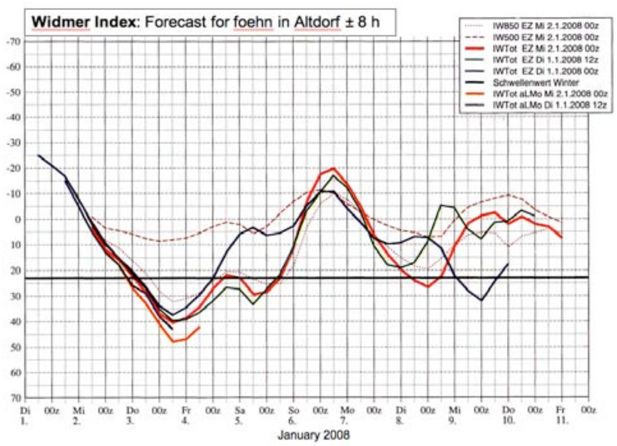


Figure 15: Example of Widmer Index. The indices are computed from pressure differences across the Alps as forecasted for defined gridpoints. Different lines relate to different forecasts and levels, or combinations. The horizontal line represents the winter threshold; a value above this indicates foehn at Altdorf (note inverted vertical scale!). Data used here are the ECMWF and COSMO-2 forecasts of January 1 and 2; ECMWF forecasts for 10 days (dashed and dotted lines), COSMO-2 for 3 days (black and orange lines). (COSMO-2 is the MeteoSwiss mesoscale forecasting model for the Alpine region with 2 km resolution.)

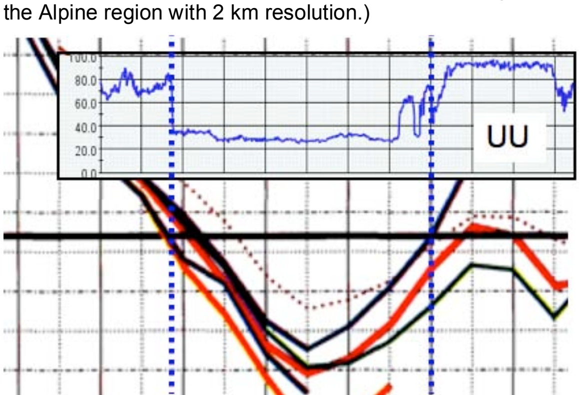


Figure 16: Comparison of observed and forecasted foehn.

Dürr (2003) developed an automated method for identifying, i.e., nowcasting foehn. His procedure is based on 10-minute real-time data from the automated Swiss surface network. The most important predictors are the differences in potential temperature between the reference station Gütsch (2282 mASL, close to the Alpine ridge) and the locations for which foehn should be nowcasted. For the time being, the application of this technique is restricted to locations on valley floors or near valley exits; since July 2008, the procedure is implemented as an automated routine forecasting tool at MeteoSwiss.

Quite recently, Drechsel and Mayr (2008) developed an objective, probabilistic forecasting method for foehn in the Wipp Valley (Innsbruck) based on ECMWF model output. As predictors, they use cross-barrier pressure differences and, additionally, the isentropic descent. A test over three years proved that - based on the two variables - reliable forecasts of up to three days for foehn and the associated gust winds can be made.

6.2. Model forecasts

As the resolution of models is improved, the topography of the complex Alpine terrain (and with this the foehn valleys) is more accurately represented. Consequently, there are well-founded hopes that models will provide sufficiently accurate foehn predictions.

At MeteoSwiss, COSMO-2, a 2.2 km grid size model, is run operationally since February 2008. Fig. 17 assesses its capability to analyze a foehn case (a test case from the pre-operational phase, Burri et al. 2007). For both stations, the analysis represents the onset of foehn too early. The increase in wind speed is significantly below the observations, the same is even more pronounced for temperature.

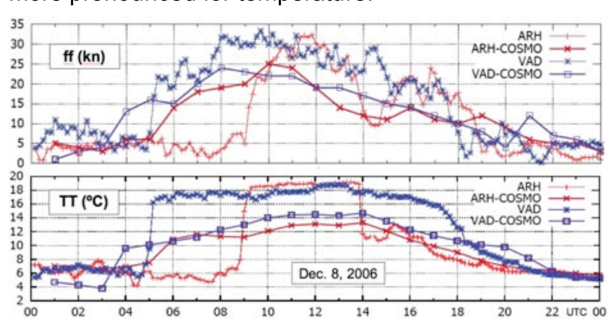


Figure 17: Wind speed and temperature for the foehn stations Altenrhein (ARH, red) and Vaduz (VAD, blue). The time series with 10-min resolution are observations (fine lines), the series with 1-hour resolution (heavier lines) are model data.

In summary it can be said that COSMO-2 forecast fields and analysis fields overestimate the spatial foehn extension and mostly underestimate temperature and wind speed at the two stations investigated here. The modeled temperature gradient between stations and the Alpine ridge site Gütsch (not shown here) never reached dry adiabatic conditions, this in contradiction to the observations. However, it should be mentioned that this was a run of the model at an early stage of development, and that the model is tuned to primarily provide reliable precipitation information.

6.3. Open problems

In practice, the skills of experienced forecasters who are familiar with the local situations are still an indispensable prerequisite for a successful forecast! They know from experience how a somewhat different wind direction might influence the onset or breakdown of foehn in a given valley, how observed wind data must be interpreted to arrive at a correct prediction. On the other hand, any tool, be it based on probability or on model output, is a welcome and appreciated support giving a first approximation which is subsequently modulated with the forecaster's experience and skill.

It seems that further improvements in models - both in resolution and parameterization - will improve future forecasting of foehn. However, a few open problems remain also after MAP.

As indicated, the role of the tributary valleys, e.g., is still not well understood. This is partly due to a lack of sufficient high-density observations, but also to a poor understanding of the interaction of air masses coming from different valleys. There are many locations where two or even more foehn valleys merge. Observations indicate that the flow does not necessarily merge also, but that one foehn "stream" might cross over the other. Which flow will go over the other depends on the synoptic fields. Also here, refined and higher resolving models might soon provide a solution.

7. SOCIETAL IMPACT OF FOEHN

7.1. Climate impact

Foehn has serious impacts on the local climate that, in turn, influences agricultural possibilities in foehn valleys. Thanks to foehn winds, wine can be grown in areas where it otherwise would be impossible. Foehn storms have also a major effect on snow melting, an effect which in springtime is not particularly liked in skiing resorts.

7.2. Air quality

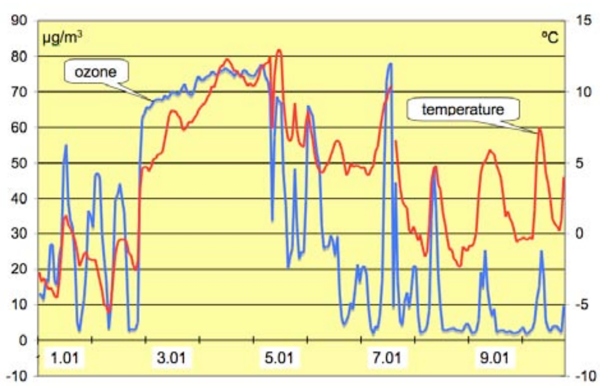


Figure 18: Ozone during foehn at Altdorf in January 2008. (All data taken from an air quality station that is not collocated with the foehn station. Hence, temperature data is not exactly the same as in Fig. 4.)

Foehn situations provide the most spectacular views of the mountains! The foehn air is usually very clean, there is no haze, and distant objects seem to be much closer. The entire fantastic Alpine panorama can be seen from places where one normally does not see any mountains at all. On the negative side of these stunning postcard-views, however, are the increases in ozone concentration. Although the values seldom reach alarm levels, foehn air easily triples existing ozone concentrations by subsiding air from high altitudes with high natural ozone concentrations (Baumann et al., 2001). Fig. 18 shows the situation for Altdorf for the foehn case discussed above.

7.3. Fires and traffic accidents

The most striking danger, however, was and still is the spreading of fires. The warm and very dry air combined with high wind speed supports and proliferates fires very efficiently. In the course of time, numerous towns burned down completely. In 1861, 600 houses of the capital city Glarus were completely devastated during a foehn storm, and only recently, in 2001, a fire maintained by foehn winds in excess of 15 m/s destroyed 15 houses in Balzers (Principality of Liechtenstein). During foehn situations, a few towns still activate a fire watch during nights, and smoking outside houses is strictly forbidden! In some mountain regions, it is - as a matter of principle - illegal to make fires outside specially designated fire areas.

Foehn winds can be dangerous to flying. Professional pilots and local airports are well aware of the problems and issue the necessary warnings. However, when hot-air ballooning, paragliding, and similar sports became popular during the last third of last century, the number of severe accidents due to high winds and large shears increased significantly. Improved training, special safety courses, and specific information and forecasts have reduced, but not eliminated, this problem.

Cable car accidents and even train accidents can be caused by strong and gusty foehn winds. Although all cable transportation systems are required to monitor wind speed and to have an alarm system, gusts and shears that slip between the different anemometers can surprise operators. Sadly, there was such an accident in January 2008 in the Jungfrau Region: High winds during a foehnstorm "derailed" the cable of a double chair cable lift. First, the lift stopped, and the cable was caught in the cable catcher, but a successive gust threw the cable out of the catcher, the chairs dropped to the ground. One person died and several were severely wounded; mean wind speed was about 25 m/s which is below the alarm level of 28 m/s. (An almost identical incident happened 2003 in Wangs-Pizol. That time the directly affected gondolas were empty and nobody was injured. The cause was again gust winds, this time associated with a thunderstorm front.)

On February 15, 1925, a train was thrown from its track in a foehnstorm in Strobl near Salzburg, Austria.

Another spectacular accident happened during a severe foehn storm in the Jungfrau region on November 11, 1996: A double motor coach of a narrow gauge railway was blown from its track. Its mass of 52 tons could not withstand a foehn gust of 52 m/s; four persons were injured, fortunately none seriously.

On lakes, foehn storms hamper scheduled boat traffic, in extreme cases, operations have to be suspended. The Swiss town of Brunnen (that is directly in the main axis of the Reuss Valley) has built a special "foehn harbor." It serves two purposes: (i) it is used by boats in storm situations as shelter, and (ii) if wind and waves still allow the scheduled ships to navigate, they can dock in this harbor, which is better protected against the waves and gusts than the wharf in the center of the town.

The most significant reoccurring damage caused by foehn winds is most probably that to boats, piers, and shores. After severe foehn storms, pictures of loose-torn boats lying on shores or damaged piers appear regularly in the news.

7.4. Biometeorological effects

Still much debated are biometeorological effects of foehn winds. Interestingly, it is primarily in the Alpine area that people blame foehn winds for almost any ailment, accident, crime, and in particular for headaches. Sferics, ion concentrations, and pressure fluctuations were considered as possible causes of foehn-related ailments. While recent measurements proof that neither sferics nor ion concentrations are correlated with foehn events, pressure fluctuations induced by gravity waves on the cold pool remain a possible link between foehn and man.

Statistical analyses of pressure fluctuations and subjective well-being show that there is indeed a statistically significant correlation between the two. However, there is no proof of any cause-and-effect mechanism. The study of short-term pressure fluctuations did not take into account the actual weather situation. Since also fronts cause high amplitude pressure fluctuations, the positive correlation might simply reflect that people feel subjectively better when the weather is good.

A direct analysis of the frequency of headaches and the occurrence of foehn (as defined in the Alpine weather statistics) did not produce any result.

Interestingly, on the American continent the interest in biometeorological research seems to pick up after a long phase of disinterest. There have been several research projects dealing with Chinook winds and headache, strokes, etc. However, so far no significant progress was made in relating ailments to foehn-type winds or weather in general (see, e.g., Cooke et al., 2000; Field and Hill, 2002)

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