SUMMARY OF OROGRAPHIC PV BANNER STUDIES IN MAP

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1. INTRODUCTION

Potential vorticity (PV) banners are low-level elongated PV anomalies that originate in close proximity to an orographic obstacle and define its wake. They have been proposed on theoretical grounds (Smith 1989) and have been a ubiquitous feature of high-resolution numerical simulations of flow past the Alps prior to the launch of the Mesoscale Alpine Programme (MAP) (Aebischer and Schär 1998). Atmospheric wakes generated by simple obstacles have been the subject of several studies during 1990's, including observational studies [e.g., Hawaii (Smith and Grubišić 1993), St. Vincent (Smith *et al.* 1997), Aleutians (Pan and Smith 1999)], and a series of theoretical and idealized modeling studies (e.g., Schär and Smith 1993a,b; Grubišić *et al.* 1995; Schär and Durran 1997; Rotunno *et al.* 1999). However, MAP was the first field experiment in which the attempt was made to document PV banners in the lee of a complex obstacle such as the Alps. Specific objectives of the MAP PV banner project were related to the existence, structure, stability, and generation of Alpine PV banners.

2. DYNAMICS, STRUCTURE, AND ORIGIN OF ALPINE PV BANNERS

In spite of a fairly small number of PVB events that occurred from 7 September to 15 November 1999 during the MAP Special Observation Period (SOP) (Bougeault *et al.* 2001), the documented PVB cases cover a variety of large-scale flow conditions. These include shallow mistral (IOP 4; Oct 1), deep mistral (IOP 15; Nov 6), northerly foehn (IOP 15; Nov 8-9), southerly foehn (IOP 8; Oct 21), and bora (IOP 15; Nov 7), which allowed the examination of PVB formation in different parts of the Alps lee under a range of large-scale conditions (Grubišić 2000; Nance *et al.* 2000).

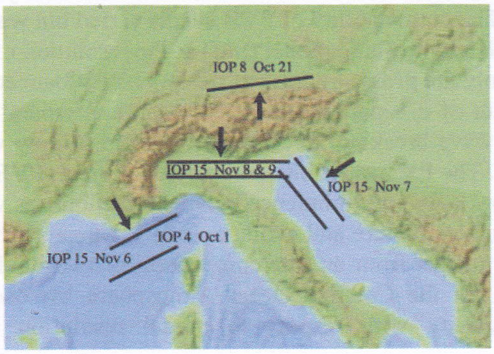

Figure 1 Summary of the MAP SOP PV banner missions with schematic illustration of flight tracks and upstream wind directions

The strong shear zone associated with the "primary" PV banner at the western end of the Alps, separating the northerly mistral to the southwest of the Alps from the quasi-stagnant air within the southern wake of the Alps, was found to be quasi-steady close to the terrain and to exhibit a complex substructure consisting of at least three pairs of PV filaments under the north-westerly flow conditions in IOP 4 (Schär *et al.* 2003). Complex wake structure with multiple "secondary" PV banners (PVB2) was found over the Po Valley during the northerly foehn event (Flamant *et al.* 2004), over Bavaria during the southerly foehn event (Grubišić 2001), and over the Adriatic during bora (Grubišić 2004). Good correlations were found between the individual jet/wake structure within the complex wake and the mountain pass/peak distributions upwind in all PVB2 events. Signs of increased transience were found further downstream in northerly events (Flamant *et al.* 2003; Schär *et al.* 2003) as well as further aloft in the shallow bora-driven PV banners (Grubišić 2004). Most of PV in both the primary and secondary PV banners in the Alps could be attributed to vertical vorticity coupled with vertical stratification. Merging of individual PV filaments resulting from flow past individual peaks and through smaller gaps was found to form larger PV banners downstream (Schär *et al.* 2003).

In some cases, one dissipation process was clearly dominant as the source of PV whereas in other cases PVB were produced by multiple mechanisms. Dissipation in low-level gravity wave breaking was unambiguously found to be the main source of PV in the PVB2 over the Po Valley in IOP 15 (Flamant *et al.* 2003; Jiang *et al.* 2005), and it appears to be the main source of PV in PVB2 over the Bavaria in IOP 8 (Grubišić 2001; Jiang and Doyle 2004). The low-level gravity wave breaking was found to be a major contributor to the IOP 15 secondary PV banners over the Adriatic (Bencetić-Klaić 2003; Grubišić 2004; Jiang and Doyle 2005) but the flow separation and splitting as well as surface friction, the latter exhibiting control over the primary generation mechanism, were also found to play an important role in the bora-generated PV banners (Gohm and Mary 2005). Both flow splitting and gravity wave breaking were contributors to the PV generation in the primary PV banner (Jiang *et al.* 2003; Schär *et al.* 2003).

3. OBSERVATIONAL SYSTEMS

The most valuable MAP SOP data for PVB studies was high resolution, high frequency *in situ* aircraft data from single- and multiple-aircraft missions (Flamant *et al.* 2004; Grubišić 2001, 2004; Jiang *et al.* 2003; Schär *et al.* 2003). Carefully designed flight patterns consisted primarily of straight flight legs at multiple altitudes within one, or, more often, two vertical planes positioned parallel to the mountain range, one located closer to the obstacle and the other one further downstream. In addition, in all PVB missions there was at least one cross-mountain track. Repeated flight legs at multitude of altitudes were an integral part of the PVB mission flight design in order to provide a capability to document the degree of flow unsteadiness. The use of aicraft involved two different flight strategies. The first strategy was employed in one single (IOP 8) and one dual aircraft mission (IOP 15-bora), with each aircraft covering a range of altitudes within its own vertical plane. The second strategy was used with two to four aircraft flying a horizontal box flight pattern (IOP 4, IOP15-mistral, IOP 15-foehn), covering both vertical planes with tracks at a range of altitudes.

GPS dropsonde data, and remotely sensed airborne lidar (SABL) data proved valuable in model verification for mapping out the flow structure in wind-parallel and/or wind-perpendicular vertical planes (Grubišić 2004; Jiang *et al.* 2003; Jiang and Doyle 2005; Schär *et al.* 2003).

4. NUMERICAL SIMULATIONS

Numerical models used in the PVB studies were predominantly non-hydrostatic (COAMPS, MC2, MEMO, Meso-NH) run at high-horizontal resolutions (1-3 km) needed to resolve fine structure of the secondary PV banners and the inner sub-structure of the primary PV banner. The predictability of PVB events varied but was in general fairly high. Some simulations were also carried out with a hydrostatic model (SM) at the resolution of 14 km (Schär *et al.* 2003), which proved capable of reproducing only the gross structure of the largest PV banners.

While the generation of orographic PV banners is the result of dissipation due to flow splitting/separation, surface friction (e.g., Ross and Vosper 2003), and/or gravity wave breaking, uncertainties remain in how well these processes are represented in mesoscale numerical models. The PV banner intercomparison project (PVBIP) was initiated to examine the degree to which different boundary layer and turbulence parameterizations, as well as explicit and implicit numerical diffusion schemes, influence the structure and evolution of PV banners within an idealized model setup (Schmidli *et al.* 2004). Preliminary results from an intercomparison of two models, namely the Advanced Regional Prediction System (ARPS) and the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS^{TM}), show considerable sensitivity with respect to model resolution and formulation.

5. DOWNSTREAM EFFECTS

As the orographic PV banners contain significant amount of PV and, if unobstructed by other terrain, extend significant distances downwind, potentially they can affect atmospheric boundary layer and/or oceanic mixed layer, as well as interact with larger-scale atmospheric balanced flow downstream. Some evidence of convection initiated by the PV-banner-induced convergences was found over the Po Valley (Marconetti and Frustaci 2001). The variability of the atmospheric boundary-layer flow associated with the bora-driven PV banners over the

Adriatic in MAP SOP was linked to the wind-driven currents in the Adriatic Sea under bora conditions (Grubišić 2004). The full extent of downstream effects of orographic PV banners has yet to be demonstrated.

Despite satisfying necessary conditions for barotropic instability, most observed PV banners appear highly stable in the immediate lee of the topography. However, further downstream some banners showed considerable transience (Flamant *et al.* 2003; Schär *et al.* 2003). It has been argued that the stable configuration in the vicinity of the obstacle is due to a deformation flow oriented perpendicular to the shear zone, which squeezes the PV banners and suppresses barotropic instabilities (Schär *et al.* 2003). Further downstream this deformation flow is absent and thus the PV filament may develop instabilities and transience.

6. CONCLUSION

The results from MAP have confirmed the existence of PV banners in the Alps wakes, eliminating the skeptics' view that they might be just numerical artifacts. They have also confirmed the pre-MAP theoretical work on PVB generation. The high predictability and steadiness of the Alpine PV banners, and a good correlation with the upwind topographic profiles support the orographic origin, with dissipation, related to gravity wave-breaking as well as flow splitting and separation, being the main physical mechanism of their generation. While the horizontal scale and structure of simulated PV banners display sensitivity to the horizontal resolution of model simulations, the observed evolution and structure of the majority of Alpine PVB cases appears well reproduced by the mesoscale model simulations with grid spacing of 1-3 km. The majority of the MAP PVB studies have been focused on the structure and evolution of PV banners and sources of PV, with only a few preliminary discussions of the downstream effects of the Alpine PV banners.

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