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TWO CASES OF HEAVY RAIN ON THE MEDITERRANEAN SIDE OF THE ALPS IN MAP

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1. INTRODUCTION

The Mesoscale Alpine Program (MAP) is a cooperative international effort to improve numerical forecasting of precipitation and circulation patterns over complex terrain (Bougeault et al. 2000). One of the primary objectives is better understanding of the mechanisms of heavy orographic precipitation. An intensive field phase of MAP was held over the European Alps from 7 September 1999 to 15 November 1999. The Alps are an ideal place to conduct such an experiment since they constitute an isolated mountain range (Fig. 1) located over a region that has a dense observing network and a prevailing low-level flow of moist air (from the Mediterranean Sea) toward the mountain barrier.

Fourteen MAP Intense Observation Periods (IOPs) had systems or events producing large precipitation amounts over the Alpine region. Two particularly interesting IOPs were IOP2 (1300 UTC 19 September 1999 to 0100 UTC 21 September 1999) and IOP8 (1200 UTC 20 October 1999 to 2200 UTC 21 October 1999). Each was associated with the passage of a strong baroclinic wave, with low-level flow generally from the southeast. Despite this basic large-scale similarity, the precipitation distribution differed markedly between the two cases. The objective of this study is to compare the stability, wind, and moisture stratification of the flow over the Alpine terrain in order to understand these different precipitation patterns.

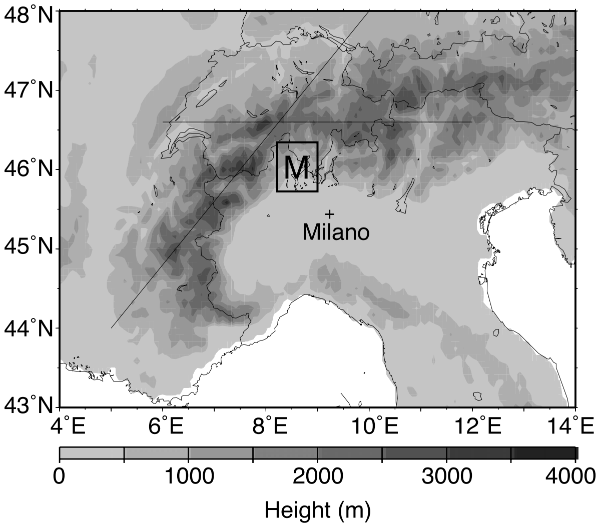

Figure 1. Topography over the Alps. See text for a description of symbols.

2. DATA

The MAP data are obtainable through the MAP Data Centre (map.ethz.ch). In this study, we use soundings taken at Milano, rain gauge data from the Italian and Swiss meteorological networks, and data from four ground-based scanning Doppler radars, the NCAR S-Pol radar, the Swiss Monte Lema radar, the French RONSARD, and the University of Oklahoma Doppler on Wheels (DOW). The locations of the first three of these radars in relation to the terrain is in Fig. 2. The DOW's location varied from case to case. The basic characteristic of these radars are listed in Table 1. The S-Pol and RONSARD were installed only for the MAP field phase, while the Monte Lema radar is a permanent facility of the Swiss Meteorological Institute. The S-Pol is a dual-polarization radar.

2.1 Precipitation Pattern

We have constructed composites of the data from the S-Pol, RONSARD, and Monte Lema research radars for each event by averaging all the available radar scans for each IOP for each radar. The composite reflectivity constructed using the Monte Lema radar volumes for IOP2 (Fig. 2) shows maximum values upslope of the Alps over the Lago Maggiore region. Rain gauge data (not shown) confirm that the rain accumulations in IOP2 were some seven

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times greater in the Lago Maggiore region (denoted by M in Fig. 1) than in IOP 8. In IOP2 the rain amounts in the Lago Maggiore region were ~100-300 mm, compared to ~20-50 mm in IOP 8. On the other hand, the composite reflectivity for IOP8 (Fig. 3) has smaller values over the same region and shows a region of high reflectivities close to Milano, upstream of the high terrain, suggesting that the flow was blocked.

2.2 Stability

A factor indicating whether a flow is going to be blocked or easily rise over a mountain range is the ratio between the kinetic energy of the flow and the potential energy needed to go over the barrier. A measure of this ratio is the Froude number (Fr), which is given by:

$$\mathrm{Fr} = \frac{U}{HN} \tag{1}$$

where *U* is the wind speed of the flow perpendicular to the barrier, *N* is the Brunt-Vaisala frequency of the incoming flow, and *H* is the height of the barrier. Flow is blocked by a two-dimensional barrier when the Froude number of the upstream flow is less than 1 (e.g. Durran 1990). Since this theory is applicable to an idealized two-dimensional case, it is questionable to what extent the Froude number gives precise information on the dynamics of the flow for a real case. However, it is still useful to look at the parameters that determine the Fr number and use these values to indicate how likely is a specific case to produce upslope enhancement or blocking. First, we examine the stability.

To indicate the stability quantitatively, we calculate the Brunt-Vaisala frequency (*N*):

$$N^2 = g\frac{d\ln\theta}{dz} \tag{2}$$

where θ is the potential temperature, *g* is the gravitational acceleration, and *z* is height.

Figure 4a shows the potential temperature profile from sounding data taken at Milano at 0000 UTC 20 September 1999 (during IOP2) and at 1200 UTC 21 October 1999 (during IOP8). *N* was calculated using finite differences over an interval *dz* (or *dp*). A close examination of the potential temperature profile of each sounding (Fig. 4a) suggests that *N* undergoes small fluctuations with height. To smooth out these fluctuations, a best fit line was calculated to approximate θ from the surface to the 850 mb level. Using the fitted values of θ, the vertical profile of N^2 is calculated (Fig. 4b). N^2 decreases slightly with height and at the surface has a value of 3.5 x 10^{-4} s^{-2} for IOP8 while for IOP2 N^2 is close to 1.3 x 10^{-4} s^{-2}, indicating that IOP8 was more stable. According to (1), a higher N^2 contributes to a lower Froude number and hence indicates that the low-level flow was more likely to be blocked in IOP8.

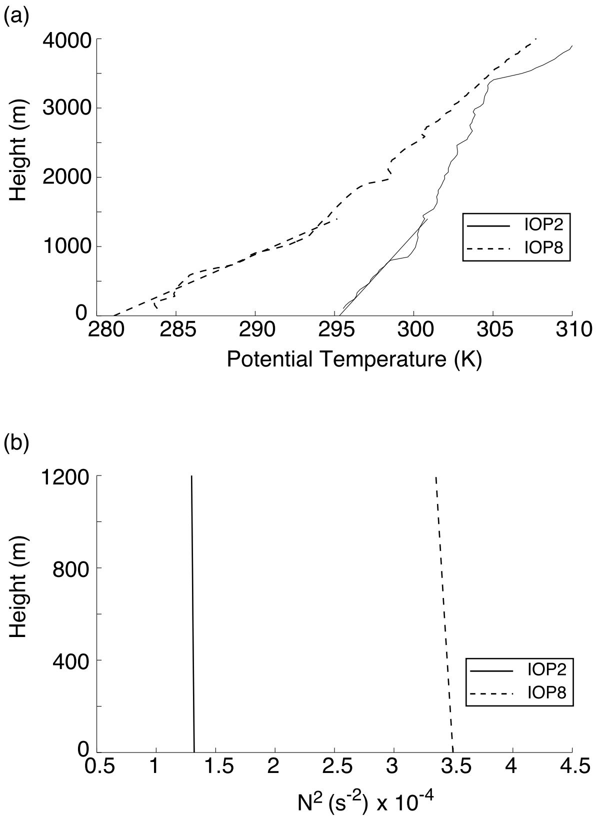

Figure 4. (a) Potential temperature for IOP2 (solid lines) and IOP8 (dashed lines). The straight lines are the best fit to the lowest 150 mb of the curves. (b) Squared Brunt-Vaisala frequency calculated using the best fitted lines in (a).

2.3 Wind

To evaluate the potential for blocking, the magnitude of the wind in the direction perpendicular to the barrier (*U*) must be taken into account in the Froude number (1). Over the Lago Maggiore region of the Alps, it would be rather difficult to choose one orientation as representative of the whole barrier. We approximate it by two distinct directions (Fig. 1). To identify them easily, we refer to the zonal direction as

"Direction 1" and the slanted one as "Direction 2". The profiles of the wind component perpendicular to both orientations of the barrier (Fig. 5) were much stronger at low levels (below 900 mb) in IOP2. Only above 900 mb and only perpendicular to Direction 2 does IOP8 have a stronger cross-barrier flow than IOP2. The weak flow normal to the barrier at low levels in IOP8, together with the greater stability in that case strongly suggest a blocked flow at low levels. This blocking was consistent with the very different precipitation patterns in IOP2 and 8, in which IOP2 had much more precipitation over the Lago Maggiore region and the Milano region had more precipitation in IOP8 (Figs. 2 and 3).

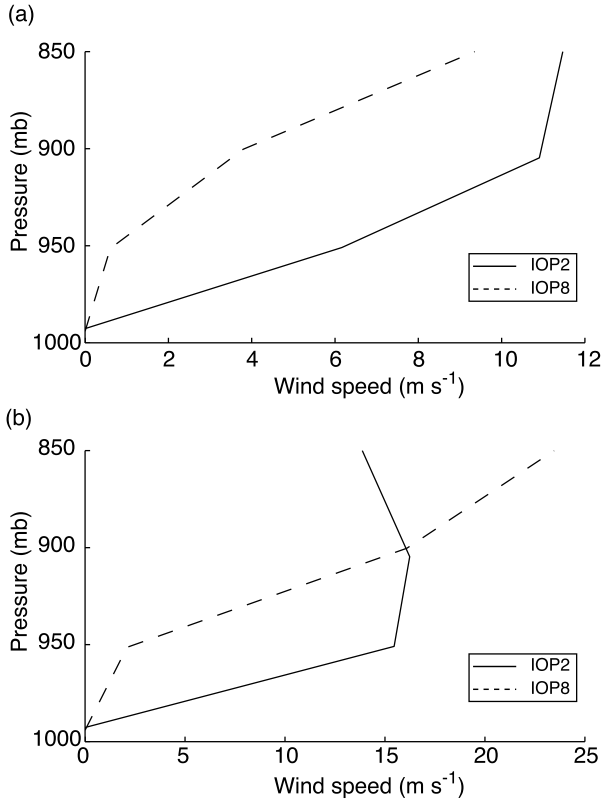

Figure 5. (a) Component of the wind perpendicular to direction 1, as indicated in Fig. 1. (b) Same as (a) but for direction 2.

To indicate the mesoscale spatial pattern of the flow relative to the terrain in these two cases, we refer to our three-dimensional storm composites of the RONSARD radar data obtained in the two IOPs (Figs. 6 and 7). The color pattern in these figures indicates the flow direction at the 0.5 km level in the region of the radar. The wind direction was perpendicular to the white zero velocity line and blowing from green to yellow. In Fig. 6, the color pattern shows a fairly straight zero velocity line indicating a generally southeast flow toward the barrier at the 0.5 km level in IOP2. In IOP8 the wind direction varies across the region observed by the radar (Fig. 7). To the south of the radar the flow at the 0.5 km level is from the east, while north of the radar it is from the northeast. The low-level flow was evidently blocked by the terrain in this case and had to find its way back toward the Po Valley and eventually out over the Ligurian Sea to the southwest of the region shown.

During MAP IOPs the DOW radar was located in river valleys to observe the valley flow blocked from the view of the fixed scanning radars: S-Pol, RONSARD, and Monte Lema. In IOP8 the DOW showed that the flow in the lower part of the valley was flowing strongly down the valley (Fig. 8). The cold colors in the lowest 1.5-2.0 km show that the flow was strongly down the valley at these levels, while above 2 km the warm colors show the strong upslope flow. The valleys apparently provided a conduit for the blocked flow to drain away from the barrier. It is possible that the precipitation particles falling out of the upslope flow cooled the layer of air below via melting and evaporation and thus further forced the lower level flow into the down-valley sub-

Table 1: MAP Radars Characteristics

Radar	MONTE LEMA	RONSARD	SPOL	DOW
Wavelength (cm)	5.6	5.4	10	3
Peak Power (kW)	251	250	1000	250
Beamwidth (deg)	1.0	0.89	0.91	0.93
Unambigous velocity interval (m s^{-1})	8.27 - 16.54	9.8 or 19.6	25	16 - 40

siding mode. This suggestion is motivated partly by the well-defined bright band in the right-hand panel of Fig. 8.

To a lesser extent this down-valley flow at low levels was seen in the other rainy MAP IOPs. Prior to MAP it had been hypothesized that the valleys would concentrate upslope flow and thus be regions of enhanced convergence and upward motion. The DOW observations indicate that the opposite is the case and that some blocking occurs at low levels in all the rain events.

2.4 Moisture

The vertical profile of mixing ratio (Fig. 9) shows that the flow had higher moisture content for IOP2 at all levels. This difference is consistent with the generally higher temperature in IOP2 (Fig. 4a). In both cases the profiles can be approximated by a two-layered structure, which suggests that the flow might have two different origins. For IOP2 the lower layer has higher mixing ratio values, while for IOP8 the opposite holds. The greater amount of rain in the Lago Maggiore region in IOP2 was evidently partly a result of the greater precipitable water content in that case.

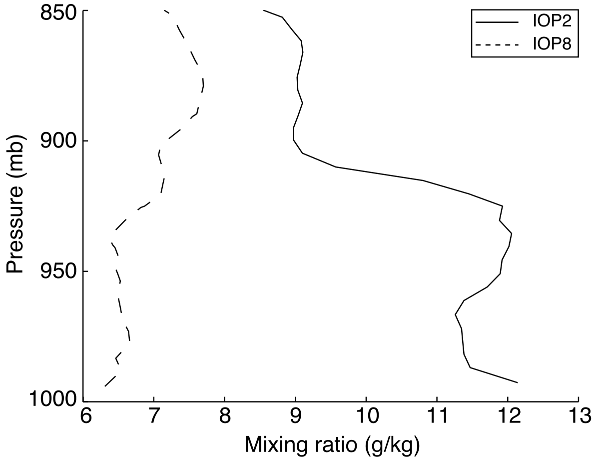

Figure 9. Vertical profile of mixing ratio corresponding to the sounding in Fig. 4a.

3. CONCLUSIONS

IOP2 and IOP8 were major rainstorms, each associated with the passage of a strong baroclinic wave. The precipitation patterns on the Mediterranean side of the Alps were highly modified by the Alpine terrain. However, the modification of the large-scale flow differed markedly between the two cases. In IOP2, the flow appeared to rise easily over the terrain. The flow toward the barrier was strong at all levels, and the precipitation amounts in the Lago Maggiore region were 100-300 mm over a period of about a day. These amounts were about a factor of seven greater than in IOP8. In the latter IOP the wind at the lowest levels had a weak component perpendicular to the terrain; the low-level air was both colder (and hence less moist) and more stable than in IOP2. These factors apparently led to the lesser rain accumulations over the Lago Maggiore region in IOP2, despite the fact that the large-scale flow at the 850 mb level perpendicular to the terrain was actually stronger in IOP8 than IOP2. The stratification of wind, stability, and moisture thus led to blocking in IOP8 and easy upslope flow in IOP2. These characteristics of the flow over the topography evidently produced major differences in rainfall in these two otherwise rather similar baroclinic systems.

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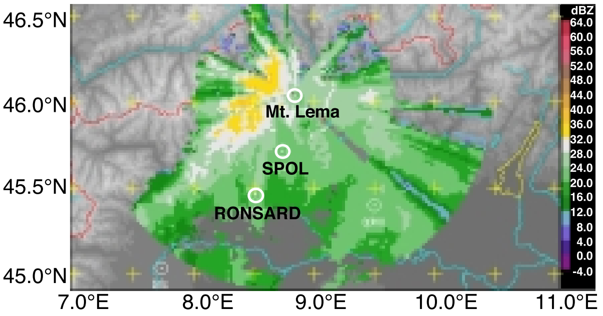

Figure 2. Constant altitude plot (2.0 km MSL) of Monte Lema composite reflectivity (dBZ) for IOP2.

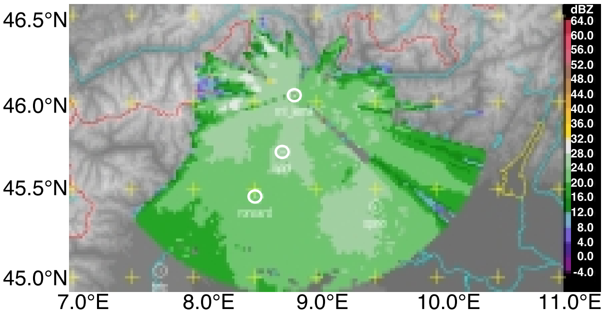

Figure 3. Same as Fig. 2 but for IOP8.

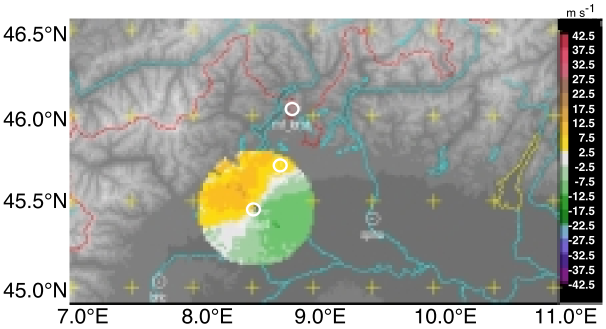

Figure 6. Constant altitude plot (0.5 km MSL) of Monte Lema composite radial velocity (m s^{-1}) for IOP2.

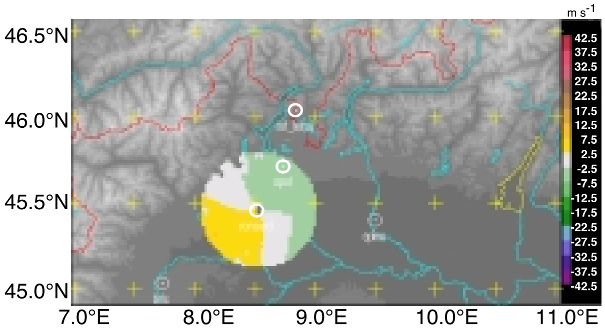

Figure 7. Same as Fig. 6 but for IOP8.

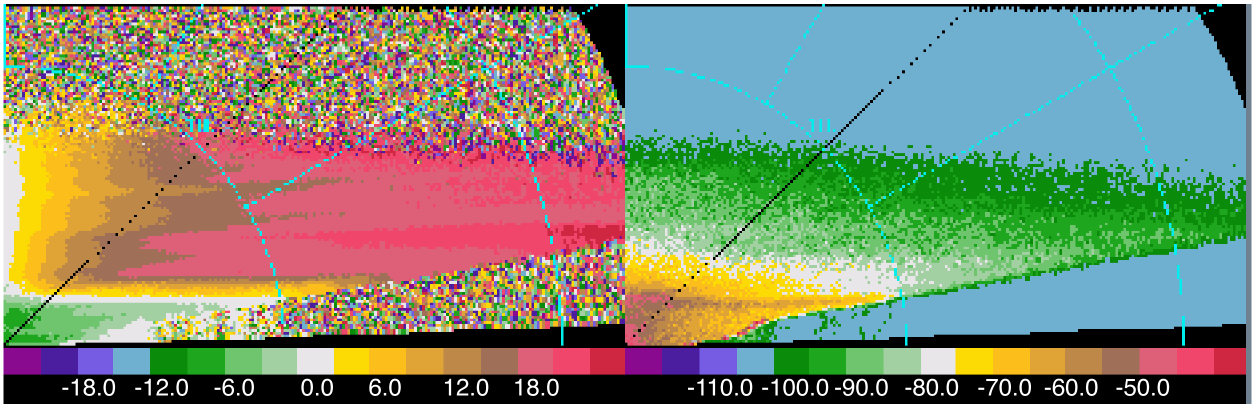

Figure 8. Vertical cross section (along a constant azimuth, with height on the y-axis and horizontal range on the x-axis) of data from the Doppler on Wheels (DOW) taken at 0911 UTC 21 October 1999. This radar pointed up the Toce River valley, from left to right in the two panels. The radar is in the lower-left corner of each panel. The left-hand panel shows the radial velocity in m s^{-1} with warm colors indicating flow up the valley and cold colors indicating flow down the valley. The right-hand figure shows returned power in dbm. Range marks are at 10 km intervals.