P3.10 CASE STUDY OF THE NORTH FÖHN IN THE EISAKTAL DURING MAP

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1. INTRODUCTION

A field study designed to examine gap flow south of the Brenner Pass during north Föhn episodes, was mounted during August - December 1999, as part of the Mesoscale Alpine Programme Special Observing Period. We were interested in examining the hydraulic characteristics of gap flow as it leaves the confines of a narrow valley to a widening. In order to assess this we installed a transect of three surface stations measuring wind and pressure precisely, and a Scintec FAS64 Doppler Sodar system. In addition, radiosondes, across-valley temperature transects, and mobile temperature measurements, were able to document Föhn events, leading to their enhanced explanation. In this paper, the deep north Föhn event of November 6-9 1999 will be examined.

2. SYNOPTIC EVOLUTION

The November 6-9 north Föhn case was initiated at the synoptic scales by the movement of a cold frontal trough southward across the Alps, which lead to the formation of a surface Low over the Mediterranean. The frontal surface extending upward north of the surface front resulted in a frontal inversion over the Alps just above the mountain ridge elevations. In Fig. 1, the height-time cross section of potential temperature and winds based on the Innsbruck radiosonde measurements shows the passage of the frontal zone through Innsbruck between 03 and 12 UTC on 6 November, and the rapid increase in the depth of the cool air layer to 3000m above sea level (ASL) by 7 November. This was associated with the southward movement of an upper low across the Alps, and the strong building of an upper ridge and surface High over the British Isles. This evolution resulted in a strong northerly flow of cool air aloft that was partially blocked by the Alps. The partially blocked cool air combined with the surface High in the north and Low over the Mediterranean resulted in a synoptic-scale sea-level pressure gradient pointing southward across the Alps ranging from 12 hPa / 100 km (on 7 November) to 7 hPa / 100 km (by 9 November). This configuration resulted in a deep northerly Föhn over the Alps with the strong northerly flow extending to the surface.

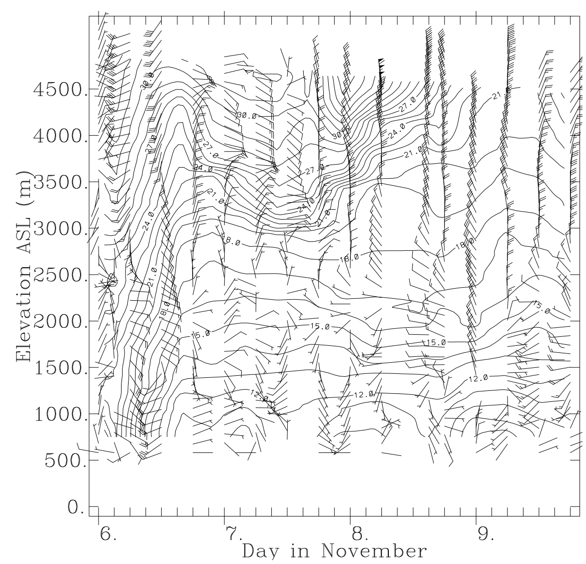

Figure 1: Height-time cross section of potential temperature (°C) and winds (each full barb represents 5 m s^{-1}) during the 6-9 November north Föhn episode.

3. FÖHN STRUCTURE

Föhn events, like other gap flow phenomena, are often characterized by having two distinct layers in the vertical: a near-surface cold layer, surmounted

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by a warmer layer. A stable zone, often an inversion, separates the two layers. An analogy can be drawn between such a two-layer system in the atmosphere and the hydraulic flow of water in an open channel. In this analogy, the air-water interface in hydraulics represents the stable zone separating the cool, dense lower layer from the warm upper layer in the atmosphere. The analogy is helpful in understanding two-layer phenomena in the atmosphere, as the simplified hydraulic system includes a variety of flow features such as supercritical shooting flow and hydraulic jumps, which are similar to features observed in the atmosphere.

For the case of two-layer flow in and over the Alps, two spatial scales are important: the scale of the mountain range itself, and the scale of individual valleys which dissect the main mountain barrier. If the stable zone is located at, or below the mountain ridge elevation, but above the elevation of mountain passes, then hydraulic phenomena at the scale of the valleys will occur. In this case, the cool, dense air from the windward side of the mountains will flow over the passes and through the valleys on the lee side. Since the stable layer is below the mountain crest in this "shallow Föhn" situation, the flow will be mostly confined to the valleys, or channels, and will resemble the open channel hydraulic flow of water.

If the stable zone is located well above the mountain ridge elevation, then hydraulic phenomena at the scale of the mountain range will occur. In this "deep Föhn" case, the air can flow over the mountain ridges, as well as through the valleys, and is not as constrained horizontally by the valley walls as in the shallow Föhn case. The air flow over the Alps is analogous to water flowing over and around a boulder in a river channel. In this situation, the scale of the mountain range itself is most important.

The present case has a very distinct two-layer structure, which was apparent at Innsbruck in Fig. 1. The two-layer structure also existed across the Alps, with considerable variation in the stable zone height, as can be seen in Fig. 2. The highest mountain peaks in the Alps are near 3500 m ASL, with average ridge elevations at around 2500 m ASL. The stable zone height is above this elevation, so that the present deep Föhn case should exhibit hydraulic characteristics consistent with flow over a 2-dimensional ridge.

The MC2 mesoscale model (Benoit et al, 1997) was run operationally at 3.3 km horizontal resolution and

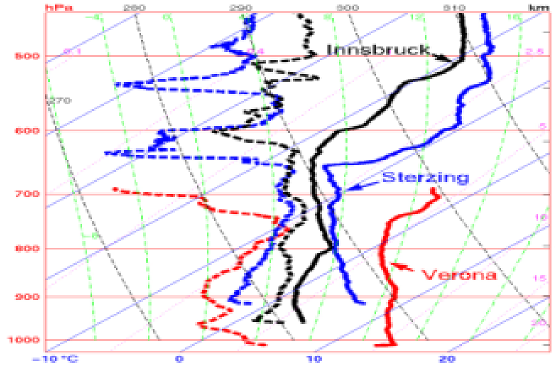

Figure 2: Skew T-log P diagrams from Verona and Sterzing at 12 UTC and from Innsbruck at 14 UTC on 8 November 1999. Adapted from Geier et al (2000)

used extensively for flight planning purposes during the MAP SOP. Figure 3 is a south-north vertical cross section from MC2 along 11.25 °E longitude, crossing the Alps near the Brenner Pass. The stable zone capping the lower cool air is indicated by the increased vertical potential temperature gradient at around the ridge crest level. Isentropic flow in this plane will be parallel to the potential temperature lines. Therefore zones where the isentropes descend and compress near the surface (i.e. on the lee-side of the mountain), which correlate with strong winds, are similar to the supercritical shooting flow of hydraulic theory. Regions where the isentropes suddenly rise upward, becoming nearly vertical (i.e. at x grid positions 114-120, 154, 176 and 186), are similar to a hydraulic jump.

In order to qualitatively compare the MC2 modeled flow across the mountain barrier, with that represented by a simple hydraulic model, the atmospheric hydraulic model *hydmod* discussed in Jackson and Steyn (1994), designed to simulate shallow Föhn - type gap flows, was modified to simulate hydraulic flow over a 2-dimensional ridge. The model settings chosen, based on typical values and the observed radiosonde profiles were: upwind northerly flow - 8 m s^{-1}; upwind boundary layer depth - 3000 m; downstream boundary layer depth - 2500 m; potential temperature difference between lower layer and upper layer - 15 °C; horizontal pressure gradient from north-south - 10 hPa / 100 m; and modified drag coefficient - .04 at all grid points. The model terrain profile was approximated by the sum of two gaussian functions and an exponential decay, with a horizontal

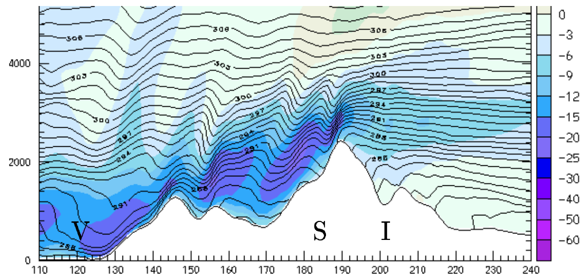

Figure 3: MC2 10 h forecast valid 8 November 1999 7 UTC. Shown is a north to south (right to left) vertical cross section along 11.25 °E (through the Brenner Pass area), of potential temperature contoured in 1 K intervals, and the v wind component shaded. North Föhn flow is from right to left. The vertical scale is in m ASL, and the horizontal scale is in model grid point dimensions: each grid point is 3.3 km apart. I, S, and V are the approximate locations of Innsbruck, Sterzing, and Verona. Image is cropped from the MAP Field catalog at http://www.map.ethz.ch/sop-doc/catalog/index.html.

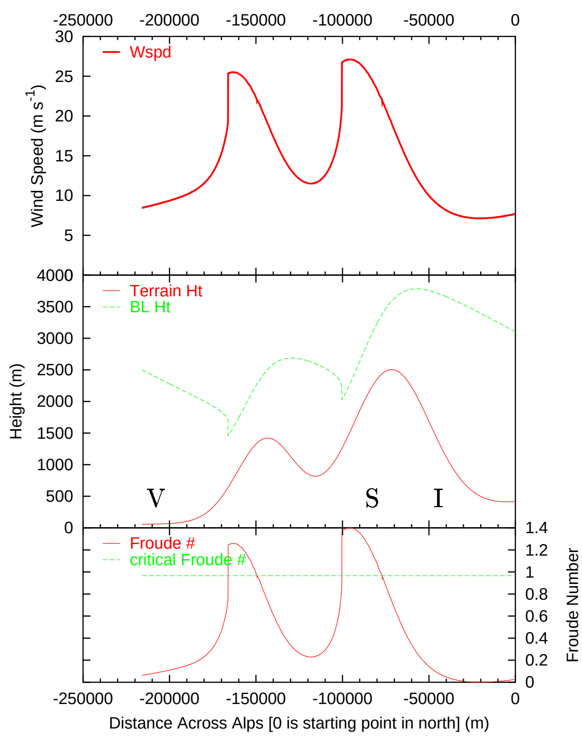

Figure 4: *Hydmod* output: Wind speed (top), Boundary Layer and terrain height (middle) and Froude number (bottom). Flow is from right to left (north to south). I, S, and V are the approximate locations of Innsbruck, Sterzing, and Verona in this idealized simulation.

resolution of 100 m. The results of the simulation presented in Fig. 4 should be compared with the MC2 simulation in Fig. 3. In *hydmod*, the flow becomes critical (Froude number becomes equal to 1) near the mountain ridge crest where it becomes shallow and transits to supercritical or shooting flow (Froude number greater than 1). This is similar to the descending isentropes and increasing wind speeds seen in the MC2 simulation downwind of the mountain ridges. In the hydraulic model, at some point downstream a hydraulic jump occurs in which the boundary layer height rapidly increase, the wind speed decreases, and the Froude number becomes less than 1 – the flow is now subcritical. This is analogous to the rising isentropes seen in the MC2 simulation.

The variability in boundary-layer depths shown in Fig. 2 and in the MC2 simulation is broadly consistent with the variability shown in the hydraulic model. The layer-averaged wind speeds indicated by the hydraulic model are also similar to those simulated by MC2.

4. MESOSCALE STRUCTURE

The mountain-scale flow discussed above resulted in a strong north Föhn near the surface in the valleys to the south of the Brenner Pass (the highest ridge in Figs. 3 and 4). To document and discuss this valley flow, we will use observations made at two of the surface stations in our network which were installed in the Eisacktal, the upper part of a valley running from the Brenner Pass south through Sterzing, Brixen, Bozen to Trento. The two stations are 8.5 km apart, with the northern (up-valley) station at 772 m ASL located in a narrow part of the Eisacktal, and the southern station near the town of Brixen at 582 m ASL located in a widening and flattening of the valley at a confluence of three rivers.

Figure 5 shows a time series of the northerly wind component at the station near Brixen, as well as the along-channel horizontal pressure gradient based on the pressure measurements at both stations. The along-channel wind speeds were very highly correlated with the along-channel pressure gradient, with the variance in along-channel pressure gradient explaining 75% of the variance in maximum northerly wind component during this episode. An interesting diurnal pattern in the windspeed and pressure gradient can be seen in Fig. 5. Overnight and before dawn on each of 7-9 November, the along channel pressure gradient and down channel winds become much smaller, or even reverse direction. Inspection of the ECMWF surface pressure analyses and forecasts across the Alps for this time period do not indicate a diurnal lessening or reversal of the across mountain pressure gradient, only a gradual decrease from around 12 hPa / 100 km on 7 November to 7 hPa / 100 km by 9 November. The daytime horizontal pressure gradient based on these two stations is consistent with the synoptic-scale estimate from ECMWF.

It seems that something is happening due to the diurnal cycle to cause this diurnal variation in the along-channel pressure gradient and winds. Sky conditions were mainly clear on the south side of the Alps during this episode, which would promote strong nocturnal radiational cooling of the surface. This would cool the near-surface air resulting in katabatic flow down slope which, it is hypothesized, collected in the valley where it widens and becomes flatter at the southern station near Brixen. As the air cooled and deepened the surface pressure over Brixen increased relative to that at the northern station, resulting in a decrease and / or a reversal in the pressure gradient and surface wind.

In order to see whether this is a feasible explanation, a calculation was made based on the hydrostatic equation using the observed temperatures and pressures at the two stations. At 7:50 UTC 8 November, the temperature at Brixen was 2 °C, while at the station to the north it was 7 °C. If the air were isothermal over the two stations, a 5 °C cooler air layer over Brixen of approximately 600 m depth would have been sufficient to reverse the synoptic pressure gradient as indicated by the pressure measurements. Since the valley depth at this location is greater than 600 m, this seems a feasible explanation for the diurnal reversal.

5. CONCLUSIONS

The north Föhn episode south of the Brenner Pass which occurred between 6-9 November 1999, was discussed. The large-scale flow across the Alps during this time was found to be qualitatively consistent with hydraulic flow across a 2-dimensional ridge by comparison with radiosonde profiles and the MC2 simulation. Within the valley, the along-channel winds were highly correlated with the along-channel horizontal pressure gradient. An interesting diurnal variation of the pressure gradient and Föhn winds was observed, which was attributed to the pooling of cold air where the valley widened and became flatter near Brixen.

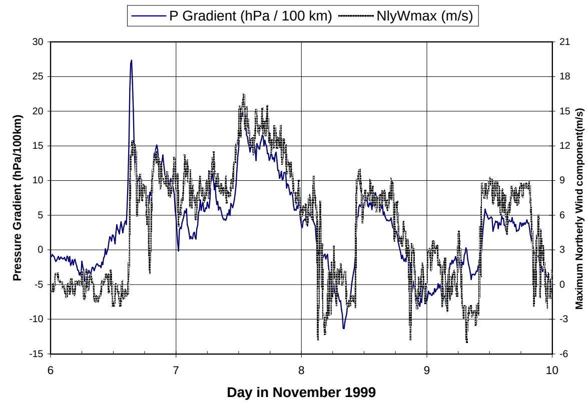

Figure 5: Maximum northerly wind component at Brixen and along-channel horizontal pressure gradient during the 6-9 November 1999 north Föhn episode. Sampling period for wind is 10 seconds, with observations stored every 10 minutes. Pressure is a one minute average every 10 minutes. Pressure gradient is based on pressure data from Brixen and the station 8.5 km up-valley to the north.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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