14.1 APPLYING SINGLE-LAYER SHALLOW-WATER THEORY TO GAP FLOWS IN THE BRENNER PASS REGION

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1. INTRODUCTION

Observations gathered during the field phase of the Mesoscale Alpine Programme MAP support the hypothesis that southerly foehn winds occurring in the Alps, especially in the Brenner pass area (Fig. 1), show characteristics similar to shallow-water flows (cf. section 2 and Flamant et al., 2002). In case of a well developed foehn, the increase in wind speed and the subsidence of the near-crest-level temperature inversion in the lee of the Brenner gap indicate a flow transition from sub- to supercritical. Further downstream, the sudden pressure recovery at weather stations aligned along the Wipp valley north of the Brenner points to the existence of hydraulic jump-like features. The similarity between foehn and shallow-water flow becomes most obvious for shallow foehn cases, which are characterized by a decoupling of the gap flow from the upper level synoptic winds due to directional wind shear together with a pronounced inversion.

2. OBSERVATIONAL EVIDENCE

The 20 October 1999 event is chosen to show observational evidence of the hydraulic behavior of the foehn flow in the Wipp valley. Figure 2 illustrates two rawinsonde soundings at Sterzing (upstream) and Gedeir (downstream of the pass) at 12 UTC. Both soundings show a nearly neutral lower layer topped by an inversion layer. The latter is a transition layer where the winds shift from southerly to westerly directions. The southerly foehn winds are confined to an altitude below 3 km MSL and are therefore called shallow foehn. Due to the subsidence of the foehn winds on the leeward side of the pass, the transition zone is located about 500 meters lower at Gedeir than at Sterzing and potential temperatures are higher. Moreover, the flow speeds up and forms a pronounced low-level jet with more than 15 m s^{-1}. The layering of the atmosphere with a distinct inversion encourages the calculation of local Froude numbers for the lower layer, with Fr=U/sqrt(g^*H) and $g^*=g\Delta\theta/\theta$. U and θ refer to the mean wind speed and potential temperature of the lower layer, H is the height of the center of the transition layer, g is the acceleration of gravity, and $\Delta\theta$ is the strength of the inversion. The calculation yields 0.45 and 0.84 for the Froude numbers at Sterzing (with H=2.9 km) and Gedeir (with H=2.4 km), respectively. The flow is therefore subcritical (Fr<1) at both locations, however nearly critical (Fr≈1) at Gedeir. It is plausible that flow acceleration (see Fig. 3, bottom) might lead to supercritical conditions (Fr>1) further downstream of Gedeir.

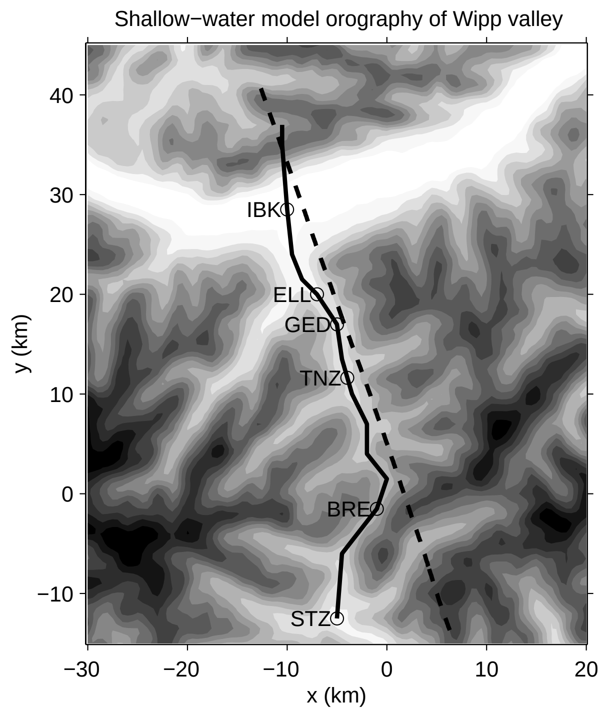

***FIGURE 1**: Orography of the Wipp valley used in shallow-water simulations with 500 m mesh size (only part of the domain is shown). Circles indicate weather stations at Sterzing (STZ), Brenner (BRE), Tienzens (TNZ), Gedeir (GED), Ellboegen (ELL), and Innsbruck (IBK). The dashed line shows the lidar cross-section of Fig. 4 and the solid line is the model cross-section of Fig. 5.*

Surface measurements from 15 weather stations aligned along the Wipp valley floor from south to north are presented in Fig. 3. Due to the subsidence of the foehn winds the reduced pressure falls rapidly and the wind speed increases along the leeward side of the pass. The pressure minimum and speed maximum is observed at Ellboegen, about 20 km north of the pass. A secondary pressure minimum and wind speed maximum occurs near Tienzens, in the middle of the Wipp valley. Between Ellboegen and Innsbruck the pressure recovers again by about 1 hPa and the flow decelerates. This indicates lifting of the top of the foehn layer, i.e. the height of the inversion, as it occurs in a hydraulic jump. In the basin of Sterzing, upstream of the pass, there is potentially cool and nearly blocked air. The sudden increase in potential temperature about 4

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km north of the pass shows that foehn is not a mere flow over a pass but a flow descending from higher altitudes. Therefore, potentially warmer air is mixed into the potentially cooler pass-flow. The pressure drop between Sterzing and Brenner illustrates that the flow starts to descend already upstream of the pass, which is consistent with hydraulic theory (see especially Fig. 5 but also Fig. 4).

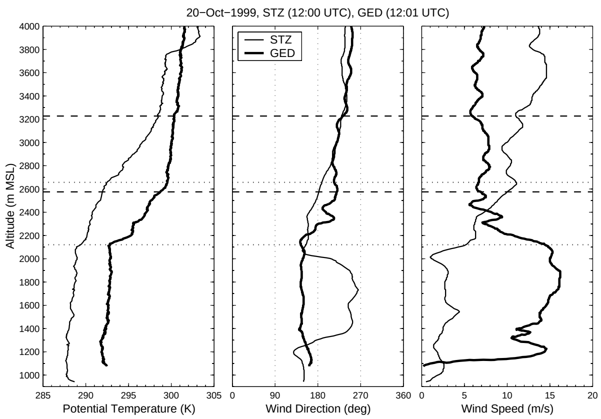

Figure 2*: Sounding at Sterzing (STZ, thin solid) upstream of Brenner and at Gedeir (GED, thick solid) downstream of the pass on 20 Oct 1999 12 UTC: potential temperature (left), wind direction (middle), and wind speed (right). Horizontal dashed and dotted lines indicate the bottom and top of the transition layer for STZ and GED, respectively.*

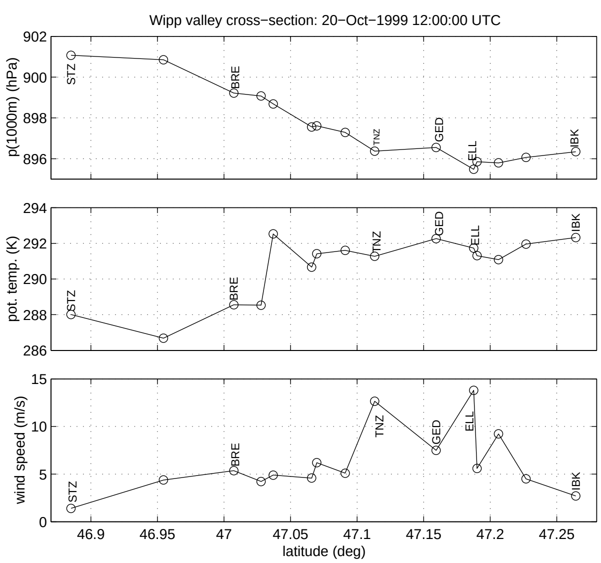

FIGURE 3*: Surface observations of 15 weather stations located along a south-to-north cross-section in the Wipp valley on 20 Oct 1999 12 UTC: pressure reduced to 1000 m MSL (top), potential temperature (middle), wind speed (bottom).*

Figure 4 shows relative backscatter data obtained from a downward looking airborne aerosol lidar. The aircraft was flying along a south-to-north cross-section parallel to the Wipp valley as indicated in Fig 1. Two pronounced layers can be identified which are separated by a sharp step in backscatter intensity and thus also aerosol concentration. The lower one with higher intensities represents the aerosol mixed layer (AML) where aerosols and clouds are trapped below the stable inversion layer indicated in the soundings of Fig. 2. Therefore, the height of the AML, which can be identified by an intensity-gradient method, is nearly equivalent to the height of the inversion and thus also the height of the dynamically active foehn layer. Upstream of the pass the AML height coincides with the top of the lower stratiform cloud layer – the so-called foehn wall cloud – at about 3 km MSL. As the foehn flow descends, the lower clouds clear on the leeward side of the pass. Consistent with the rawinsonde data, the AML height is approximately 500 m lower near the middle of the Wipp valley than upstream of the pass. North of the sounding site of Gedeir the AML height shows an even stronger subsidence of the foehn winds which probably leads to supercritical flow. Near the Wipp valley exit the AML top loses its sharp structure. This is caused by strong turbulent mixing such as in a hydraulic jump. The barrier north of Innsbruck forces the AML height to rise again to 2.5 km – the flow seems to become subcritical again.

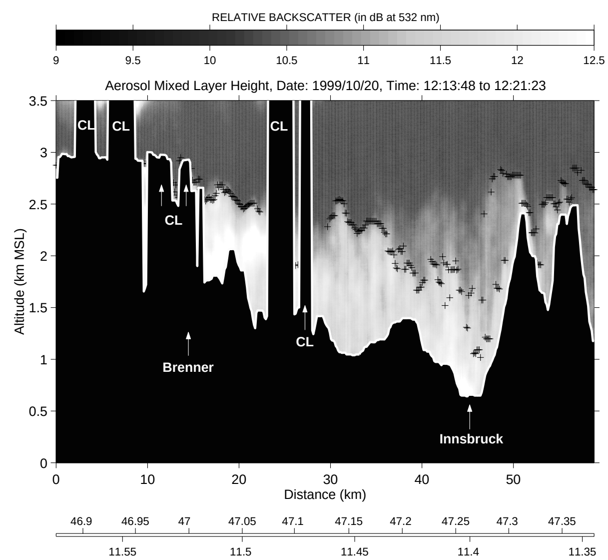

FIGURE 4*: South-to-north cross-section along the Wipp valley of relative backscatter intensity at 532 nm obtained from airborne aerosol lidar SABL on aircraft NCAR-Electra on 20 Oct 1999 around 12 UTC. Crosses indicate the aerosol mixed layer (AML) height. Cloud layers attenuating the lidar signal are marked with CL.*

3. NUMERICAL RESULTS

A single-layer shallow-water model (Schär and Smith, 1993) was used to study the shallow foehn flow over the three-dimensional Brenner pass topography (Fig. 1). The model was initialized in a way to match typical shallow foehn conditions upstream of the pass (comparable to the one of 20 Oct 1999) after reaching a quasi-steady state at the end of the simulation. Figure 5 shows the distribution of the local Froude number (Fr) and layer height (H) along a Wipp valley cross-section (as shown in Fig. 1). At Sterzing, upstream of the pass, Fr=0.34 (i.e. sub-critical, Fr<1) and H=2.96 km MSL at the end of the simulation. The model results show locations with transition to a supercritical state (Fr>1) just in the lee of the pass, further downstream near Ellboegen where surface measurements also indicated the location of the wind speed maximum, and also near the Wipp valley exit. Hydraulic jumps occur a few kilometers north of the pass (x=15 km), at the location where the Stubai and Wipp valley merge (x=38km), and near Innsbruck (x=45km). Subcritical regions between Ellboegen and the Wipp valley exit can be associated with zones of pressure recovery observed by the surface stations (cf. Fig. 2). The mountain range north of Innsbruck forces the upstream flow to become subcritical, however the flow is supercritical again on the leeward side of the northern range. The overall subsidence of the layer height in the lee of the pass agrees well with the subsidence of the AML height observed by the lidar (cf. section 2). Moreover, even smaller scale fluctuations in the AML height and in the simulated layer height match well. It therefore seems to be self-evident that some of the observed local AML height variations indicate flow transitions from sub- to supercritical and vice versa.

Additional simulations with different initial Froude numbers and layer heights (not shown) indicate that flow transitions and hydraulic jumps only occur in the Wipp valley if the reservoir height far upstream is significantly higher (e.g. by 0.5 to 1 km) than the one far downstream (e.g. along the northern Alpine foreland). In all simulations, including the one presented here, the model was initialized with constant layer height everywhere. In the numerical experiment of Fig. 5 the reservoir difference between up- and downstream at the end of the simulation is mainly produced by partial blocking of the flow upstream of the pass which raises the layer height. Orographic blocking occurs also in real atmospheric flows, as illustrated, for example, by the lifting of the stratiform cloud layer as the flow impinges on the Alpine ridge near the Brenner pass. Furthermore, a reservoir height difference between north and south can be established in reality also by a synoptic-scale pressure gradient due to a low-pressure system northwest of the Alps, which is typical for south foehn.

4. SUMMARY

For shallow foehn winds, which are confined to heights below the main Alpine crest, the hydraulic concept seems to be applicable to characteristic features of the lower, dynamically active foehn layer. Simulated flow transitions from a sub- to a supercritical state and vice versa can be related to observed variations of the AML height along the Wipp valley. The modeled flow acceleration downstream of the pass agrees well with the speed-up of winds observed by surface stations and vertical soundings, as well as with the subsidence of the AML height. Predicted locations of hydraulic jumps are verified by zones of turbulent mixing near the top of the AML and by regions of surface pressure recovery.

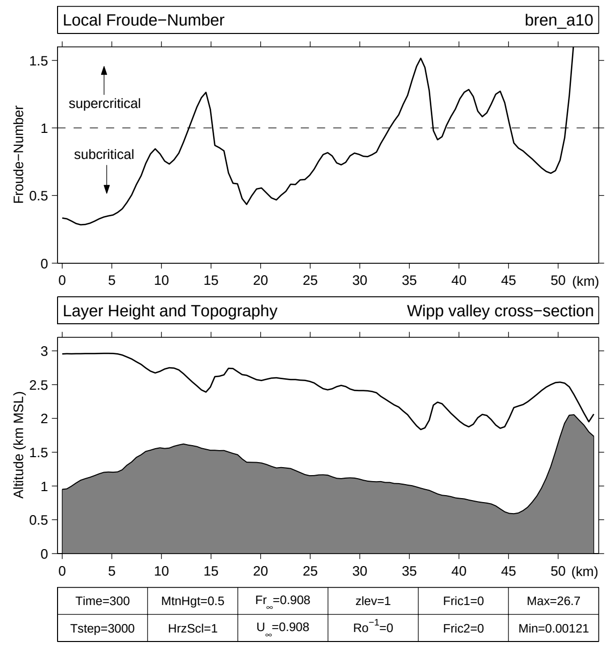

***FIGURE 5**: Cross-section of local Froude number (top) and layer height with orography (bottom) along Wipp valley from Sterzing (x=0 km) to Innsbruck (x=45 km) based on a single-layer shallow-water simulation in a quasi-steady state. Near Sterzing, conditions at t=0 (300) are Fr=1.25 (0.34) and H=2 (2.96) km MSL.*

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References

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