GAP FLOWS – OUR STATE OF KNOWLEDGE AT THE END OF MAP

Georg J. Mayr

Institute for Meteorology and Geophysics, University of Innsbruck, Innrain 52, 6020 Innsbruck, Austria
E-mail: *georg.mayr@uibk.ac.at*

Abstract: A summary of gap flow results within MAP is given including conceptual models, dynamical understanding, observational and modeling tools, and open issues.

Keywords – *MAP, gap flow, foehn, hydraulics, gravity wave*

1 INTRODUCTION

Mountain ranges are rarely smooth ridges. They are criss-crossed by indentations of various depths. Some of these gaps allow air to flow from one side to the other without having to detour over or around the mountain range. The constriction of the cross-sectional area that air encounters on its way through the gap can lead to an asymmetric flow configuration with a relatively slowly moving but deeper layer on the upstream side and a faster and thinner layer on the downstream side of the gap. Such gap flows often show the characteristics of foehn as defined by WMO (1992) as a strong, gusty *wind warmed and dried by descent, in general on the lee side of a mountain.* And indeed, most of the famous foehn and downslope wind locations are downstream of a gap, e.g. the Wipp Valley and Innsbruck (Austria), Rhine and Reuss Valleys (Switzerland), Senj (Croatia; bora), Independence (Owens Valley; site of Sierra Wave Project and currently T-REX), and Boulder. MAP was the first international field program with an explicit goal of studying gap flows, selecting the central Alpine Wipp Valley as target area (Mayr et al., 2004). Pan and Smith (1999) summarize the gap flow studies prior to MAP.

2 PURE AND HYBRID GAP FLOWS IN THE WIPP VALLEY

Depending on the synoptic conditions on a scale larger than the gap-scale, air from one side of the mountain range may flow to the other either only through the lower terrain provided by the gaps (”pure” gap flow) or also across the higher surrounding ridges (”hybrid” gap flow). Fig.1 depicts two examples from the MAP SOP. The

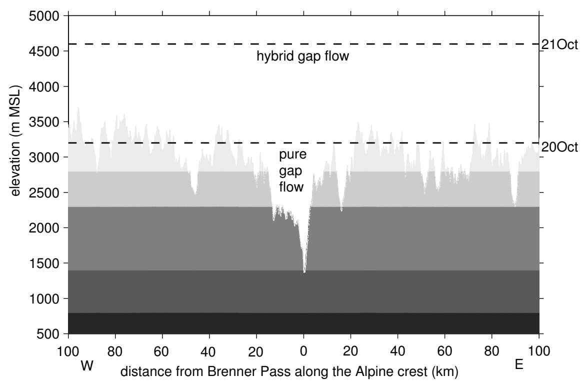

Figure 1: Main Alpine Crest along the Austrian-Italian border looked at from the south (Italy). The deepest of the pronounced indentations is the double gap of the Wipp Valley at the Brenner Pass. The altitude of the top of the layer flowing from south to north indicates a pure gap flow on 20 October 1999 and a hybrid gap flow on the following day. (Adapted from Armi and Mayr, 2005).

shallow depth of a pure gap flow (like the one of 20 October 1999 studied in more detail in Marić and Durran (2005)) allows to apply the reduced-gravity shallow water approximation (”hydraulics”) as a *conceptual model* (e. g. Pan and Smith, 1999; Flamant et al., 2002; Gohm and Mayr, 2004). The advantage of this concept, which Schweitzer (1953) first applied for the explanation of foehn flow, is the retention of nonlinear terms in marked contrast to the linearized gravity wave concept that has proved so useful for deeper flows over mountains. A relatively deep upstream layer accelerates before it reaches the narrowest part, where it changes from a subcritical to a supercritical state, becoming thinner and faster. The change back to a subcritical state and thus the adjustment of the flow to the larger-than-gap scale environment downstream mostly takes place at the exit of the Wipp Valley near Innsbruck. (Reduced) surface pressure is an integral measure for this acceleration of the flow, which is evident even on average over the whole MAP SOP (Fig. 2a). Since the Wipp Valley is not a smooth and homogeneous channel modulations of this overall acceleration occur. In particular, ridges protruding sideways into the main valley (cf. Fig. 2b) cause some local transitions between supercritical flow down their lee slopes and subcritical flow upstream of the next ridge. Given appropriate moisture conditions these abrupt transitions back to a thicker, slower flow are visible from cumuliform clouds. Surface pressure either increases again or slows its decrease (e.g.immediately after Brenner Pass (Bre) in Fig. 2a). Hydraulic simulations (Gohm and Mayr, 2004) in Fig. 2b give an overall impression of the connection between small-scale topography and transitions of flow state.

When the depth of the flowing layer increases to also spill over the surrounding ridges, the interaction between

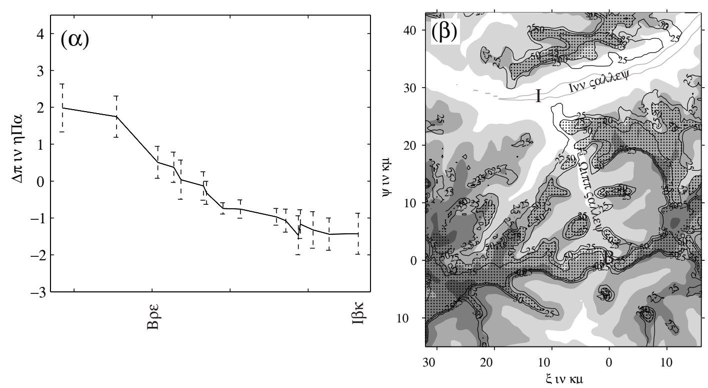

Figure 2: (a) Average and standard deviation (bars) of reduced pressure along the Wipp Valley from automatic weather stations over the MAP SOP (from Gohm and Mayr (2004)). (b) Relative frequency of supercritical flow in hydraulic simulations with a wide variety of initial conditions. Locations that were supercritical in at least 50% of the simulations are stipled. Frequency isolines of 25, 50, and 75% are drawn. Topography is shaded grey and the locations of Brenner Pass (B) and Innsbruck (I) are marked. (Adpated from Gohm and Mayr, 2004).

gap and ridge flows and in particular the launch of three-dimensional gravity waves modifies the gap flow (Gaberšek and Durran, 2004; Zängl, 2002c, 2003) yet does not drastically alter it. Overall, the flow descends further in the case of hybrid gap flow, accelerates more, and produces a stronger pressure decrease along the lee slope.

Several scenarios may lead to flow that accelerates through a gap.The obvious one is a larger-scale flow that has a component in the gap flow direction. The second one has different air masses on either side of the gap. The typical situation for the Wipp Valley is that a passing cold front has left cold air on the northern and southern side of the Alps. With the approach of a synoptical scale ridge, warm air is advected with westerly to southwesterly flow along the western flank of the Alps to the north resulting in relatively warmer air to the north of the Wipp Valley. The ensuing hydrostatic pressure difference then drives the gap flow and also leads to southerly flow upstream of the gap below the crest (Zängl, 2003). The hydrostatic pressure difference driving bora through the gaps of the Dinaric Alps is frequently due to the difference between a cold continental air mass and a warmer maritime one over the Adriatic Sea. Numerical simulations in highly idealized flow and topographical settings (Sprenger and Schäer, 2001; Zängl, 2002a) examined the possibility of gap flows forming with a geostrophic flow parallel to the mountain ridge, i.e. perpendicular to the gap. The results show a strong sensitivity to the shape of the mountain range due to the resulting mesocale modifications of the flow and pressure field. Also identified was the crucial role of surface friction. Its inclusion might lead to a reversal of the gap flow direction.

If (turbulent) friction influences important flow characteristics even for such highly idealized and smooth orography, its influence will increase with the increased roughness of real gap orography (Zängl, 2003). Flow separation (Gohm and Mayr, 2005) and the establishment of potential vorticity banners (Ross and Vosper, 2003) are strongly shaped by turbulence; not only in the atmosphere but also the ocean (e. g. Armi and Farmer, 2003; Farmer and Armi, 1999, 2001).

3 TOOLS

The small-scale nature and the fixed location of gap flow make it possible to obtain a comprehensive picture of the flow with a limited set of instrumentation. Since up- and downstream conditions play a crucial role in hydraulics, which adequately describes pure gap flows, radiosoundings up- and downstream of the gap are needed for the vertical profile. At least for the central Alps, the mesoscale and synoptic scale environment change rapidly enough to need soundings every three hours. Despite the relatively short distance of about 30 km, in-situ stacked measurements by a research airplane may take too long for the flow to remain stationary. Better are dropsonde curtains. Targeting, however, may be difficult because of wind shear.

Remote sensors can also map gap flow quickly. Airborne aerosol lidars (e. g. Flamant et al., 2002; Gohm et al., 2004; Gohm and Mayr, 2004) are ideal for identifying the top of the gap flow layer and thus observe depth changes and consequently changes of the flow state. A caveat: reflectivity of saturated aerosols is higher so that clouds complicate the interpretation. An airborne Doppler lidar was only in the test phase during MAP but has since become operational and is better suited for wider gaps due to the required spatial oversampling. A Doppler lidar on the ground suffers little of its usual limitation by only measuring the wind component along its beam: channeling within the valley makes that a good approximation of the actual wind (Durran et al., 2003) and the Doppler lidar a very useful tool for the observation of gap flow (e. g. Weissmann et al., 2004; Gohm et al., 2004; Gohm and Mayr, 2004). Unfortunately, there seems to be no remote sensor capable of measuring temperature and thus the mass field of a large part of the gap flow. Integral information about the flow state (via pressure) and the descent of isentropes is provided by fixed and mobile (Mayr et al., 2002) platforms along the ground. Calibration of the automatic weather stations is imperative.

An essential tool are numerical models. Computing power had just become sufficient at the time of MAP to perform simulations with the required mesh sizes of a few hundred meters. A detailed field experiment data set can be used to tune the numerical model setup. The model in turn fills the spatial and temporal data gaps that even an international pooling of observational resources leaves, makes it possible to study the relative importance of the various terms in the dynamic and thermodynamic equations, and to isolate crucial mechanisms with sensitivity studies.

4 OPEN ISSUES

One of the explicit goals of MAP was the improvement of (numerical) weather forecasting. A direct result is the development of an objective forecasting method (Drechsel and Mayr, 2005). Research models, precursors of operational models' future capabilities, passed the test against the high-density gap flow data set (Gohm et al., 2004; Zängl et al., 2004). A problem, however, is the steep and narrow topography of a gap in two respects: the already patched one (Zängl, 2002b) is that ”horizontal” numerical diffusion has to be computed truly horizontally instead of along the terrain-following model levels. Ultimately models with horizontal levels might be required and are under development. The unsolved aspect is ”surface friction”, i.e. the turbulent fluxes, which are only parameterized to come from the bottom of a grid cell, but not from the side as is the case for a deep gap. The underestimation of surface friction leads to an underestimation of the descent of the isentropic surfaces downstream of the gap (Gohm et al., 2004). The second problem for the numerical models is the very stable but thin layer (often an inversion) that caps the gap flow layer on the upstream and downstream side (where it is widened). Usually there is only a hint of this cap in the initial conditions provided by operational NWP analyses and the finer-scale simulations themselves produce it too weakly and generally not at the correct altitudes, which significantly deteriorates the resulting gap flow field. For gaps in other locations capping inversions are even stronger (e.g. Falklands: Mobbs et al., 2005) than for the Wipp Valley. For space reasons, only one of the open dynamical issues can be mentioned here (more in the talk): the interaction of gap flow with and its determination by downstream conditions.

Acknowledgments: *I thank the GAP community (see the references for all the names) for their great contributions. This work was partly supported by the Austrian Science Foundation through FWF15070.*

References

Armi, L., and D. Farmer, 2003: Stratified flow over topography: bifurcation fronts and transition to the uncontrolled state. *Proc. Roy. Soc.*, **458**, 513–538.

Armi, L., and G. J. Mayr, 2005: Stratified flow across an alpine crest with a pass: Shallow and deep flows. *to be submitted to Quart. J. Royal Meteorol. Soc.*, **-**, –.

Drechsel, S., and G. J. Mayr, 2005: Objective forecasting of foehn for the subgrid-scale wipp valley. *Preprints International Conference on Alpine Meteorology/MAP Meeting, Zadar*.

Durran, D. R., T. Maric, R. M. Banta, L. S. Darby, and R. M. Hardesty, 2003: A comparison of ground-based Doppler lidar and airborne in situ wind observations above complex terrain. *Quart. J. Roy. Meteor. Soc.*, **129**, 693–713.

Farmer, D. M., and L. Armi, 1999: Stratified flow over topography: the role of small-scale entrainment and mixing in flow establishment. *Proc. Roy. Soc. London A*, **455**, 3221–3258.

Farmer, D. M., and L. Armi, 2001: Stratifid flow over topography: models versus observations. *Proc. Roy. Soc. A*, **457**, 2827–2830.

Flamant, C., P. Drobinski, L. Nance, R. Banta, L. Darby, J. Dusek, M. Hardesty, J. Pelon, and E. Richard, 2002: Gap flow in an Alpine valley during a shallow south föhn event: Observations, numerical simulations and hydraulic analogue. *Quart. J. Roy. Meteor. Soc.*, **128**, 1173–1210.

Gaberšek, S., and D. R. Durran, 2004: Gap flows through idealized topography. part i: Forcing by large-scale winds in the nonrotating limit. *Journal of the Atmospheric Sciences*, **61**(23), 2846–2862.

Gohm, A., and G. J. Mayr, 2004: Hydraulic aspects of föhn winds in an alpine valley. *Quart. J. Roy. Meteor. Soc.*, **130**(597), 449–480.

Gohm, A., and G. J. Mayr, 2005: Numerical and observational case study of a deep Adriatic bora. *Quart. J. Roy. Meteor. Soc.*, **in press**.

Gohm, A., G. Zängl, and G. J. Mayr, 2004: South foehn in the Wipp Valley on 24 October 1999 (MAP IOP 10): Verification of high-resolution numerical simulations with observations. *Mon. Wea. Rev.*, **132**, 78–102.

Marić, T., and D. R. Durran, 2005: Observation and modeling of gap flow in the Wipp valley on 20 Oct 1999. *Preprints International Conference on Alpine Meteorology/MAP Meeting, Zadar*.

Mayr, G. J., L. Armi, S. Arnold, R. M. Banta, L. S. Darby, D. R. Durran, C. Flamant, S. Gaberšek, A. Gohm, R. Mayr, S. Mobbs, L. B. Nance, I. Vergeiner, J. Vergeiner, and C. D. Whiteman, 2004: Gap flow measurements during the Mesoscale Alpine Programme. *Meteorol. Atmos. Phys.*, **86**, 99–119.

Mayr, G. J., J. Vergeiner, and A. Gohm, 2002: An automobile platform for the measurement of foehn and gap flows. *J. Atmos. Oceanic Tech.*, **19**(10), 1545–1556.

Mobbs, S., S. Vosper, P. Sheridan, R. Cardoso, R. Burton, S. Arnold, M. Hill, V. Horlacher, and A. Gadian, 2005: Observations of downslope winds and rotors in the Falkland Islands. *Quart. J. Roy. Meteor. Soc.*, **131**, 329–351.

Pan, F., and R. B. Smith, 1999: Gap winds and wakes: SAR observations and numerical simulations. *J. Atmos. Sci.*, **56**, 905–923.

Ross, A. N., and S. B. Vosper, 2003: Numerical simulations of stably stratified flow through a mountain pass. *Quart. J. Roy. Meteor. Soc.*, **129**, 97 – 115.

Schweitzer, H., 1953: Versuch einer Erklärung des Föhns als Luftströmung mit überkritischer Geschwindigkeit. *Arch. Meteor. Geophys. Bioklimatol.*, **5A**, 350–371.

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

Weissmann, M. D., G. J. Mayr, R. M. Banta, and A. Gohm, 2004: Observations of the temporal evolution and spatial structure of the gap flow in the wipp valley on 2 and 3 october 1999. *Monthly Weather Review*, **132**(11), 2684–2697.

WMO, 1992: *International meteorological vocabulary*. Number 182. WMO, 784 pp, 2nd edition.

Zängl, G., 2002a: Idealized numerical simulations of shallow föhn. *Quart. J. Roy. Meteor. Soc.*, **128**, 431–450.

Zängl, G., 2002b: An improved method for computing horizontal diffusion in a sigma-coordinate model and its application to simulations over mountainous topography. *Mon. Wea. Rev.*, **130**, 1423–1432.

Zängl, G., 2002c: Stratified flow over a mountain with a gap: Linear theory and numerical simulations. *Quart. J. Roy. Meteor. Soc.*, **128**, 927–949.

Zängl, G., 2003: Deep and shallow south foehn in the region of innsbruck: Typical features and semi-idelized numerical simulations. *Meteorol. Atmos. Phys.*, **83**(3-4), 237–262.

Zängl, G., A. Gohm, and G. Geier, 2004: South foehn in the Wipp Valley - Innsbruck region: Numerical simulations of the 24 October 1999 case (MAP-IOP 10). *Meteorol. Atmos. Phys.*, **86**(3-4), 213–243.