Multiple Expressions of Upstream Orographic Blocking During MAP

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1. Introduction

The occurrence of upstream blocking is one means by which airflow approaching steeply rising terrain may be significantly modified, thus impacting the intensity and location of orographically enhanced precipitation relative to major mountain barriers. For instance, Houze et al. (2002) recently found that the nature and location of precipitation over the Lago Maggiore region [a main focus of the Mesoscale Alpine Programme (MAP) experiment conducted during autumn 1999 over the European Alps (Bougeault et al. 2000)] was strongly correlated with the local upstream Froude number (Fr), which is traditionally used to predict whether flow encountering mountain slopes will either rise and surmount a mountain barrier (Fr >1) or be deflected around it (Fr <1). This latter situation, commonly referred to as "upstream blocking," is the focus of this paper. While Froude number concepts are readily applicable to idealized flows and mountain shapes, they become more complicated to apply in regions of more complex, realistic terrain such as that comprised by the combined Alps and the Apennines ranges ringing the western Po valley in northern Italy. In this respect, the Fr <1 (Medina and Houze 2002) orographic precipitation event of 21 October 1999 observed during the MAP IOP8 is particularly interesting.

The well documented IOP8 storm was forecast to produce heavy orographic rainfall over the steep slopes surrounding the Lago Maggiore Target Area (LMTA), but in actuality produced only moderate accumulations of stratiform precipitation, which were moreover displaced to extend well upstream of the Alpine barrier. By exploiting a spatially extensive description of the low-level flow afforded by airborne Doppler radar measurements on this day, Smull et al. (2001) suggested that the unrealistically large and misplaced forecast rain amounts were the result of a systematic underestimate of the depth and extension of blocked flow in high-resolution numerical simulations. In addition to its utility for evaluating the performance of large-domain mesoscale models, the IOP8 dataset also allows investigation of the impacts of upstream blocking on the formation of precipitation (Bousquet and Smull 2002). Here we extend the analysis of these uniquely comprehensive observations to develop a "basin-scale" mass budget to determine more precisely the degree of blocking and the location of sources and sinks of mass within the western Po valley in order to more fully illuminate actual characteristics of the blocked flow predicted by theory.

2. Data sources and analysis techniques

Observations from the scanning X-band (3.2 cm) Doppler radar aboard one of NOAA's WP-3D research aircraft are used to infer the kinematic structure of the rain event that developed on 21 October 1999 through application of the Multiple Doppler synthesis and continuity adjustment technique (MUSCAT) proposed by Bousquet and Chong (1998), and recently improved by Chong and Cosma (2000) to account for boundary conditions over complex terrain. Once retrieved, the initial estimation of the 3D wind is refined using the algorithm proposed by Georgis et al. (2000). In order to obtain a maximum coverage spanning the broad Po valley, data collected over two discrete intervals (0700-0825 and 1110-1150 UTC) are combined. Despite the relatively long period being considered (~5h), the resulting composite flow field exhibits reasonable agreement with that continuously modeled (MC2) and observed (over a more limited domain via ground-based radars), which both show relatively steady conditions during this period within the prolonged IOP8 rain event.

3. Mesoscale radar-derived flow structure

Figure 1 presents the low-level (500m MSL) flow derived from the aforementioned composite analysis of P3 Doppler radar observations. Overall, the circulation shows a strong (~20 m/s) and broad region of easterly flow approaching the barrier from the eastern Po Valley that progressively decelerates and turns so as to parallel the curving terrain. Having been derived from the deflection of incident southerly low-level winds ahead of an advancing baroclinic wave, this easterly flow may thus be considered as "blocked." A unique observation afforded by the extensive airborne radar coverage is that, upon approaching the cul-de-sac comprised by the curved face of the Alps, a portion of this blocked flow ultimately turned away from the barrier and escaped through a narrow gap between the Maritime Alps and the Apennines via a narrow zone of northerly winds jetting out over the Mediterranean Sea. This continuous and deep layer of blocked flow extending southward

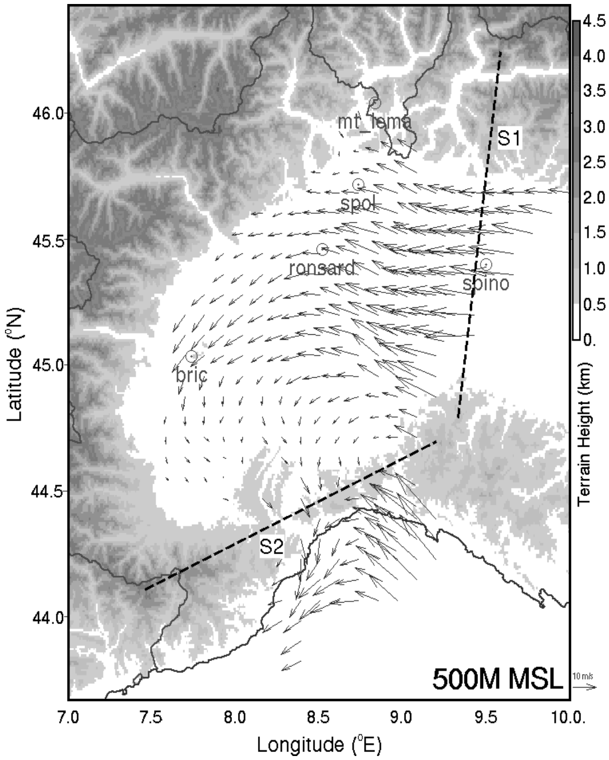

Fig. 1. Airborne dual-Doppler radar analysis of absolute flow (vectors, key at lower right) superimposed and terrain height (shading, key at far right) at 500m MSL within a 250 km x 300 km display domain centered on ~ (45N, 8.5E). Observations are derived from several P3 tracks from 0707-0847 UTC and 1110-1150 UTC on 21 October 1999. Horizontal and vertical resolutions are 1.5 km and 0.25 km, respectively. One every fourth vector is plotted. Dashed lines S1 and S2 represent the location of the sections shown in Figs. 2 and 3.

some ~150 km from the lower Alpine slopes to the Gulf of Genoa shows that the influence of the Alps was felt far much upstream than could ever be expected before the MAP field phase.

Figure 2 presents mean vertical profiles of wind speed and direction along sections S1 (Po valley) and S2 (Apennines), as located in Fig. 1. Low-level flow of 15-20 m/s across S1 originated in the eastern Po valley (and ultimately over the Adriatic Sea), and exhibited relatively constant speed while veering to become southerly aloft. This easterly flow was thus strongly channeled up to a height of 1.5 km. At low-levels, this vertical structure dramatically contrasts with that observed in the Apennines region (along S2, cf. Fig. 2b), where *northerly* flow could be observed up to 1 km altitude. Note that the depth of this northerly flow could locally extend up to 2 km MSL, as shown by Bousquet and Smull (2002). Above 2 km, the wind structure along S1 and S2 was quite similar, with southerly winds of ~17 m/s observed at both locations.

Precipitation type and intensity (not shown) varied considerably over this large domain. Moderately intense cellular convection was observed over the Maritime Alps, Apennines and Mediterranean Sea, while widespread stratiform precipitation developed over the

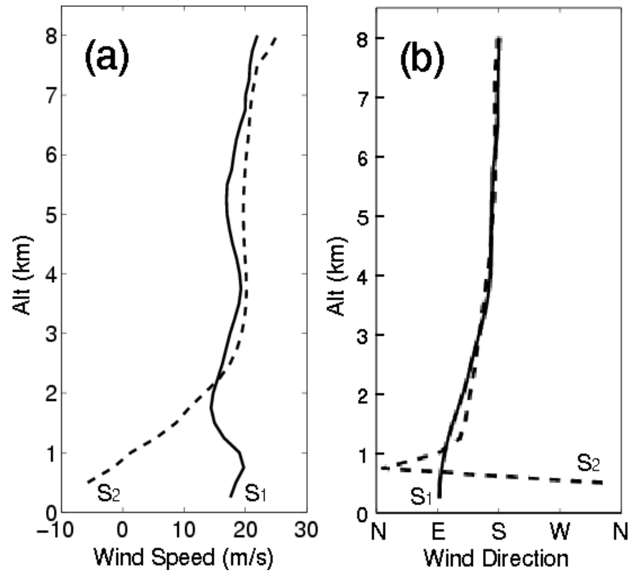

Fig. 2: Mean vertical profile of (a) wind speed and (b) wind direction along sections S1 (solid) and S2 (dashed) as located in Fig. 1.

Po valley and lower Alpine slopes. Bousquet and Smull (2002) have shown that the convective nature of the precipitation over the Mediterranean Sea and the Apennines, while primarily due to the passage of a synoptic scale through and its associated cold front, was likely enhanced through convergence forced by this cool northerly flow escaping the Po basin. This situation effectively prevented moisture-rich low-level Mediterranean air from reaching the slopes of the LMTA by triggering release of convective instability well south of the Alpine barrier. These observations help to explain why precipitation over the Po basin and Alpine slopes was mainly stratiform. What remains unclear, however, is the degree to which this precipitation derived from the limited contribution of lifting within the mid-level southerly feed of air originating over the central Mediterranean (e.g., Fig. 2b) vs. forced ascent of the stable but saturated easterly low-level flow lifted over relatively cool, stagnant air in the boundary layer accumulating in the western Po valley.

As suggested by Seibert (1990), the Alps and the Apennines together comprise a large basin closed on three sides, with an opening to the east that is the lower Po valley. Figure 1 shows that an additional opening, we will refer to as the “Apennine channel,” exists to the south where some of the low-level flow during IOP 8 was able to escape. According to Fig. 3, which shows the detailed topography along S1 and S2, the height of the local crest line that defines the width the western Po valley (Fig. 3a) and the Apennine channel (Fig. 3b) is approximately 1.25 km. Up to this level, the Po basin can thus be viewed as a large volume bounded by the Alps to the north and west, and sections S1 and S2 to the east and south, respectively (Fig. 1). To investigate the origins and ultimate destination of blocked flow during MAP IOP 8, we have performed a mass budget within this volume.

4. Basin-scale mass budget

Despite its the unique size and shape, a mass budget for the volume being considered may be constructed following an approach similar to that of Chong et al. (1987) to estimate horizontal and vertical transports relevant to the layer of blocked flow.

The mass Mz of air transported vertically through a horizontal area A per unit of time may be expressed as:

$$Mz=\rho(z)w(z)A(z) \qquad (1)$$

where ρ is the air density, and w is the mean vertical velocity over A at reference level z (note that in our case the surface A varies with height). If we consider a pair of horizontal surfaces ‘A’ separated by a height Δz, it is then possible to express the differential vertical mass transport through these surfaces as:

$$F_z\ (z+\Delta z/2)=Mz\ (z)-Mz\ (z+\Delta z) \qquad (2)$$

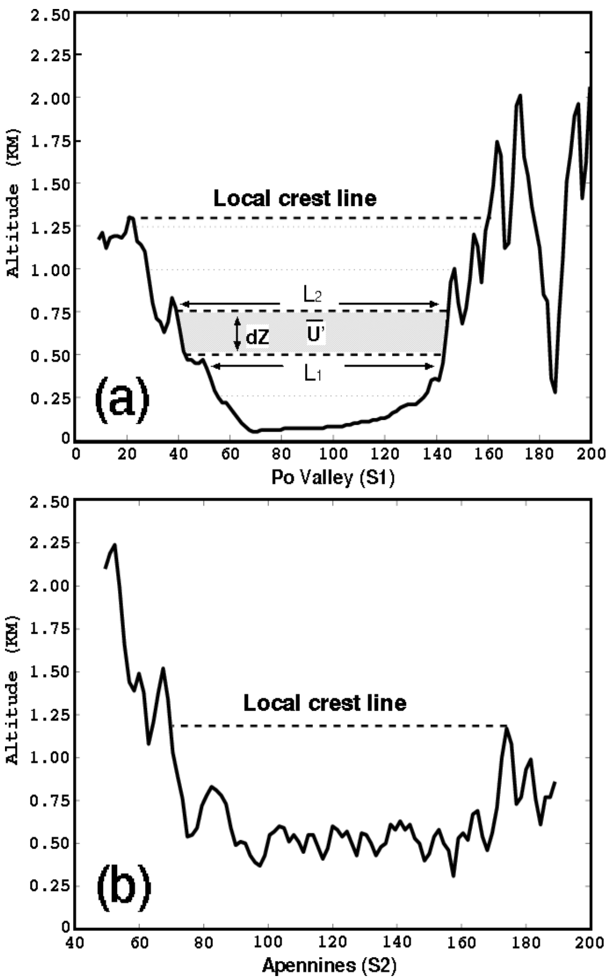

Fig. 3: Topography along sections (a) S1, and (b) S2 shown in Fig. 1. U’ defines the averaged velocity through the surface area $dZ(L_1+L_2)/2$.

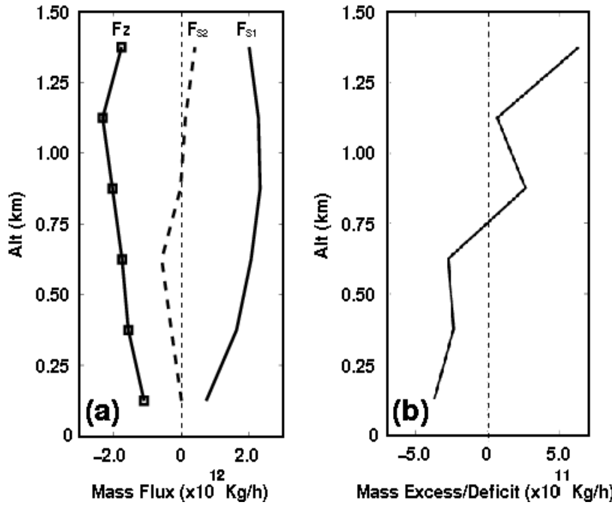

Fig. 4. Results of the mass-transport budget within a domain bounded by the Alps and sections S1 and S2 as represented in Fig.1. In (a), F_{S1}, F_{S2}, and F_Z show the horizontal and vertical mass flux convergence as a function of altitude. The residual is shown in (b). Note the factor 10 difference between (a) and (b).

where z+Δz/2 defines the reference level of the considered slab and Δz is equal to the native resolution of the radar-derived wind field (0.25km). Within the domain represented in Fig. 1, one can similarly deduce the differential horizontal mass transport F_{S1} and F_{S2} through the Po valley and Apennine channel. In the present case, however, the expression of the horizontal mass transport is greatly simplified due to the presence of the Alpine barrier. For S1 it can for instance be expressed as:

$$F_{S1}\ (z+\Delta z/2) = \rho(z+\Delta z/2)U'A \qquad (3)$$

where A is given by $\Delta z(L_1+L_2)/2$ (see fig. 2) and U' is the mean component of the wind through A.

According to the mass conservation equation, these quantities are related by:

$$F_{S1} + F_{S2} + F_Z = 0 \qquad (4)$$

Radar-derived profiles of these estimated mass transports within the Alpine-bounded domain are shown in Fig. 4. One can note that the mass conservation (Eq. 4) is not exactly satisfied, but that the residuals (Fig. 4b) are relatively small—attesting of the rationality of this approach. Moreover, the vertical structure of the residual terms appears to be consistent with previous studies of the MAP IOP8 that have revealed the existence of a deep return flow within numerous valleys of the Po basin (Steiner et al. 2002, Bousquet and Smull 2002). As illustrated in Fig. 5, high-resolution airborne Doppler analyses demonstrate that all the major rifts ringing the LMTA were filled with this “down-valley” flow. If taken into

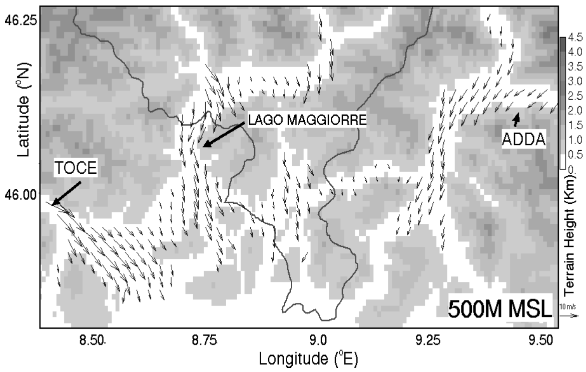

Fig. 5. As in Fig. 1 but for a 100 km x 50 km domain centered on ~(46N, 9E). Observations are derived from P3 tracks at 1255-1305 UTC 21 October 1999. Horizontal and vertical resolutions are 0.5 and 0.25 km, respectively. Only every fourth vector is plotted.

account, this source (not resolved in the basin-scale composite) would reduce the deficit seen below 0.75 km in Fig. 4b. The mass excess above 1.25 km is less significant owing to the unbounded nature of the volume aloft.

Terms F_{S1} and F_z, which respectively represent the amount of mass entering the basin from the Po valley and exiting (negative value) the basin through vertical transport, strongly dominate the budget. The amount of air exiting the basin horizontally through the Apennine channel represents only ~20% of the mass entering from the Po valley. Given the small Froude number reported for this event (which was however measured within the region of blocked flow at Milano), one might reasonably expect a balance between terms F_{S1} and F_{S2} and minimal upward transport. However, the extension of net upward vertical transport seen in Fig. 4a to a height dominated by widespread southerly flow (cf. Figs. 2 and 4a) indicates that much of this "blocked" flow eventually escaped by flowing northward over the Alpine crest vs. horizontal deflection around the barrier.

5. Conclusions

Idealized descriptions of airflow upstream of a isolated mountain barriers (as embodied by Froude number theory) generally hold that air unable to directly ascend the barrier must flow around it. A rudimentary mass budget made possible by extensive airborne Doppler radar observations encompassing the western Po basin during MAP IOP8 shows that a relatively small fraction (~20%) of blocked easterly flow observed adjacent to the south face of the Alps escaped southward over the Mediterranean Sea. Widespread stratiform precipitation observed to blanket the south side of the Alps and adjacent Po basin (vs. heavy convective showers that were forecast to develop over the steep Alpine slopes) thus at least partly derived from forced lifting of cool, saturated low-level air as blocked easterly flow approached the cul-de-sac represented by the curved Alpine/Apennine barrier ringing the western Po basin. We have further demonstrated the prevalence and reproducibility of down-valley flow, which high-fidelity airborne dual-Doppler analyses show to have been present within multiple deep Alpine drainages surrounding the Lago Maggiore region during MAP IOP8. Though perhaps indicative of key dynamical/microphysical processes associated with upstream blocking, this down-valley flow was evidently a relatively minor contributor to blocked flow arriving at low levels on the south face of the Alps, esp. when compared to strong easterly flow originating over the Adriatic Sea and channeled into the western Po basin.

Acknowledgements

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References

Bougeault, P., P. Binder, A. Buzzi, R. Dirks, R. Houze, J. Kuettner, R. Smith, R Steinacker, and H. Volkert, 2001: The MAP special observing period. *Bull. Amer. Meteor. Soc.,* **82**, 433-462.

Bousquet, O., and B. F. Smull 2002: Observations and impacts of upstream blocking during a widespread orographic precipitation event. *Quart. J. Royal Met. Soc. (Cond. accepted).*

Bousquet, O. and M. Chong, 1998: A multiple Doppler synthesis and continuity adjustment technique (MUSCAT) to recover wind components from Doppler radar measurements. *J. Atmos. Ocean. Tech*., **15**, 343-359.

Chong, M. and S. Cosma, 2000: A formulation of the continuity equation of MUSCAT for either flat or complex terrain. *J. Atmos. Ocean. Tech*., **17**, 1556-1564.

Georgis, J. -F., F. Roux and P.H. Hildebrand, 2000: Observation of precipitating systems over complex orography with meteorological Doppler radars: A feasibility study. *Meteor. Atmos. Phys*., **72**, 185-202.

Houze, R. A., C. N. James, and S. Medina, 2002: Radar observations of precipitation and airflow on the Mediterranean side of the Alps: Autumn 1998 and 1999. *Quart. J. Royal Met. Soc,* **127**, 2537-2558.

Medina, S. and R. A. Houze, 2002: Air motions and precipitation growth in Alpine storms, submitted to *Quart. J. Royal Met. Soc.*

Seibert, P., 1990: South foehn studies since the ALPEX experiment. *Meteor. Atmos. Phys.*, **43**, 91-103.

Smull, B., O. Bousquet and D. Lüthi, 2001: Evaluation of real time MC2 simulation results for a case of significant upstream blocking during MAP. MAP Newsletter **15**, 84-87.

Steiner, M., O. Bousquet, R.A. Houze, B.F. Smull and M. Mancini, 2002: Airflow within major alpine river valleys under heavy rainfall. *Quart. J. Royal Met. Soc. (Cond. accepted).*