

Concomitants of unseasonably warm air
advection in Central Europe on 17.11.2009
- Elevated mixed layer, shallow foehn and gravity
waves in radiation fog

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Abstract

The case study of the 17. November 2009 addresses to a shallow foehn event in the Wipp Valley and Innsbruck associated with a low stratus deck to the south of the Alps. It belongs to a non-precipitation foehn event which is in contradiction to many old textbook foehn theories where precipitation is thought to be the main contributor of downstream warming. A cloud phenomenon similar to the well-known Maloja serpent in the Upper Engadine could be observed downstream of the Brenner Pass. Radiation fog in the morning hours has been accompanied by wave structures. The superposition of a cold, weak down-valley wind and a warmer, stronger foehn flow excited gravity waves, evidently in the shape of Kelvin-Helmholtz-Waves. Another interesting feature of this large-scale foehn situation is the excess of temperature records in Bavaria. Sounding ascents and backward trajectories revealed that a combination of a well-defined elevated mixed layer and foehn air has been responsible for the unseasonably high temperature maximums to the north of the alpine main crest.

1 Introduction

The south foehn climatology in Innsbruck reveals a secondary maximum in the late autumn months, especially during the first and second decade of November (Foest 2006). Then, weather situations favouring south foehn events become more likely as the polar front jet advances southward and the upper-level flow subsequently increases towards the Alps. The decrease of foehn events compared to the main occurrence in spring is lesser in the Wipp Valley than in the Inn Valley due to the stronger radiative cooling and cold pool formation in the flat floor of the Inn Valley. As a result, the foehn flow does not always reach Innsbruck while the Wipp Valley exhibits a foehn flow with nearly every south flow.

The first decade of november has been characterized by slightly below-average, later above-average temperatures until the 13. November. After the establishment of a quite persistent southwesterly flow, temporarily weak south foehn

occurred. The south foehn event of the 17. November 2009 belongs to the shallow kind since westerly to northwesterly winds blew above crest level. Local temperature records have been the result of the overall warm air mass. Some temperature maximums above 20°C are listed as follows (Source: Austrowetter and Meteomedia Switzerland/Germany):

- Sonthofen, Allgaeu (741m): 22,4
- Fischen, Allgaeu (764m): 20,5
- Baechli-Hemberg, Eastern Switzerland (800m): 20,6
- Appenzell, Eastern Switzerland (780m): 20,4
- Zeltweg, Styria (669m): 20,6
- Mattsee, District of Salzburg (505m): 20,3

The maximum temperature in Sonthofen arose due to a combination of foehn air and warm air advection. The southwesterly to westerly flow comes across the Hoernergruppe (maximal 1787m) respectively through the Kleinwalsertal Valley into the Iller Valley. As the 850 mb temperatures rootedly rose to 11-14°C, the contribution of foehn to the warming should have been comparatively small. However, the maximum values would not have been reached without the mountain flow regarding the lower maximum temperatures downstream of the Alps. Although foehn air has been present, the maximum temperatures at Innsbruck-University (15,7°C) and Innsbruck-Airport (15,0°C) have been distinctly lower than in the adjacent regions. At the university, the southerly foehn flow became perceptible with stronger gusts between 15 and 18 UTC while the airport only obtained weak southerly winds between 15 and 16 UTC. Notice the sudden wind direction change with decreasing temperature at the university.

Before the shallow foehn broke through in Innsbruck, radiation fog has been present as the prefoehn down-valley wind temporarily ceased. For a short time period in the morning hours (about 5.45 to 6.10 UTC), gravity waves have been visible in the webcam pictures. The following case study deals with the reason of these waves as well as the development of the shallow foehn in the Wipp Valley and in Innsbruck. At first, the background of foehn mechanisms will be illuminated, then the synoptical development with a variety of charts will be present. In section (4), the theory of Kelvin-Helmholtz-Waves will be linked to the observations by webcam pictures. The next section (5) deals with the origin of the warm air masses. Finally, the case study is completed with a summary.

2 Foehn

The subsequent subsections will be limited to the essential basics of foehn in association with the Alps. An exhaustive consideration of this topic can be cleaned from the section foehn on the website www.inntranetz.at

2.1 Definition

Foehn is a wind which becomes warmer and relative drier by descent - in general on the lee side of the mountains. (WMO 1992)

We might add *gusty* to underline the roughness and insteadness of foehn winds. The attribute *general* refers to the so-called gap flow dynamics implying foehn winds in absence of a mountain flow.

2.2 Generation

Horizontal air mass differences, expressed by the potential temperature, are fundamental for the generation of foehn. They cause pressure differences prompting the wind to compensate them. In opposition to bora, the dry-adiabatic warming on the lee side is sufficient to create a temperature excess. In Switzerland, the majority of south foehn winds is accompanied by precipitation while in Austria, only the half of the events do in such a way. The role of precipitation with foehn remains still elusive to the scientists and is object of current studies respectively diploma thesis.

The horizontal pressure differences may arise not only from the synoptic-scale flow, but also from differential temperature advection and different radiation fluxes, for example with upstream cloudiness reducing or even stopping the daytime pressure drop

2.3 Types

Shallow and deep foehn, gap flows and dimmerfoehn are commonly-used terms in mountain meteorology. Dimmerfoehn arises from measurable precipitation in the downstream side of the mountain ridges. Gap flows develop at all incisions below the crest level, even without a synoptic-scale flow (see e.g. Mayr and Gohm 2006). Then, potential cooler air is forced to flow through the gaps into the lee side. A foehn flow above the crest level is called deep foehn and a foehn flow below the crest level is called shallow foehn.

Three gaps with different cross-section areas exist in the Wipp Valley at the location of the Brenner Pass (according to Mayr and Gohm 2006 respectively Mayr et al. 2007):

- a lower part with 1 km width and 1400-2300m depth
- a middle part with 15 km width and 2300-2800m depth
- an upper part with 2800-3200m depth

The majority of foehn events which I observed since the beginning of my studies in Innsbruck is that over the lower and middle gap when the valley stations reveal a well-mixed temperature run up to the Sattelberg (2108m) and/or Wolfendorn (2777m) close the Brenner Pass. Pure deep south foehn events and pure shallow foehn events (below 2300m) seem to be relatively seldom.

It also appears representative for foehn in Innsbruck that the maximum temperatures in the foehn air are reduced in comparison with adjacent foehn areas. In fact, the tap into potentially cooler air upstream lowers the maximum temperature in the Wipp and Inn Valley whereas the foehn air in the Rhine Valley, Brandner Valley, Iller Valley, etc... originates from higher potential temperatures indicating a deeper foehn flow.

3 Synoptic-scale development

The first subsections deal with the synoptic-scale development as well as the prerequisites for the observed shallow foehn. In section ..., a closer look at the generation of the waves will be given.

3.1 Reanalysis charts

The large-scale weather pattern can be easily illustrated by means of the Satreponline Tool which combines both satellite information and ecmwf model analysis. In figure (1), a broad upper-level ridge with center over Libya extends up to Central Europe, with a southerly flow crossing the Alps. The jetstream is splitted into two branches as the elongated trough axis stretches to the Canary Isles. The northern branch reaches from Newfoundland over the British Isles up to Germany where it merges with the southern branch advecting unseasonably warm air masses from Northwest Africa to Europe. While warm subsidence air dominates wide parts of the ridge, the upper-level temperature decreases towards northwest, which becomes later decisive for the question whether shallow or deep foehn has been present.

The determining weather system for the alpine region is a matured low centered over the North Sea whose wavy cold front excited a flat secondary cyclogenesis over Central Europe. At that time, the wave is situated over Southern Germany, but it shows vast inactivity in the satellite imagery as neither substantially cyclonic vorticity, upper-level cold air nor sufficient moisture are present.

Main focus of the sequence of the analysis maps in figure (2) is the flat secondary cyclogenesis crossing Southern Germany as well as the temperature distribution between the Pyrenees and the Alps. In anticipation of the station data, it should be noticed that the foehn at Sattelberg lasted to 16.11.2009, 18.00 UTC, and the foehn in the Wipp Valley startet at 16.11.2009, 13.00 UTC.

The time series shows a primary low over Scotland slowly moving northeastward until the end of the time period. It advects relatively high 850 mb temperatures to the north of the Alps into Central Europe. The alignment of the 850 mb isohypses indicate a westsouthwesterly flow in the alpine region during the whole time period. The low pressure can be always found to the north of the alpine main crest which produced a synoptic-scale pressure decrease across the Alps. Furthermore, slightly lower temperatures have already been present to the south of the Alps on 16.11.2009, 12 UTC, with 5°C in Bozen and 7°C in Upper Bavaria. By 18 UTC, as Sattelberg became decoupled from the foehn layer, the cold pool still lied to the south of the main crest (notice the difference between model and real topography).

A flat wave cyclogenesis set up in the morning hours of the 17.11. over Central France strengthening the pressure gradient over Southern France. As a consequence, the warm air advection increased with the development of a low-level jet to the west respectively north of the Alps. The advected warm air was not capable to protude into the stable-stratified cold pool in the Po Valley respectively was deflected at the Western Alps. Subsequently, the temperature difference beyond the main crest arose considerably. On 17.11., 12 UTC, that difference was 9 Kelvin between Bozen and Munich. However, the strong warming over Bavaria and Upper Austria should be only partially caused by the foehn as the

region in Southern France (where an alpine foehn flow does not exist) had 850 mb temperatures of 13-15°C, too.

In Innsbruck the foehn temporarily broke through with the passage of the secondary low in the afternoon when the pressure gradient reached its peak. The beginning of radiative cooling after sunset rapidly uncoupled the foehn flow. The pressure gradient persisted until the passage of the cold front in the second half of the night (not shown) and increased again with the approaching cold front. As a consequence, the southern flow became stronger at Sattelberg and the wind direction more invariable indicating a temporary deepening of the foehn flow.

3.2 Satellite imagery

Many german textbooks name cloudiness and precipitation as a precondition for the generation of a foehn flow. This is obviously wrong respectively fragmentary since foehn can exist without one of these components, too. The 17.11.2009 is an impressive example for an "anticyclonic" foehn event. The cloudiness does not act as a heat contributor, but it allows the enhancement of the horizontal pressure difference. The satellite images from NOAA (figure 3) and Sat24 (figure 4) exhibit a persistent low stratus deck to the south of the alpine main crest totally inhibiting the solar radiation. The period of interesting extends from sunrise to sunset of the 17.11.2009. At sunset, complete South Tyrol is covered by a compact low stratus deck. Solely the upper mountain groups protude out of the stratus, like the Ortler Massiv, the southern Zillertaler Alps and the southern Oetztaler Alps. some mountain peaks of the Sarntaler Alps are visible, too. The stratus deck ends near the italian-austrian border. The Wipp Valley exhibits clear skies, shallow fog is present in the Lower Inn Valley.

In the Po Valley, the top of the low stratus deck lied at 2500 m at midnight and lowered to 2300 m by noon. This is in line with the webcam pictures (see figure 17) from wich the top of the stratus can be estimated at about 2200m.

As displayed in figure (4), in South Tyrol the low stratus deck has been compact throughout the daytime while the Inn and Wipp Valley obtained much solar radiation until the early afternoon hours. As a result, the sensible heat flux beneath the cloudy region has been much lesser than in the sunny regions to the north of the Alps. Respectively, the daytime heating to the north of the Alps could produce a stronger drop in pressure than to the south. Thus, the pressure difference beyond the main crest increased during the day as it will be shown in subsection (3.3).

3.3 Large-scale weather data

Station data from Milano or Munich seem to be too far from the area of interest. However, these data are exempt from orographic influences making them representative for the large-scale pressure and temperature distribution.

Table (1) shows that high pressure prevailed throughout the time period to the south of the Alps. The pressure difference between Bozen and Munich lied above 5 mb, rising to 9 mb in the afternoon. The pressure difference between Bozen and Innsbruck has been smaller, with temporarily balanced conditions in the morning hours due to the low stratus in South Tyrol barring from a stronger

radiative cooling while clear skies in Innsbruck allowed for a strong nighttime cooling.

During the day, the pressure differences rapidly increased as the sunshine has been inhibited by the low stratus deck in South Tyrol and dynamically-induced (passage of the secondary low) as well as thermally-induced (sunshine) pressure drop occurred in the Inn Valley.

As the foehn broke through in Innsbruck-University (15-18 UTC) respectively Innsbruck-Airport (15-16 UTC), the pressure difference reached its culmination with 6-7 mb between Bozen and Innsbruck.

The distribution of potential temperature beyond the Alps in table (2) reveals that the potential temperatures have been warmer to the south in 700mb correlating well to the synoptic-scale conditions with the strong ridge. As far as the prerequisites for the foehn is concerned, the necessary potential colder upstream air mass existed in 800 mb and 850 mb, with increasing difference during the noon hours. According to Mayr and Armi (2008), the depth of the layer with lower upstream potential temperature determines also the depth of the foehn layer. It reaches from about 800 mb (about 2000m) downward which is in line with the top of the low stratus deck in the Wipp Valley.

Without information about the local-scale weather data (see 3.5), it can be concluded that the observed pressure and temperature values suggest that shallow foehn occurred in the Wipp Valley. The top of the foehn layer is characterized by the low stratus deck flowing through the Brenner Pass to the downstream side.

3.4 Sounding ascents

Main feature of the subsequent sounding ascents is an elevated mixed layer (abbreviated EML as follows) which is especially pronounced in the case of Milano and Munich. The plots of the backward trajectories in section (5) were made to clarify the findings after interpreting the sounding of Munich.

The sounding ascent of Innsbruck-Airport in figure (5) is not easy to understand due to the lack of a well-defined foehn layer. There is a nighttime inversion which includes radiation fog. The temperature decreases above 1000 m up to 1600 m. The depth of this layer represents the depth of the foehn layer. The relative high moisture content is possibly due to the moist upstream air mass. At the date of the sounding ascent, the valley stations in South Tyrol as well as at the Brenner Pass had small dewpoint differences below 2K. A weak west wind blew above the foehn layer up to the subsidence inversion.

The sounding ascent of Milano in figure (6) reveals calm at the surface. The boundary layer managed to warm in the lowest decameters, a well-mixed layer is situated between 1500 m and 2300 m, possibly caused by the French Maritime Alps while the EML between 2300 m and 3500 m is produced by the large-scale warm air advection also indicated by the strong veering from southwest to northwest. The large-scale EML marks the top of the low stratus deck.

The sounding ascent of Munich in figure (7) is quite impressive as a deep mixed layer is present in the lower atmosphere. At the surface, a weak inversion has developed. Above, dry and well-mixed conditions with strong southwesterly to westerly winds prevail. The subsidence inversion starts at 600 mb. The dry-adiabatic layer can be separated in two parts. The lower part is characterized by a decreasing dewpoint from 640 m to 1500 m and the upper part shows a

dewpoint following the lines of constant mixing ratio reaching from 1500 m to 3100 m. It appears quite unlikely that the well-mixed upper part is the result of foehn or mechanically-induced mixing as the wind blew nearly parallel to the alpine mountain range. The upper EML already developed at midnight (not shown) and deepens until the noon ascent. The EML is not present before. According to the backward trajectories for Munich, 2000 m AGL, in figure (23), see section (5), the air from this layer was located to the east of Bordeaux at midnight. The 00 UTC ascent of Bordeaux (not shown) exhibits a well-mixed layer between 700 m and about 2200 m. As it can be seen from the height distribution of the trajectories, the 2000 m - trajectory has been lifted until noon.

It can be concluded that the well-mixed upper part has been advected by the strong west winds and is the result of an *elevated mixed layer (EML)* which is a concomitant phenomenon of severe convective weather situations in the summer season. It does not only occur in the Great Plains of North America (see e.g. Lanicci and Warner 1990), but also in Western and Central Europa during strong southwesterly flow patterns (Mayr 2009). . The influence of foehn is confined to the lower mixed part with strongly decreasing dewpoint. In absence of a foehn flow the EML would have acted as a lid and the observed temperature maximums probably did not materialize since the progressed season would not have allowed for a such deep mixing.

Main thesis is that the foehn act as a connector between the EML and the surface. The coupling led to a deep mixed layer. Without that deep mixed layer, the maximums would have been much lower than observed.

3.5 Local-scale weather data

The area of interest, as depicted in figure (8), covers the Wipp Valley starting downstream of the Brenner Pass and the Inn Valley in the vicinity of Innsbruck. The Wipp Valley is aligned parallel to the foehn flow which facilitates the foehn breakthrough with nearly every southern flow. Weather data is collected by valley stations (red dots) and mountain stations (blue dots). All data used in this case study are open to the public on the website of the Institute for Meteorology and Geophysics in Innsbruck (IMGI), of the Central Institute of Meteorology and Geodynamics (ZAMG) and of Austrowetter (Private Weather Service Ubimet). The stations are (from south to north)...

- Brenner Pass (1373 m) - ZAMG
- Sattelberg (2108 m), to the west of the Brenner - IMGI
- Wolfendorn (2777 m), to the east of the Brenner - IMGI
- Steinach (1025 m) - ZAMG
- Ellboegen (1080m) - IMGI
- Patscherkofel (2246 m) - ZAMG
- Rinn (917 m) - ZAMG
- Innsbruck-University (580 m), in prolongation to the mouth of the Wipp Valley - IMGI

- Innsbruck-Airport (584 m) in Innsbruck-West - ZAMG

The diagrams of the IMG1 weather stations (figure (9) to (14)) are described below. The time period covers the 16.11. and 17.11.2009. Wolfendorn is not shown as the foehn flow stayed below its altitude.

As depicted in the figures (9) and (10), south foehn at Sattelberg is characterized by little fluctuations of the wind direction, typically $180^\circ \pm 5^\circ$. The begin of the time period, 16.11., 00 UTC, to about 17 UTC, shows such a case. The temperature run is relative constant, with slight increase. After 18 UTC, the wind becomes clearly weaker, the gustiness decreases, the wind direction fluctuates stronger. Temperature and relative humidity show large variations until the end of the time period. Sattelberg has been located at the top of the foehn layer. Ellboegen (see below) was not mixed with the altitude of Sattelberg at any date. However, the foehn layer revealed vertical instability, with a swashing top throughout the time which may explain the strong variability in all parameters, i.e., Sattelberg sometimes became part of the foehn layer.

The situation in Ellboegen, displayed in the figures (11) and (12) appears to be clearer: the foehn breaks through on 16.11., 13 UTC. The relative humidity decreases with 17 % and the temperature increases with 3 K. The wind direction changes from up-valley wind to down-valley wind, and blows persistently, increasing towards the end of the time period with 7 - 10 m/s in average. At the date of the foehn breakthrough, Ellboegen shows isentropic mixing with about 2000 m, after midnight about 1800 m and lesser. Interestingly, the temperature drops just after the onset of the foehn flow. This can be deduced to the weakening pressure difference between Bozen and Innsbruck. Respectively, the depth of the foehn layer falls, too. The date of the temperature minimum in Ellboegen correlates well with the minimum of pressure difference Bozen - Innsbruck.

Finally, the situation at Innsbruck-University is illustrated in figures (13) and (14). The thermally-induced down-valley wind blew from 16.11., 8 UTC to 18 UTC. Then, the wind increased to 2 m/s in average and gusts of 5 m/s, known as "prefoehn west wind". The temperature was $11,5^\circ\text{C}$, with a dewpoint of 8°C at sunset which is an unseasonably high value. At 06 UTC, temporarily decoupling of the prefoehn westwind led to a stronger surface cooling, with the minimum of $3,9^\circ\text{C}$. The minimum in temperature and wind speed coincided with the occurrence of the radiation fog. Daytime heating after the clearing fog produced a temperature amplitude of $11,8\text{K}$. By 8 UTC, the down-valley wind became stronger and changed into the prefoehn west wind. The foehn broke through at 15 UTC at both university and airport. Gusts up to 16 m/s have been measured at university while the airport had much weaker winds and no clear foehn wind direction. The foehn ended at 16 UTC at the airport and continued until 18 UTC at university. Subsequently, the foehn passed into the prefoehn west wind again. The date of foehn breakthrough in Innsbruck correlates well with the largest pressure difference of about 6-7 mb between Innsbruck and Bozen. It remains elusive whether the foehn has already been present at 13 UTC as Innsbruck and Ellboegen exhibit a mixed atmosphere and the relative humidity decreased with about 8%. However, the wind direction argues against foehn. Another remarkable point is that the strongest gusts

happened after the sun disappeared behind the thicker cloudiness. Followingly, the temperature decreased stronger than in Ellboegen. Therefore, the foehn flow became decoupled of the Inn Valley.

4 Generation of Kelvin-Helmholtz-Waves in the radiation fog

Kelvin-Helmholtz-Waves (abbreviated as KHW as follows) are so-called external gravity waves which are generated at the interface between a thicker and a thinner medium. That interface is stable stratified concerning the vertical temperature difference as the thinner medium lies above the thicker medium. The necessary shear instability to excite wave generation is produced by vertical wind shear, i.e., the thinner (warmer) air mass flows quicker than the underlying thicker (colder) air mass. As depicted in figure (16), the streamlines can be seen as isentropes. The overhanging part of the wave crest possesses a lower potential temperature than below, the layering becomes static unstable. By $t = 2$, the wave crests start to break (compare with waves of the sea). Kelvin-Helmholtz-Waves typically cause the clear-air-turbulence in higher levels which pose a serious threat for air traffic.

The webcam pictures give rise to the existence of gravity waves during the shallow foehn. A possible explanation for the observed wave phenomenon is the generation of Kelvin-Helmholtz-Waves (KHW). There are two facts arguing for KHW:

- The wind speed at the valley floor temporarily decreased to 2-3 m/s as the radiation fog formed. The foehn flow above blew with 7-8 m/s in average. Thus, a vertical wind shear has been present.
- The foehn air has been warmer than the thermally-induced down-valley wind. Thus, a thicker medium lied beneath a thicker medium.

The view of the Patscherkofel to the north in (figure 21) shows the best agreement with the theory of KHW. Researchers in medicin meteorology arguing for KHW, too., e.g. de Rudder (1948) and Richner (1983). De Rudder states that the meteorosensitivity in case of foehn is most pronounced in Innsbruck and diminishes up- and down the valley. Generally, the people are less meteorosensitive to pain when the foehn already broke through, and they are most meteorosensitive when the foehn is immediately before the breakthrough, i.e. when a shallow cold air layer still exists. This is in line with self-observations on 14.11.2009 as I had migraine just before south foehn broke through which has been literally blown away with the onset of the foehn winds. De Rudder brings forward the argument that the surface cold air flow and above-gliding south foehn flow create a strong wind direction change at the interface between the thinner and thicker medium. This state corresponds to the prerequisites of KHW. The stronger the vertical wind shear, the more intensive the generation of gravity waves (coincident to a strong decrease of the Scorer-Parameter with height) leading to an up- and downward swashing of the warm- and cold air which causes periodic pressure fluctuations. Meteorosensitive people feel these fluctuations.

Richner (1982 and 1983) carried out statistical examinations with meteorosensitive people affirming de Rudder's theory. Women seem to be more sensitive than men. The meteorosensitivity decreases in Zirl and Hall (farther upstream respectively downstream of Innsbruck) although the foehn is present there, too. De Rudder reasons this with the absence of a crossways orientated valley where a strong south foehn flow could slide over the cold air flow. Respectively, the upper-level flow is much lesser than in Innsbruck and the pressure fluctuations are less pronounced.

Summarizing there is evidence that the observed wave structures in the radiation fog have been the result of KHW. The prerequisites of KHW have been fulfilled, previous examinations support this theory and the quasi plane-view in figure (21) suggests as well that KHW could have been present.

5 Extrem temperatures in Southern Bavaria

The temperature values of the Zugspitze suggest that deep mixing up to 3000m has been present. However, the strong west winds, veering to northwest in the afternoon, contradict that assumption. Patscherkofel had weak southeast winds between 7 and 11 UTC, and northwest winds with concomitant temperature increase and fluctuation between 12 and 17 UTC. Thus, it appears unlikely that the warm air in Southern Bavaria originated from much higher levels than the foehn air in the Wipp Valley.

Moreover, at the date of temperature maximum, the temperature at Feldberg (1496m) in the Black Forest was $+11^{\circ}\text{C}$. The Feldberg is far enough from foothills of the Swiss Alps, and therefore representative for the synoptic-scale warm air advection in 850 mb. The station data correlate well to the model analyses.

There are two possibilities to obtain the high temperatures near the foothills of the Bavarian Alps:

- The maximums originate completely from the warm air advection. The maximum in 850 mb is a result of maximized warm air advection
- The maximums result of a combination of warm air advection and foehn air. Fischen is nearly at the same height as Sonthofen but has been 2 K lower while the maximum temperature has been reached. As the same air mass prevailed within this area, the little temperature excess could be attributed to the foehn air.

To corroborate the second explanation approach, three trajectory plots have been carried out with the NOAA Hysplit Model, see figure (23). The plots of Basel and Munich exhibit the source of the air masses in the vicinity of the Canary Isles respectively Morocco - in all altitudes. The 500 m trajectory crossed the Pyrenees in both cases suggesting that subsidence/foehn air has been present. As shown in 3.4, the crossing of the Pyrenees led to the generation of a well-defined elevated mixed layer. The connection of the foehn flow to the elevated mixed layer could explain the unseasonably high 850 mb temperatures.

The plot of Milano displays the weak low-level winds in the Po Valley while an air mass change occurred in mid-levels across the Western Mountain Range. The resulting warm air advection strengthened the inversion in the Po Valley

and created classic conditions for a shallow foehn flow: immobile cold air to the south of the main crest and shallow, but strong warm air advection to the north of the main crest.

6 Summary

The large-scale weather pattern exhibited summery features regarding the development and advection of a pronounced elevated mixed layer which brought unseasonably high 850 mb temperatures to the north of the Alps. The intense warm air advection has been caused by a prolonged trough reaching to the Canary Isles transporting maritime subtropical air across Western Europe to Central Europe, with lifting the air masses across the Pyrenees. The case study revealed that the connection of the elevated mixed layer and local foehn winds has been responsible for the positive temperature records close to the foothills of the Northern Alps.

As the upper-level flow came from westerly directions, a shallow foehn has been established which was presented in this case study above. Shallow foehn in the Wipp- and Inn Valley is characterized by lowered maximum temperatures due to the tap into potentially cooler air masses upstream of the Brenner Pass. Above all, the lack of precipitation to the south of the Alps and the presence of a persistent low stratus deck point at a classic anticyclonic foehn whose horizontal pressure differences are mainly driven by differential sensible heat fluxes and differential temperature advection.

A cloud phenomenon similar to the Maloja serpent developed with the low stratus deck crossing the Brenner Pass from the south. The top of the low stratus also marked the top of the foehn flow layer.

As the prefoehn west wind was hardly defined as a result of the shallow and cool foehn flow, radiation fog could evolve in the Inn Valley during the second half of the night. At sunrise, the wind temporarily faded away and a thick radiation fog layer developed over the center of Innsbruck. In a short period of twenty or thirty minutes, well-defined wave structures arose, most likely due to Kelvin-Helmholtz-Instability.

7 References

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Notice: That document is thought to be a draft article. It is *not* published in any scientific journals.

Appendix

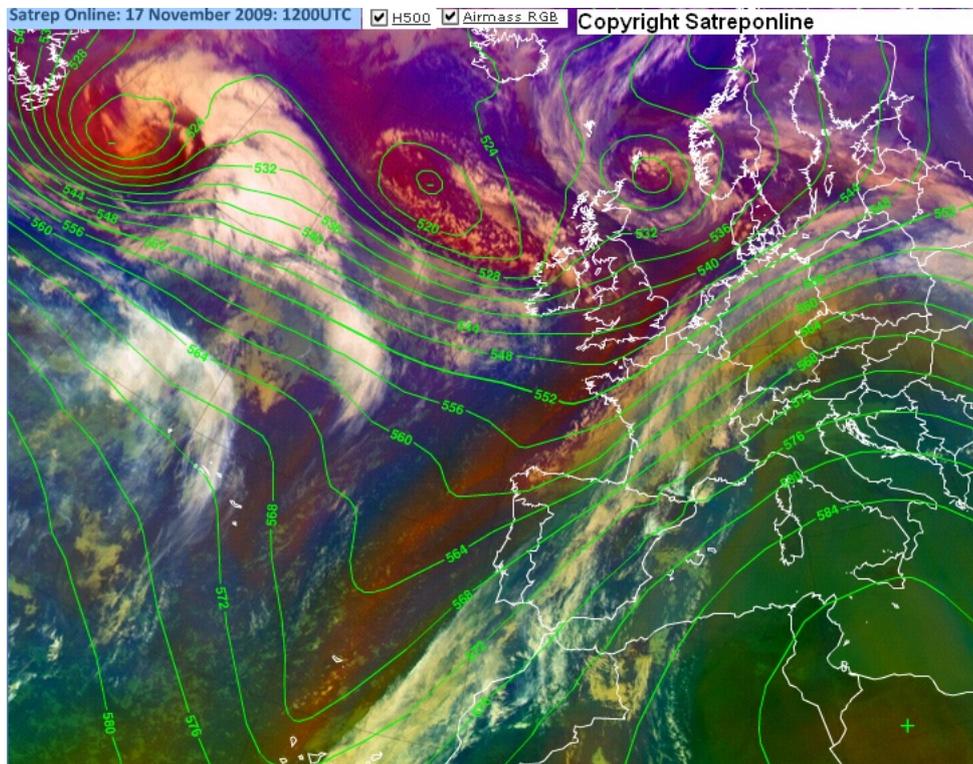


Figure 1: RGB- satellite image with overlay of 500 mb geopotential heights (green) - 17.11.2009, 12.00 UTC

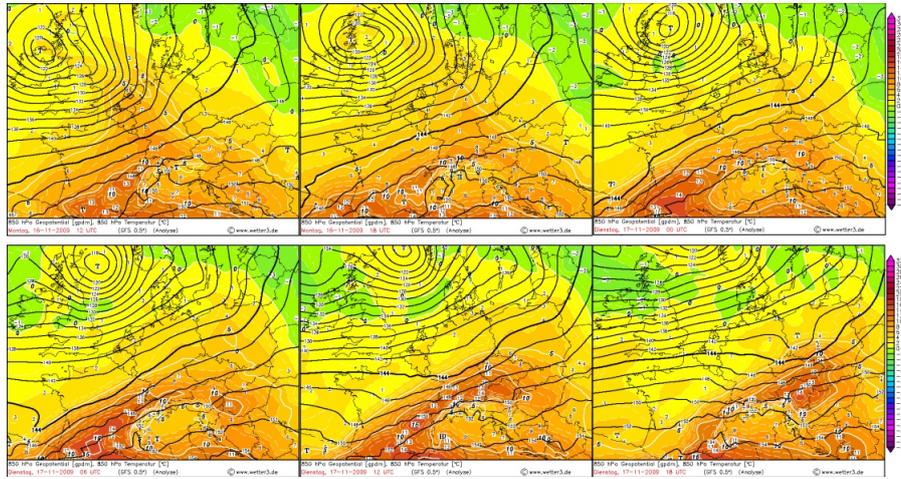


Figure 2: GFS analysis, 850 mb geopotential (solid lines) and temperature (shaded), spaced in 6 h, from Monday, 16.11.2009, 12.00 UTC, to Tuesday, 17.11.2009, 18.00 UTC

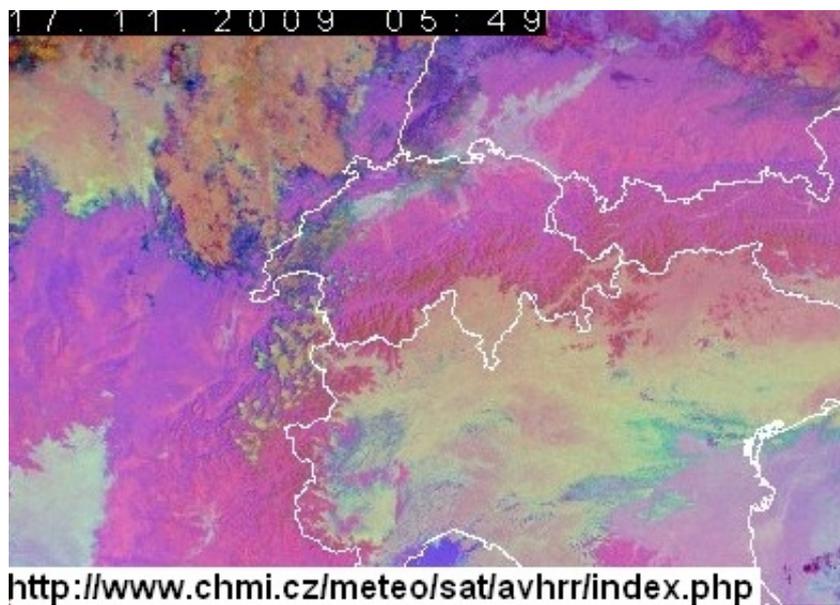


Figure 3: NOAA Satellite image, 17.11.2009, 05.49 UTC, red and yellow colors indicate mid-level and upper-level clouds, white colours fog or low stratus

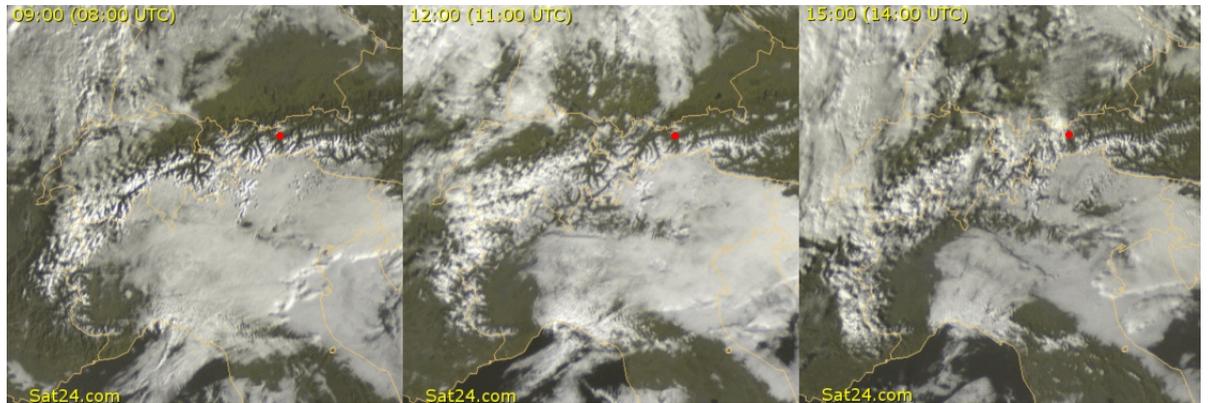


Figure 4: Sat24, visible channel, valid for 17.11.2009, 08.00 UTC (left), 11.00 UTC (center) and 14.00 UTC (right). The satellite images represent the cloudiness in the forenoon, noon and afternoon hours.

Date	Bozen	Innsbruck	Munich
18	1019	1016.5	1013
00	1020	1018.5	1014
06	1021	1020.0	1015
12	1022	1016.0	1013
15	1022	1015.0	1013
16	1021	1015.5	1013
17	1022	1016.8	1013
18	1022	1016.0	1014

Table 1: Air pressure at different stations in mb, time in UTC, from 16.11. to 17.11.

Pressure level	Milano 0z	Milano 12z	Munich 0z	Munich 12z
850	292.6	292.4	296.2	298.9
800	293.0	293.0	297.0	299.0
700	306.2	303.0	301.7	301.0

Table 2: Pressure level in mb, Θ in Kelvin, 800 mb is interpolated by soundings, valid for 17.11.2009

11120 LOWI Innsbruck-Flughafen

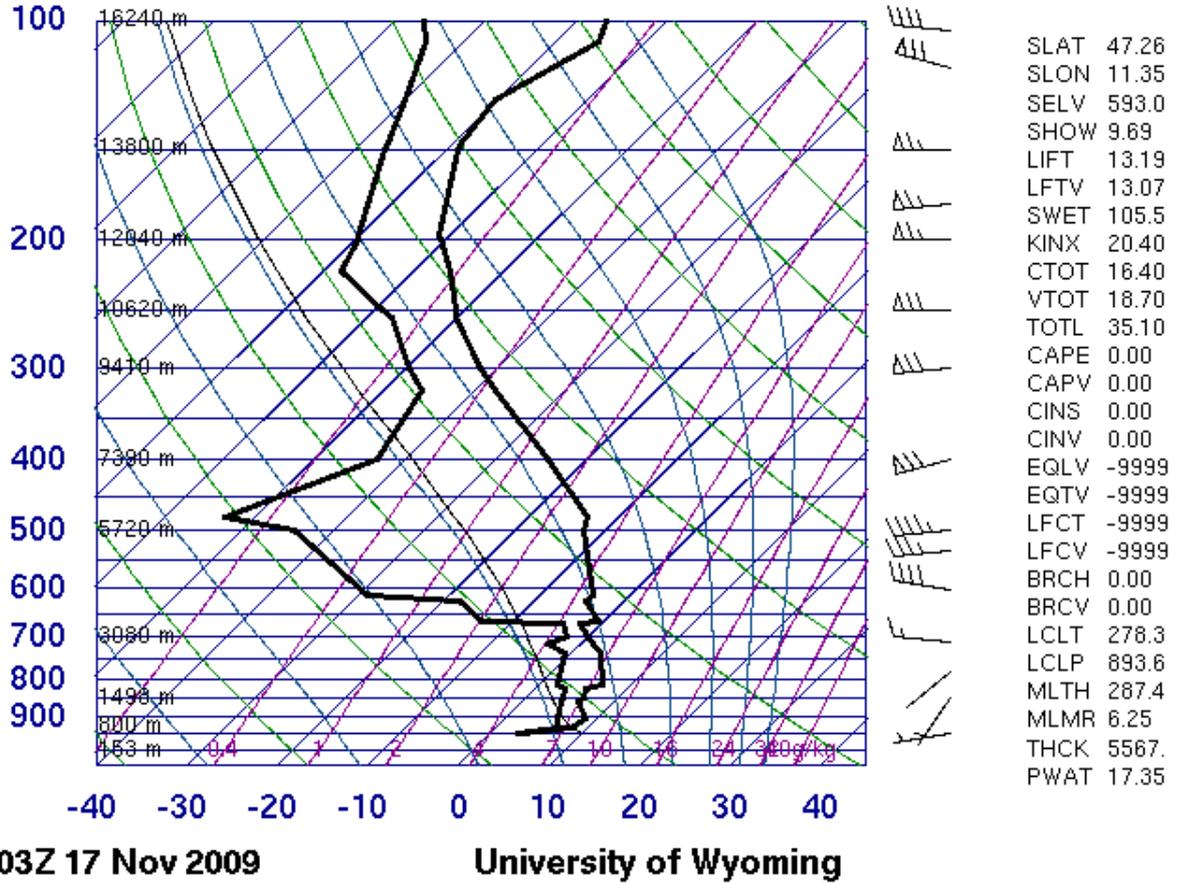


Figure 5: Sounding Innsbruck-Aiport, 17.11.2009, 03 UTC

16080 LIML Milano

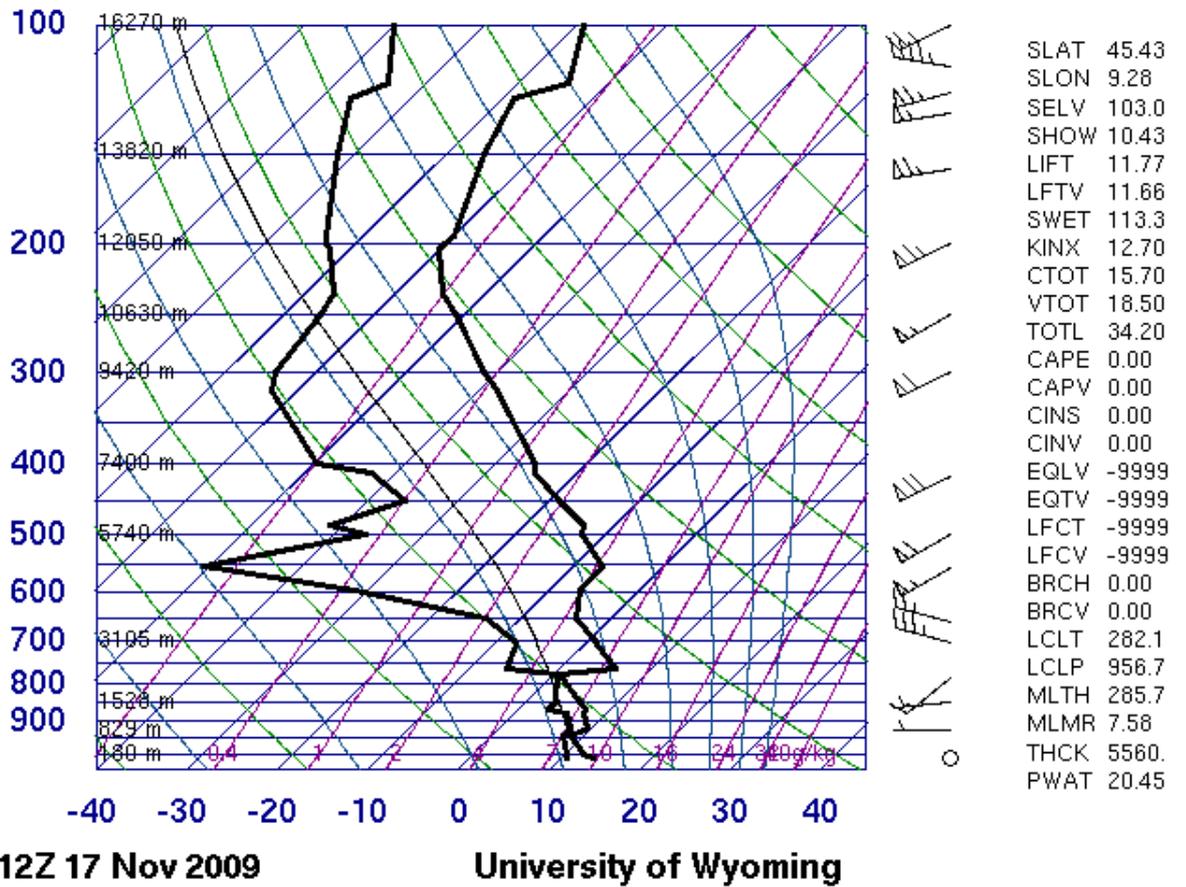


Figure 6: Sounding Milano, 17.11.2009, 12 UTC

10868 Muenchen-Oberschlsheim

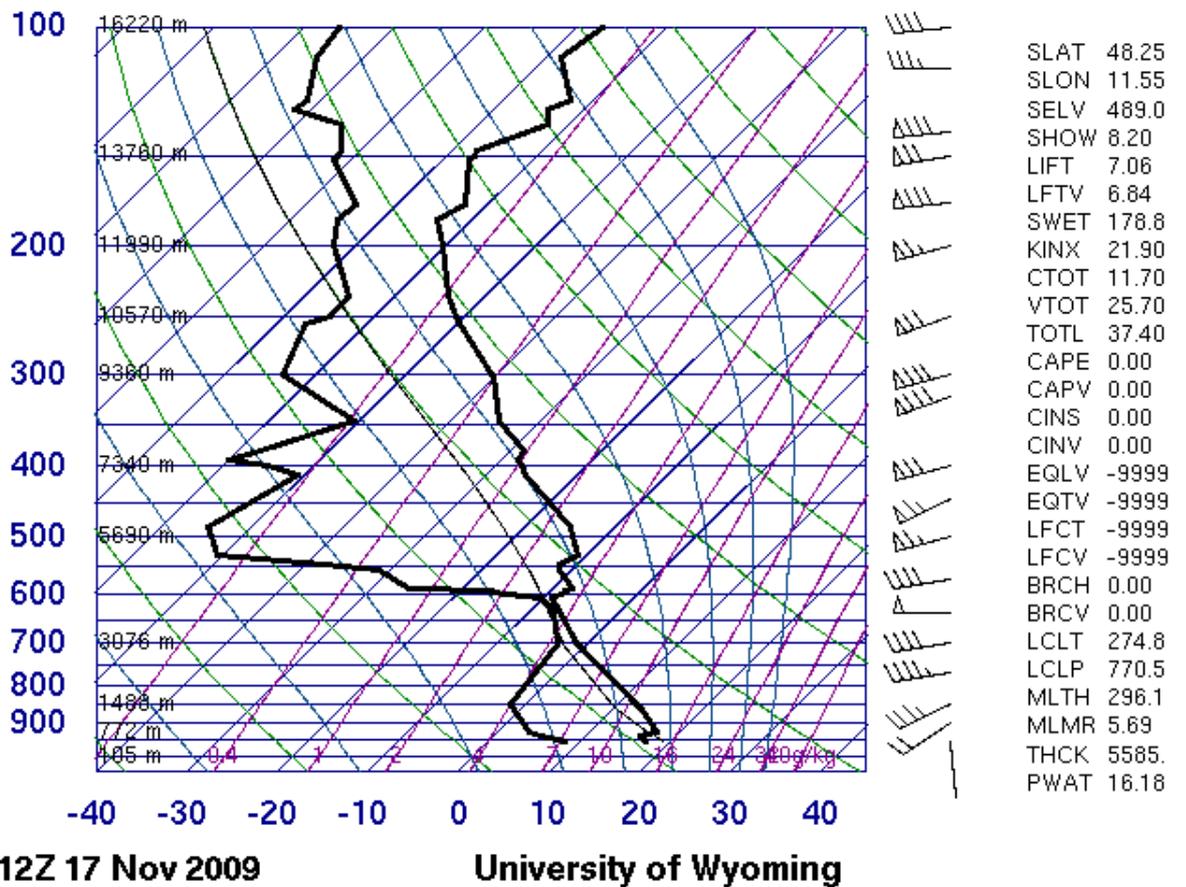


Figure 7: Sounding Munich, 17.11.2009, 12 UTC

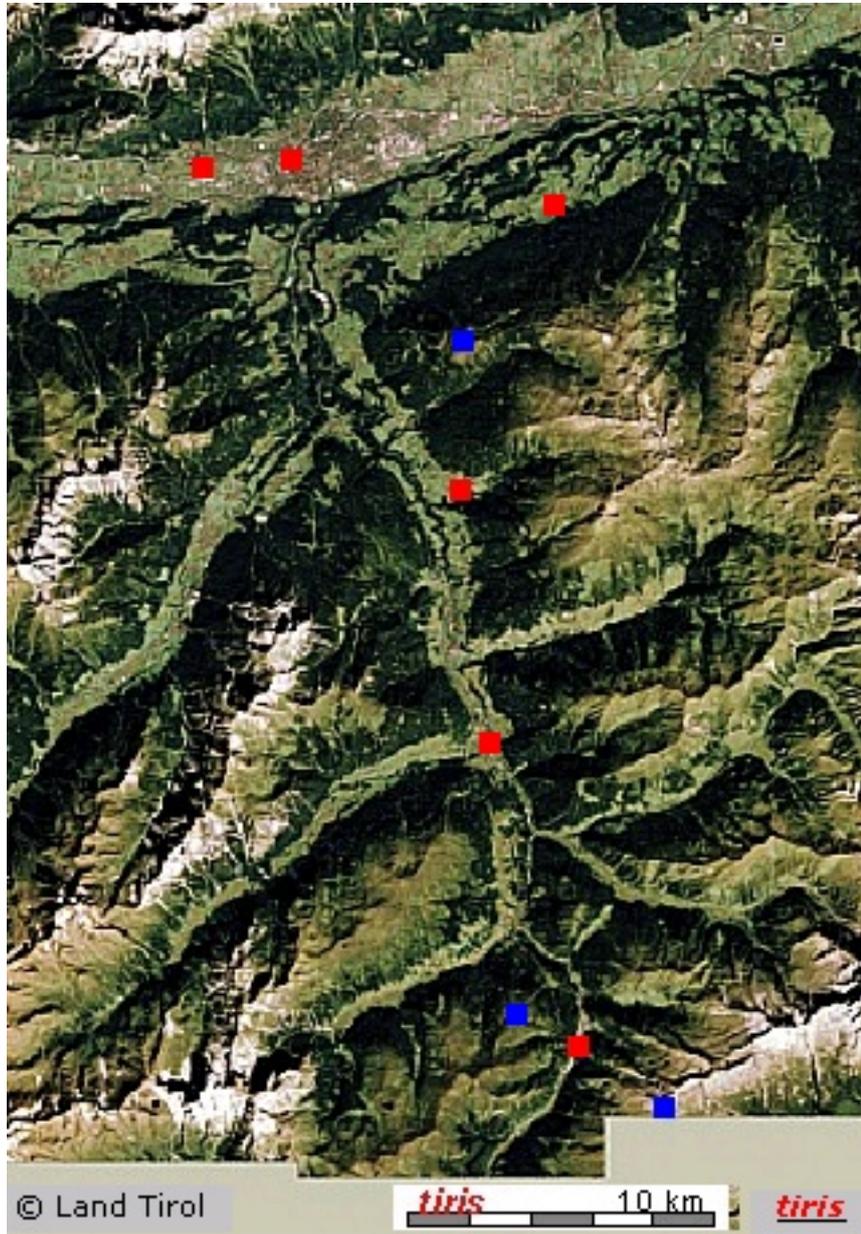


Figure 8: Area of interest. Red dots indicate valley stations, blue dots mountain stations

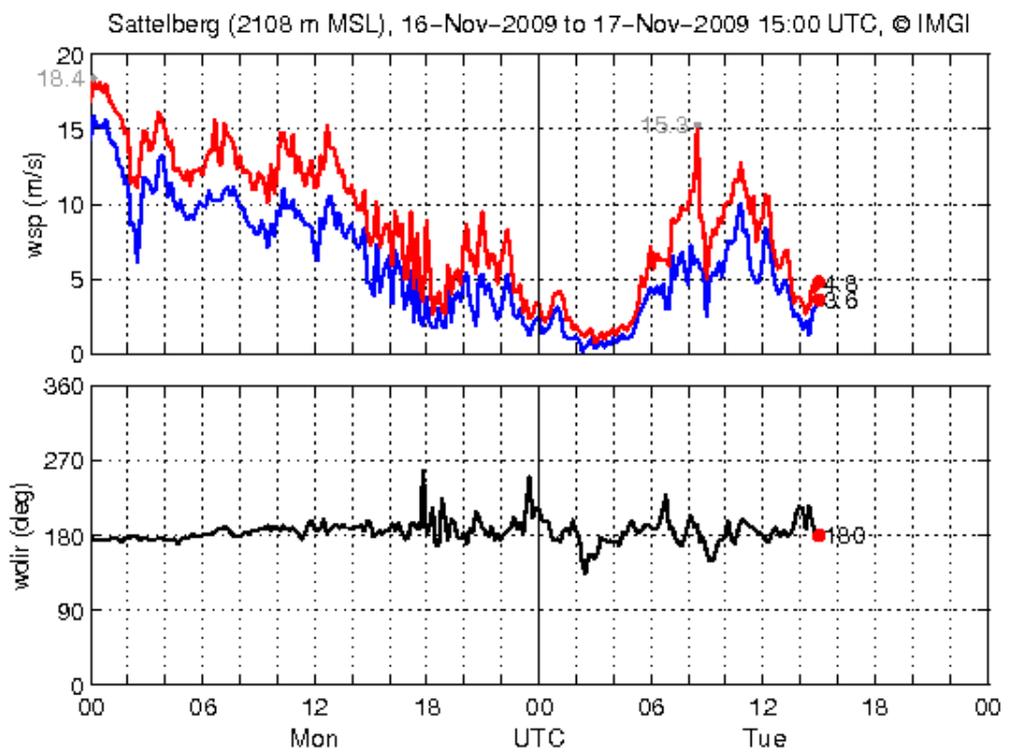


Figure 9: Sattelberg, Wind direction and speed (m/s), 16.11. to 17.11.2009

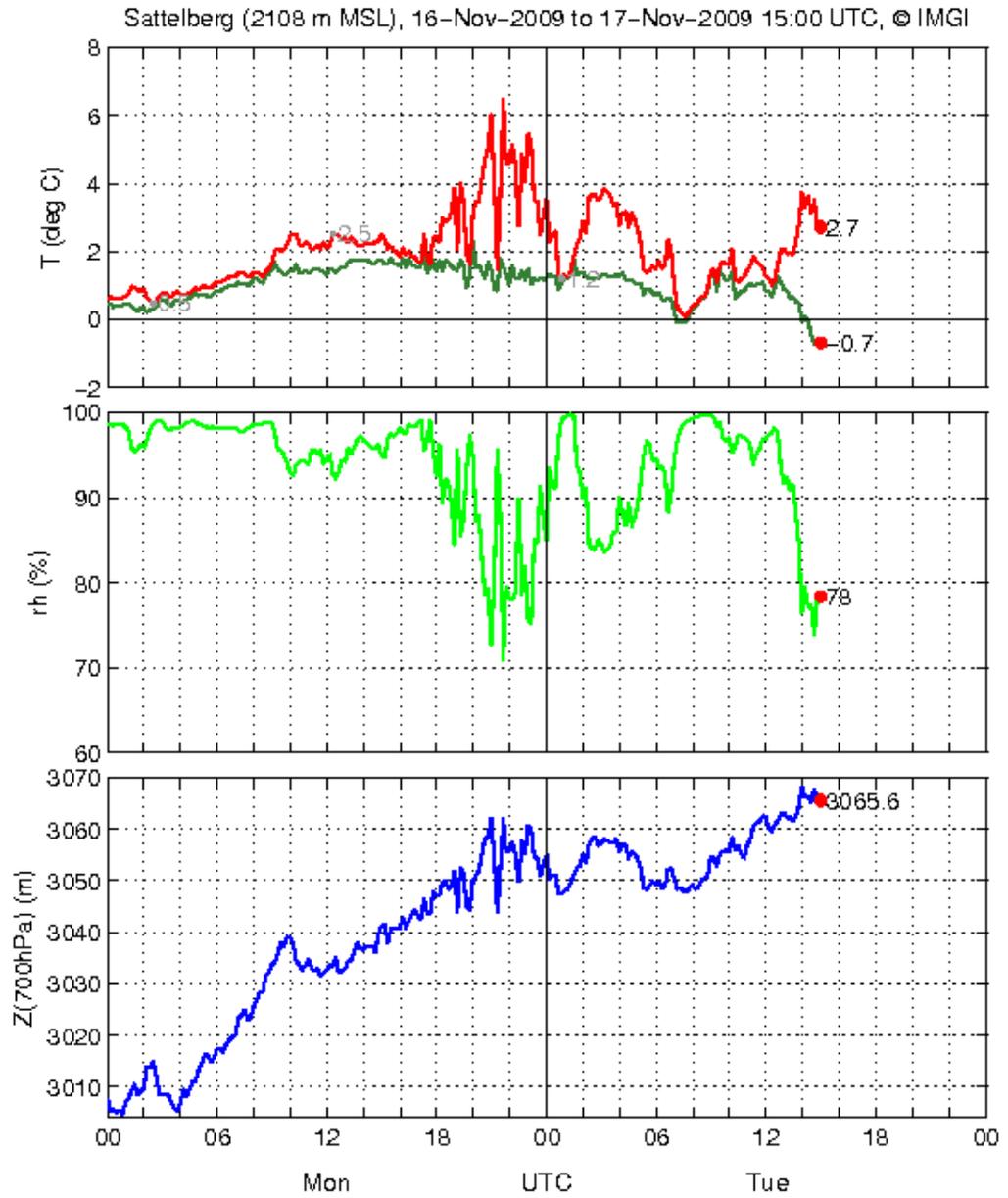


Figure 10: Sattelberg, Temperature and Dewpoint, Relative humidity and Geopotential, 16.11. to 17.11.2009

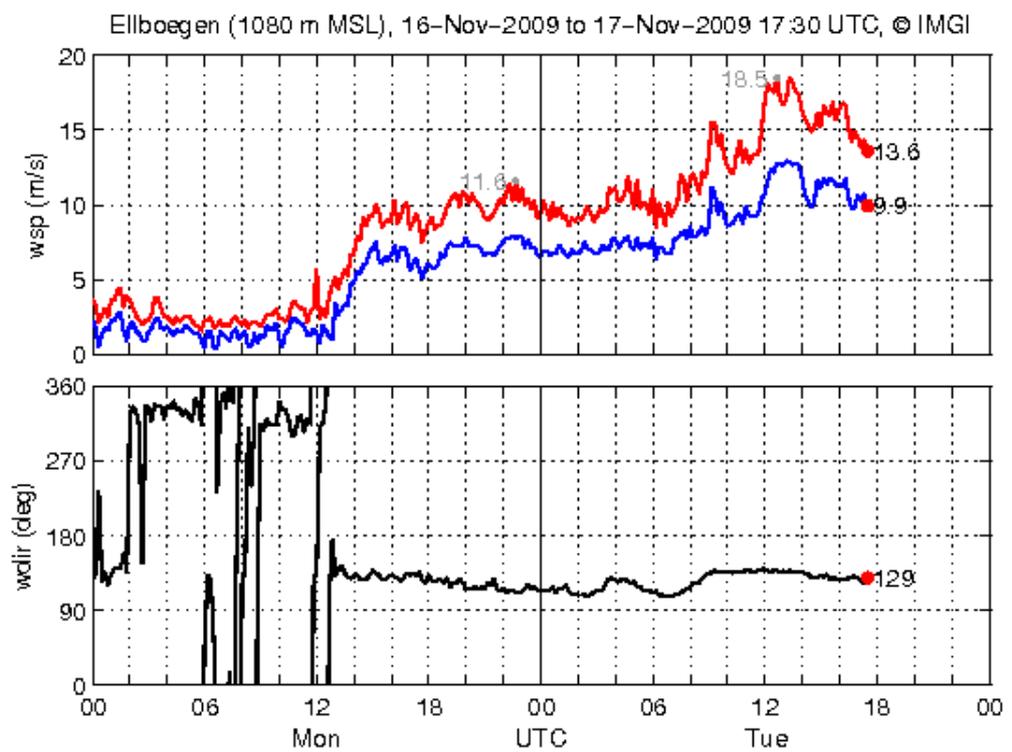


Figure 11: Ellboegen, Wind direction and speed, 16.11. to 17.11.2009

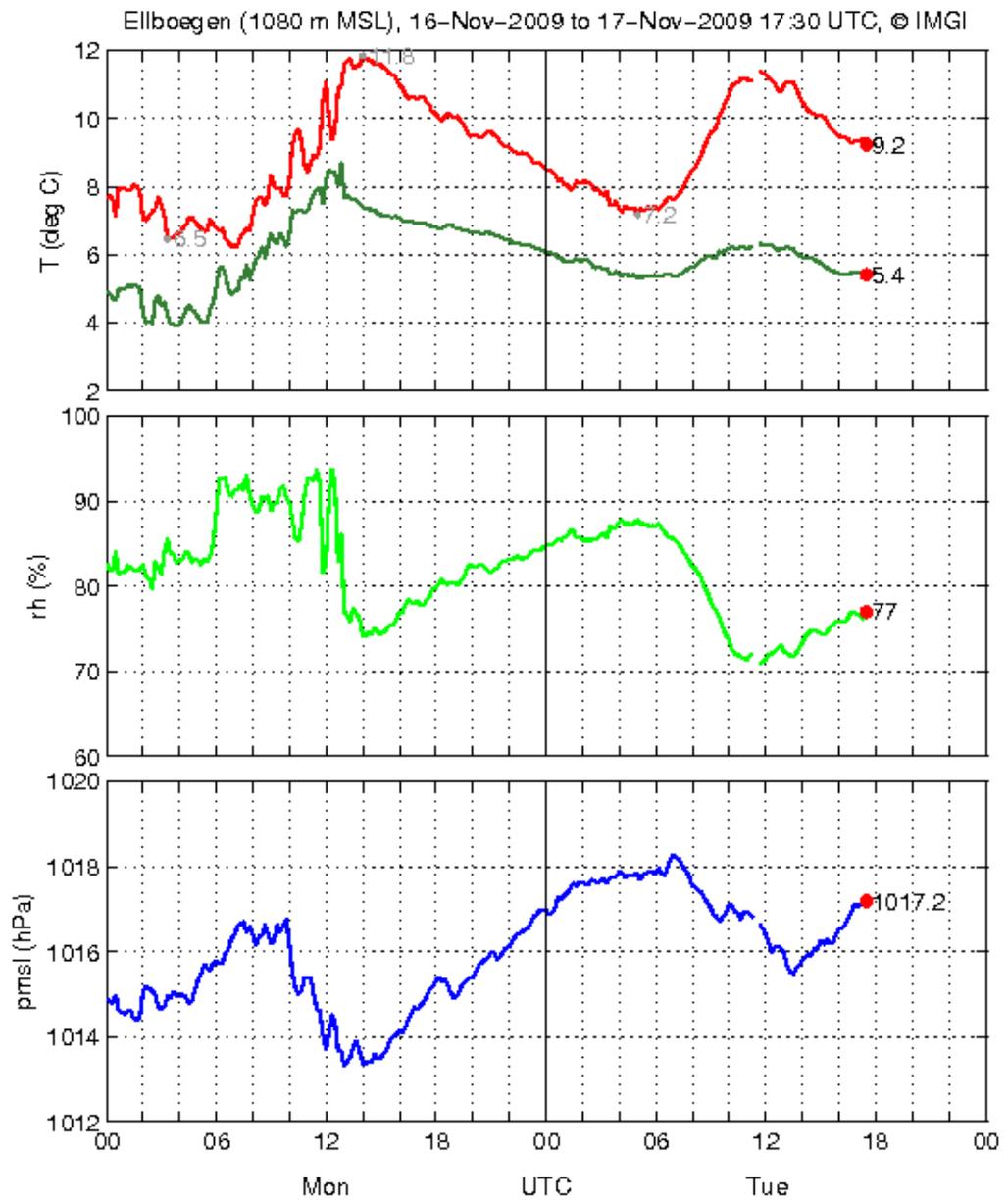


Figure 12: Ellbogen, Temperature and Dewpoint, Relative humidity and Reduced pressure, 16.11. to 17.11.2009

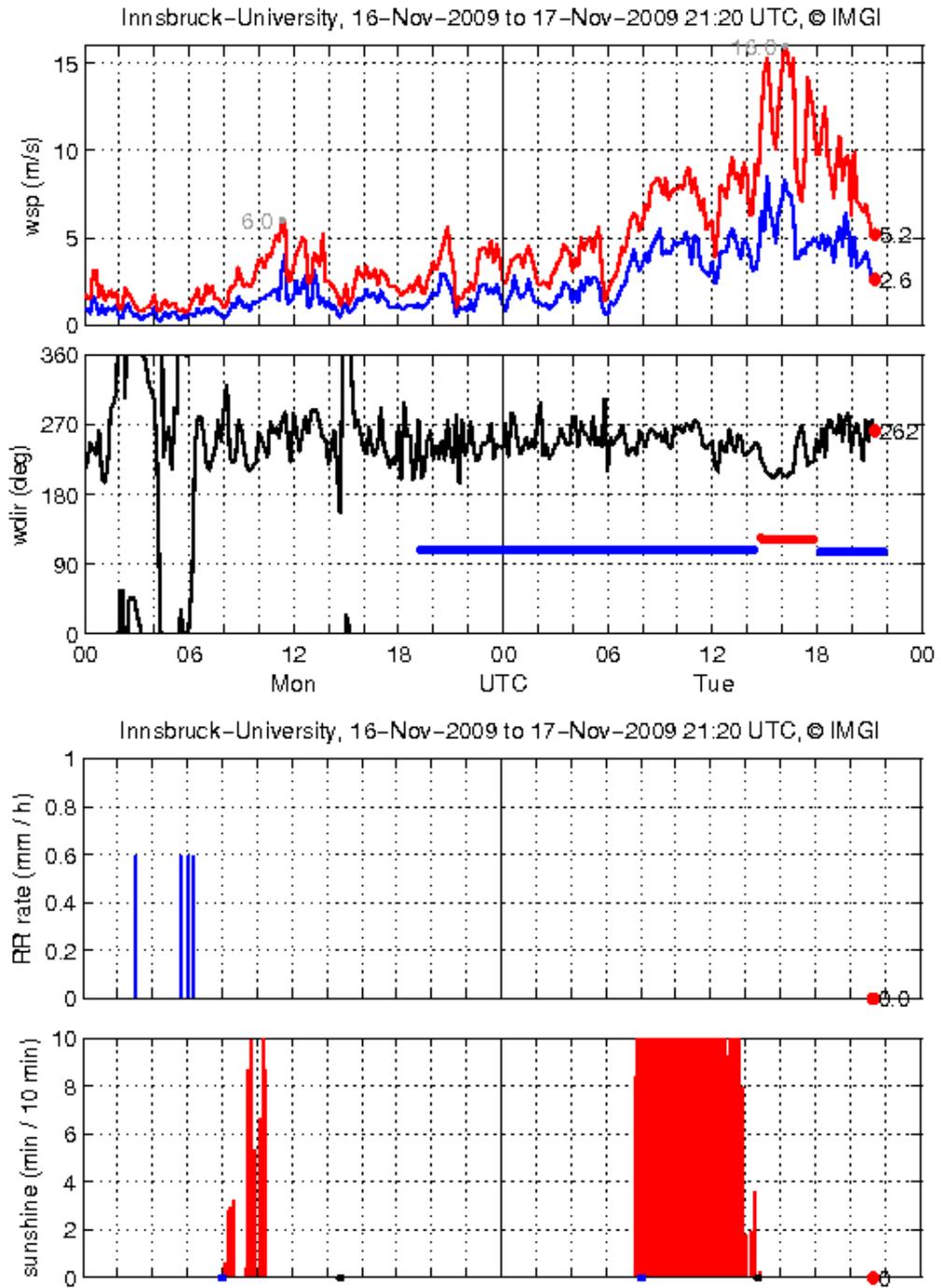


Figure 13: Innsbruck-University, Wind direction and speed, precipitation and sunshine, 16.11. to 17.11.2009

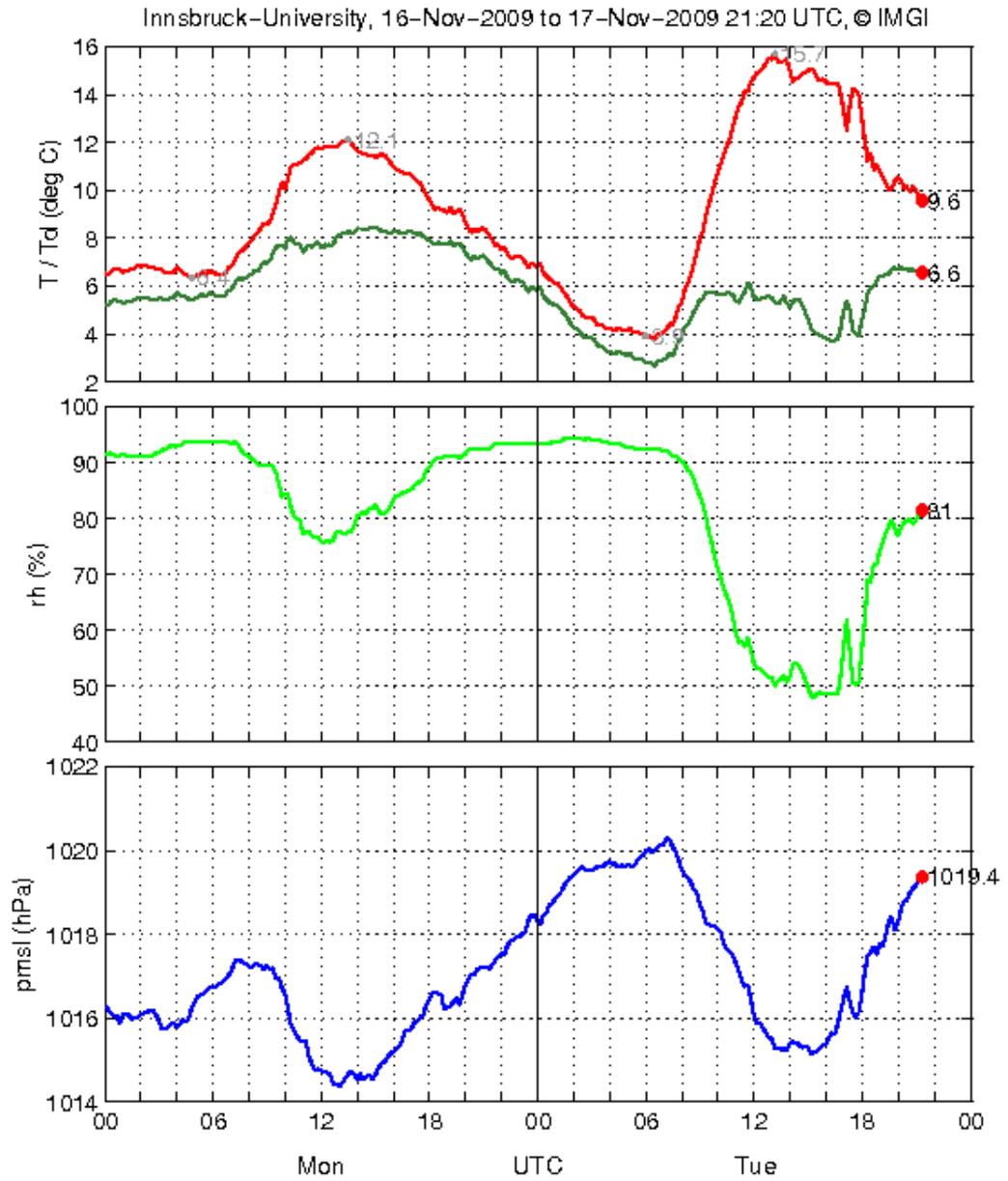


Figure 14: Innsbruck-University, Temperature and Dewpoint, Relative Humidity, air pressure, 16.11. to 17.11.2009



Figure 15: Kelvin-Helmholtz-Waves ©Brooks Martner

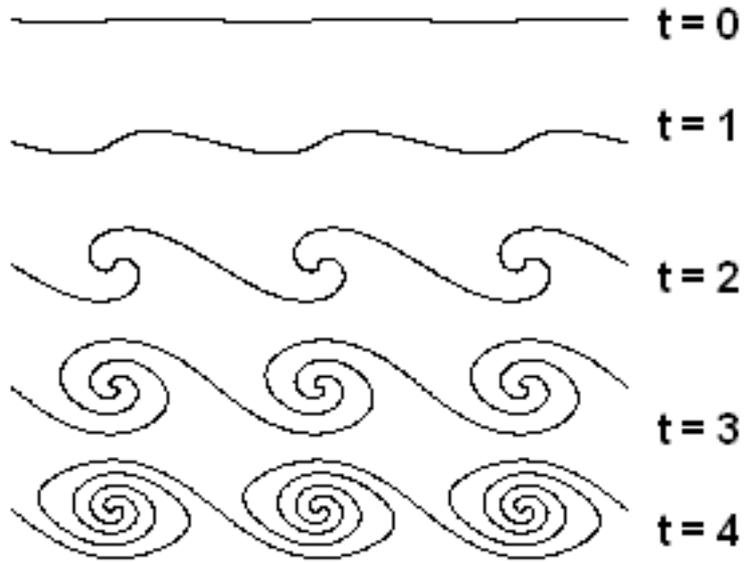


Figure 16: Schematical sketch to the development of KHW with progressing time

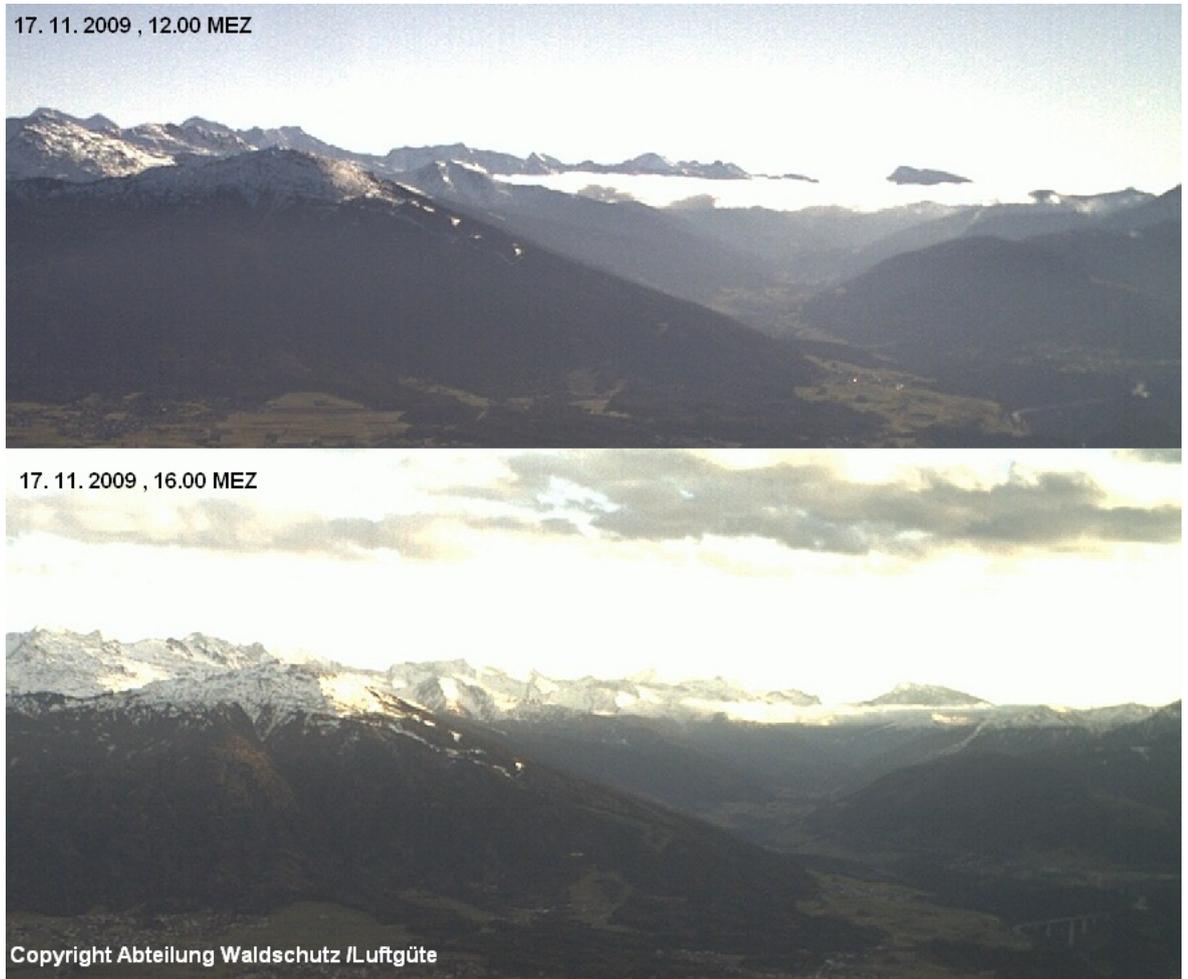


Figure 17: Webcam pictures, Nordkette, 17.11.2009, 11 UTC (above) and 15.00 UTC (below), view to the south. A persistent low stratus deck with a top of about 2200m and a lower limit of about 1800m is present in the upper part of the Wipp Valley. It resembles the notorious Maloja serpent developing when the potentially cooler and moister air flow from the Bergell Valley crosses the Maloja Pass into the Upper Engadine leading to lifting condensation. As the air in South Tyrol has been potentially cooler and moister, the similarity to the Maloja serpent is quite obvious.



Figure 18: Webcam picture, Nordkette, 17.11.2009, 5.40 UTC, view to the south. The Radiation fog already breaks up.



Figure 19: Webcam picture, Nordkette, 17.11.2009, 5.50 UTC, view to the south. Distinct wave structures appear. The axis of the flow is perpendicular to the orientation of the fog bands and turns the southwest corresponding the bending foehn flow. The alignment of the fog bands seem to be periodic.



Figure 20: Webcam picture, Nordkette, 17.11.2009, 6.00 UTC, view to the south. The fog temporarily extends farther upstream.

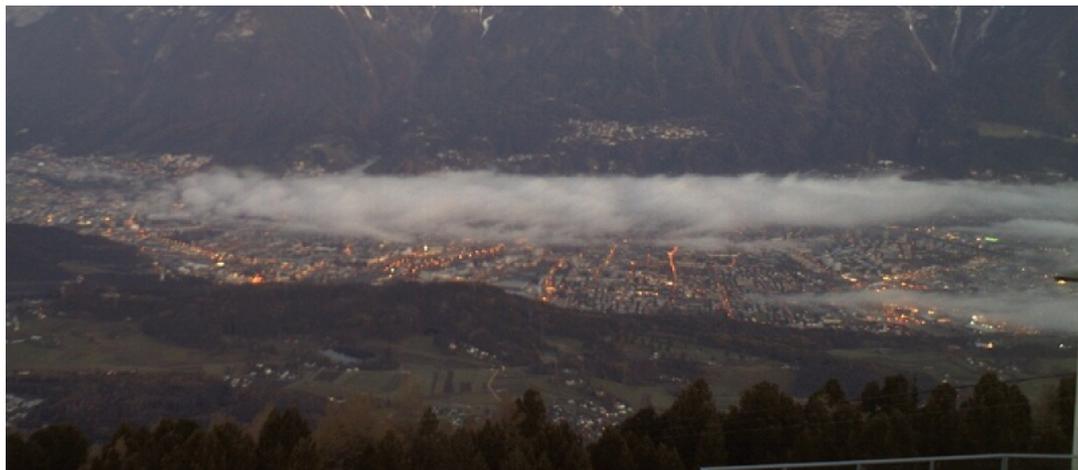


Figure 21: Webcam picture, Patscherkofel, 17.11.2009, 06.00 UTC, View to Innsbruck. The best picture of the series since the downstream slope of the fog waves arouses the suspicion of overhanging wave crests characterizing KHW.



Figure 22: Webcam picture, Nordkette, 17.11.2009, 6.10 UTC, view to the south, the wave structures are vanishing, the fog breaks up finally.

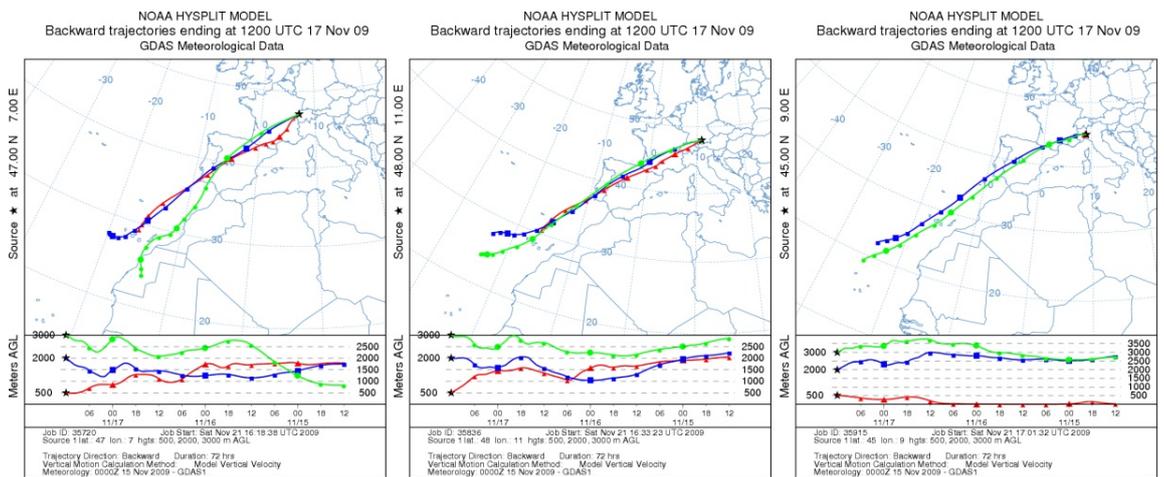


Figure 23: Backward Trajectories at 17.11.2009, 12 UTC, for Basel (left), Munich (center) and Milano (right), the vertical motion is calculated by model vertical velocity. The trajectories start 120 hours ago, ending up at 500 m (red), 2000 m (blue) and 3000 m (green)