7.3 STRUCTURE OF WAKE NORTH OF THE ALPS: STUDY OF PV BANNERS DURING AN EPISODE OF DEEP SOUTH FOEHN

Vanda Grubišić*
Desert Research Institute, Reno, NV

1. INTRODUCTION

The main objectives of the Mesoscale Alpine Programme (MAP), a large internationally coordinated effort, is to improve numerical forecasting of precipitation and circulation patterns in complex terrain. The Special Observing Period (SOP) of MAP took place from 7 September to 15 November 1999 in the Alps (Bougeault et al. 2001). The objective of the PV banner project (Grubišić 2000), which falls within the scope of "dry" MAP, was to observationally document structure of a major mountain-range wake, with its characteristic horizontal shear-lines and potential vorticity (PV) anomalies. Extensive MAP data sets provide an excellent data base for verification of high-resolution numerical simulations, and will provide important clues, if not direct answers, to unresolved questions such as the source of vorticity and PV in complex, real-world, orographic flows.

Orographic PV anomalies (banners) are indicators of significant horizontal wind shear in the presence of stratification. For the Alps, numerical studies (e.g., Aebischer and Schär 1998) show individual PV banners originating from the end points of the range ("primary banners") as well as from the edges of major massifs along a complex ridgeline ("secondary banners") that can extend significant distances downstream. However, prior to MAP the questions of horizontal scale of individual PV banners and the process of scale selection in the wake of the Alps remained without a clear answer since numerical simulations had shown significant sensitivity to horizontal resolution, with higher-resolution simulations producing a larger number of finer PV filaments.

Six PV banner missions, summarized in Fig. 1, were flown during MAP SOP. This paper focuses on the analysis of data collected north of the Alps in the research mission flown in IOP 8 on 21 October 1999 during an episode of deep south Foehn.

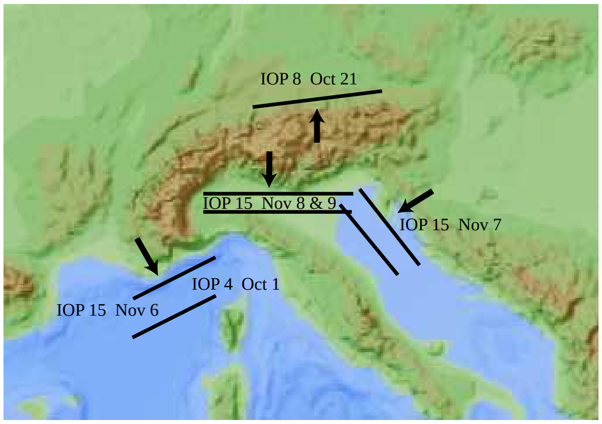

Figure 1: PV banner missions flown during the MAP SOP. Labels refer to dates and Intensive Observation Periods (IOPs) during which missions took place. Bold arrows indicate winds driving PV banners along surveyed portions of the Alps. Straight lines represent aircraft flight tracks flown at a number of different altitudes during each mission.

2. MESOSCALE AIRFLOW IN IOP 8

The synoptic scale flow during IOP 8 was characterized by an approaching deep baroclinic trough from the west, and a generally strong southerly flow ahead of it. As previously noted in the IOP 8 precipitation studies by Houze et al. (2000) and Smull et al. (2000), air over the Po Valley ahead of the front was stably stratified, which caused blocking and the westward deflection of the incoming southerly flow throughout the depth of the boundary-layer. Our COAMPS simulations (section 3) of this case reveal that only air at and above ~1,200 m was able to enter into and flow upslope the deeply cut valleys on the southern side of the Alps, and to flow over the main portion of the Alpine barrier further aloft.

The wake survey portion of this research flight took place between 8:12 and 11:14 UTC. By 8:00

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[*] *Corresponding author's address:* Dr. Vanda Grubišić, Desert Research Institute, Division of Atmospheric Sciences, 2215 Raggio Pkwy, Reno, NV 89512–1095; e-mail: grubisic@dri.edu

UTC the cold front has reached the western end of the Alps and continued to propagate east. Upwind of the surveyed portion, however, the flow at 850 hPa level and heigher up remained southerly throughout the entire period of the wake survey.

3. NUMERICAL SIMULATIONS

Numerical simulations of this case were carried out with the Naval Research Laboratory (NRL) Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) (Hodur 1997). The four nested domains were centered on the examined portion of the Alps with the finest mesh having a horizontal grid increment of 3 km and 30 vertical levels. The model was run with a full suite of physical parameterizations.

4. AIRCRAFT IN SITU OBSERVATIONS

In this single-aircraft PV banner mission, National Center for Atmospheric Research (NCAR) Electra research aircraft carried out multiple transverses (at 5, 8 and 14 kft) within one Alps-parallel vertical plane with the end points at (9.5° E, 47.6° N) and (13.1° E, 48.0° N). The two lower tracks were flown to document the horizontal variation of the wind in the wake north of the Alps. In addition, ten Global Positioning System (GPS) dropsondes were released from 14 kft to obtain high vertical resolution wind and thermodynamic data within this same vertical plane.

Figure 2 displays track-perpendicular component of wind speed measured during two passes at 5 kft flown 1.5 h apart. This diagram reveals a rather complex structure of the wake north of the Alps with a number of "jets" and "wakes" of varying widths. Close agreement of the two measured profiles suggests quasi-stationarity of the documented features and their orographic origin. Close inspection of the upwind orographic profiles shown in the lower portion of this figure reveals that the three major massifs of the high Alps (from east to west: Hohe Tauern, Ötztaler Alps and Rätische Alps) roughly stand behind the three encountered "wake" zones. However, it is the orographic profile on the northern side of the Inn Valley[1], shown in black, that is best correlated with the observed wind speed variation at 1,500 m. The black profile represents essentially the northern "edge" of the Alps before they flatten out into the Bavarian plane. A wide jet between 11.6° and 12.1° E, with average wind speed of ~ 12 m s^{-1}, is found to be colocated with the outflow region of the Inn Valley. An indication of another jet over the Rhine Valley is seen at the western end of the track. Two more strong jets in the middle of the track are located at the lateral edges of the wake behind the northern extension of the Wildspitze peak. Furthermore, the raw, unfiltered data profiles reveal several even narrower jets located over deep valleys (e.g., Ziller) or within wider strong shear zones.

In the upper portion of this figure, shown are also the track-perpendicular wind speed profiles extracted from the COAMPS simulation data. While there is a good agreement of the observed and modeled wind speed variability along the track, especially for the 12 UTC model profile, we find that at this horizontal resolution the model significantly overpredicts the velocity magnitude.

5. VORTICITY AND PV ANALYSIS

In order to diagnose the horizontal scale and the strength of shearlines and PV banners, vertical component of vorticity and PV are computed from the aircraft in situ data using the simplified equations

$$\zeta \approx \frac{\partial v}{\partial x} \qquad \text{and} \qquad \mathrm{PV} \approx \frac{1}{\rho}\frac{\partial \theta}{\partial z}\,\zeta\ , \tag{1}$$

where x is positive in the direction of aircraft heading, v is the track-perpendicular component of velocity, and the track-parallel component of velocity as well as the two horizontal components of vorticity are assumed to be negligible. This leaves only the vertical component of vorticity (ζ) contributing significantly to PV. The vertical gradient of potential temperature was estimated using one-sided difference and temperature values at 5 and 8 kft. Before applying (1), the aircraft in situ data was digitally filtered to remove small scale features below approximately 3 km using the digital smoothing polynomial filter of the second order with a moving window of 120 points (Press et al. 1992). Figure 3 displays the results of this analysis for the data measured along the later pass at 5 kft ($\sim 1,500$ m) ASL together with the COAMPS data.

Given the degree of simplification introduced in the analysis based on (1), vertical vorticity (Fig. 3d) and PV (Fig. 3e) computed from the observational data and extracted from the simulation data agree remarkably well. The most significant differences in the vertical vorticity profiles stem from the differences in the width of jets and wakes as well as the range of wind speed variation

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[1] Inn Valley is the WSW-ENE oriented valley in the northeast portion of the Alps, which cuts deeply into the orography of the Alps. The exit region of this valley into the Bavarian plane is marked in Fig. 2.

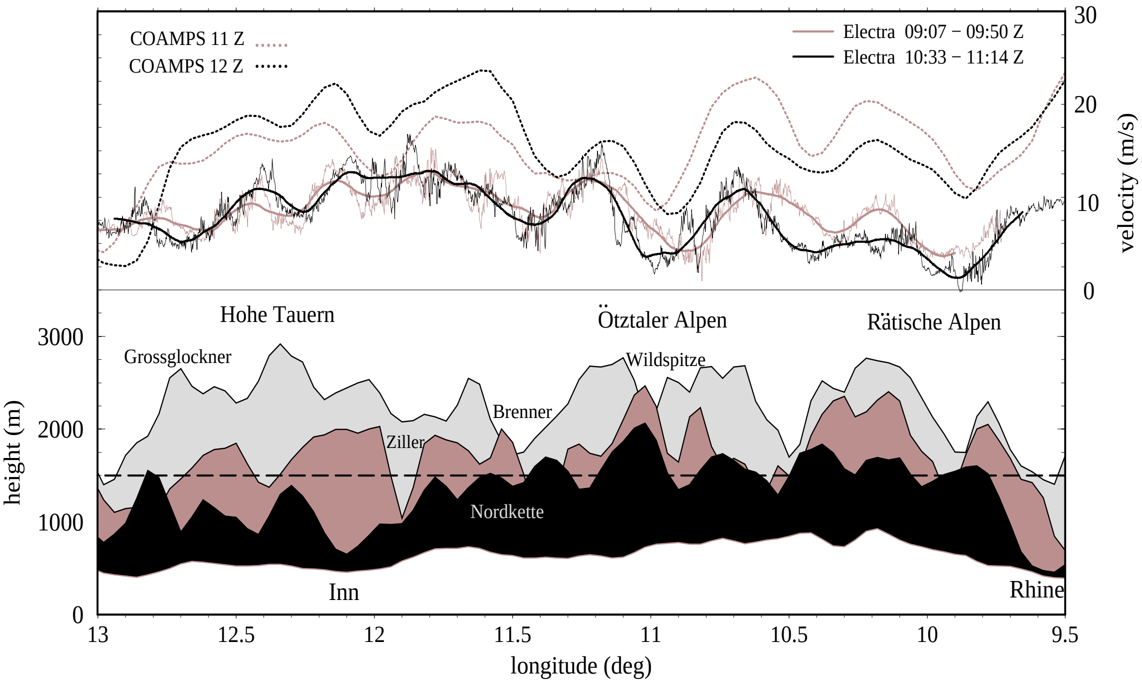

Figure 2: Upper panel: Measured and COAMPS simulated track-perpendicular wind speed at ∼1,500 m (5 kft) ASL for two passes along the same flight track with the end points at (13.1° E, 48.0° N) and (9.5° E, 47.6° N). Thin irregular and thick smooth solid curves represent raw measured and digitally filtered data, respectively, whereas the dotted lines are profiles extracted from the COAMPS simulation data. Lower panel: Orographic profiles of the eastern section of the Alps as seen in the innermost COAMPS domain (Δx=Δy= 3 km). White area is the terrain height below the flight track, and the remaining three profiles correspond to upwind track-parallel sections with the latitude end points at (47.65°, 47.25°) N (black), (47.4°, 47.0°) N (dark grey), and (47.2°, 46.8°) N (light grey). The dashed line marks the approximate flight level altitude.

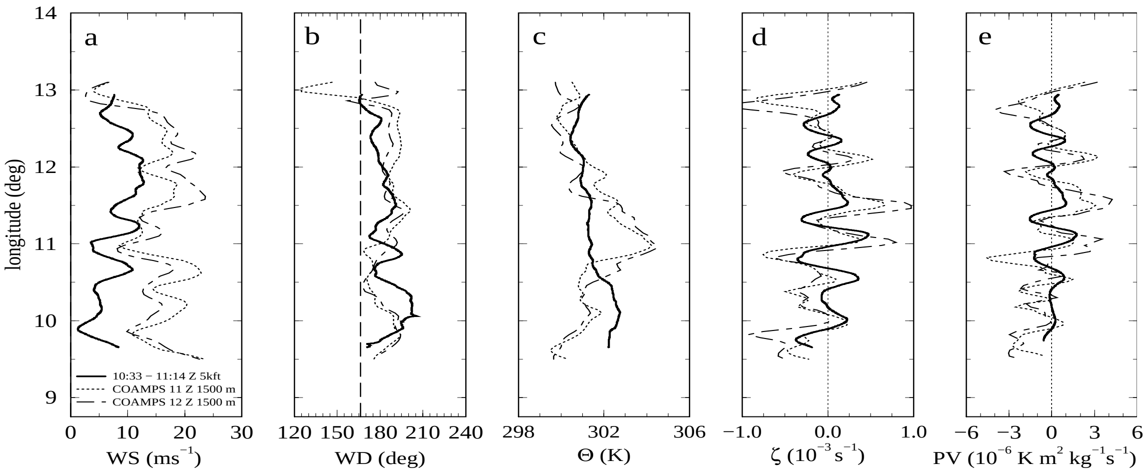

Figure 3: Measured and COAMPS simulated: a) track-perpendicular wind speed, b) wind direction, c) potential temperature, d) vertical vorticity, and e) PV along the Electra flight track (Fig. 1) at ∼1500 m (5 kft) ASL flown at 10:33–11:14 Z on 21 October 1999. The aircraft data was digitally filtered to remove fine scale features below 3 km. The long dashed vertical line at 166° in panel b marks the nominal track-perpendicular wind direction.

(from minima to maxima) in the observed and the modeled wind speed. Additionally, the discrepancies in the PV reflect (1) neglect of horizontal components of vorticity, and (2) errors in the computation of the vertical potential temperature gradient. The latter is likely to be significant between 10.5° and 11.5° E, where the model predicted potential temperature is several degrees higher than observed. The preliminary subjective analysis of the temperature field in the vertical cross section using the dropsonde data (not shown) indicates a complicated temperature structure between 5 kft and 8 kft at this location with a deep isothermal layer between 800 and 750 hPa. There is also a strong warm anomaly between 850 hPa and the top of the boundary-layer inversion at 900 hPa. Both of these features are suggestive of strong wave activity and downslope flow in this region, which the model could be overestimating or placing at a slightly different altitude.

6. CONCLUSIONS AND FUTURE DIRECTIONS

Portion of the wake north of the Alps, documented during an episode of deep south Foehn in IOP 8, represents only a small part of the entire north wake of the Alps. Thus, we have been able to document and analyze only the "secondary" PV banners in this case. The surveyed segment of the wake north of the Alps was found to contain a number of 20–60 km wide jets and smaller wakes in a nearly uniform southerly flow. Furthermore, these features were found to be closely correlated with the variation of the orographic height along the northernmost "edge" of the Alps. With only two altitudes flown by the aircraft within the wake, it is hard to infer the vertical extent of the observed features. In the next step, the objective analysis of the dropsonde data as well as the COAMPS data will be used in answering this question.

At the horizontal resolution of 3 km, the COAMPS closely reproduces the structure of the observed velocity variation at $1,500$ m in the wake while overpredicting the width of the jets and wakes only slightly and the velocity amplitude more significantly. The reason for the latter is most likely the difference in height between the model and real orography that is leading to weaker orographic blocking and to stronger Alpine-wide downslope flows in the model solutions. This point will be investigated further, within the existing model solutions as well as future runs at higher horizontal resolutions.

Once the full confidence in the model's ability to reproduce the structure and amplitude of the observed velocity variation in the wake is gained, we will use the model as a sophisticated tool in answering the more fundamental questions of PV banner origin.

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