DETAILED STRUCTURE OF MOIST, SHEARED, STATICALLY STABLE, OROGRAPHIC FLOWS

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Abstract: When a mid-latitude cyclone approaches a mountain range, the airflow at low-levels is modified by the orography. This study uses detailed, high-resolution Doppler radar observations and numerical modeling to analyze moist flows upstream of the Alps for a case of statically stable strongly sheared flow in the Lago Maggiore region, on the Mediterranean side of the Alps. A synoptic-scale south-southwesterly upper-level flow was located above ~2 km, a barrier-scale east-southeasterly mid-level flow between ~1-2 km and a smaller-scale north-northwesterly low-level flow below 1 km. The heights of these flows are underestimated by a mesoscale simulation, which then has less blocking and more upslope flow than in the real case. Within the layers of strong shear separating the three flows, turbulence occurs and has the structure of Kelvin-Helmholtz waves.

Keywords: *Orographic moist airflow, shear, turbulence, Doppler radar*

1. INTRODUCTION

The Intensive Observing Period 8 (IOP8) of the Mesoscale Alpine Program (MAP, Bougeault et al. 2001) occurred on 20-21 October 1999 as moist statically stable air was confined and constrained by the Alpine Barrier ahead of a mid-latitude cyclone. This case, which had low-level blocked airflow on the Mediterranean side of the Alps, has been widely studied by the MAP community [e.g., Asencio and Stein 2006 (AS06), Bousquet and Smull 2003 (BS03), 2006 (BS06), Hoggarth et al. 2006, Lin et al. 2005 (L05), Medina and Houze 2003, Rotunno and Ferretti 2003 (RF03), Steiner et al. 2003 (S03)]. These studies have shown that in Lago Maggiore region, shown in Fig. 1a, the direction of the flow changed markedly with altitude. In this study we examine the shear at low levels in more detail to (a) understand why mesoscale numerical simulations tend to place the maximum precipitation over the lower windward slopes (e.g., AS06, RF03, L05) even though the actual maximum occurred upstream (Frei and Häller 2001); and (b) to investigate the nature of the turbulent motion found by Houze and Medina (2005) to have been occurring in the shear layer and likely enhancing the precipitation fallout over the windward slopes of the mountain barrier.

2. OROGRAPHIC FLOWS IN THE LAGO MAGGIORE REGION

The radial velocity data collected at 3.8° elevation by the NCAR S-Pol radar is shown in Fig. 1b. Since altitude increases with range, the radial velocity pattern is related to the vertical profile of the wind. An S-shape pattern in the zero velocity line indicates veering of the wind with height (Baynton et al. 1977), while a closed maximum and minimum of radial velocity at roughly equal range on opposite sides of the radar signifies a jet at that altitude (Houze et al. 1989). Figure 1b shows sharply veering wind at low levels, with a north-northwesterly (NNW) jet at an altitude of 0.7 km[1] (range ~7 km). This northerly component flow was overlain by an east-southeasterly (ESE) jet at 1.6 km (range ~20 km). At higher levels the flow was south-southwesterly (SSW). These radar-observed flows were consistent with the winds from the Milan sounding (wind profile labelled 'OBS' in Fig. 1e).

[1] Unless otherwise stated, all altitudes are above mean sea level (MSL).

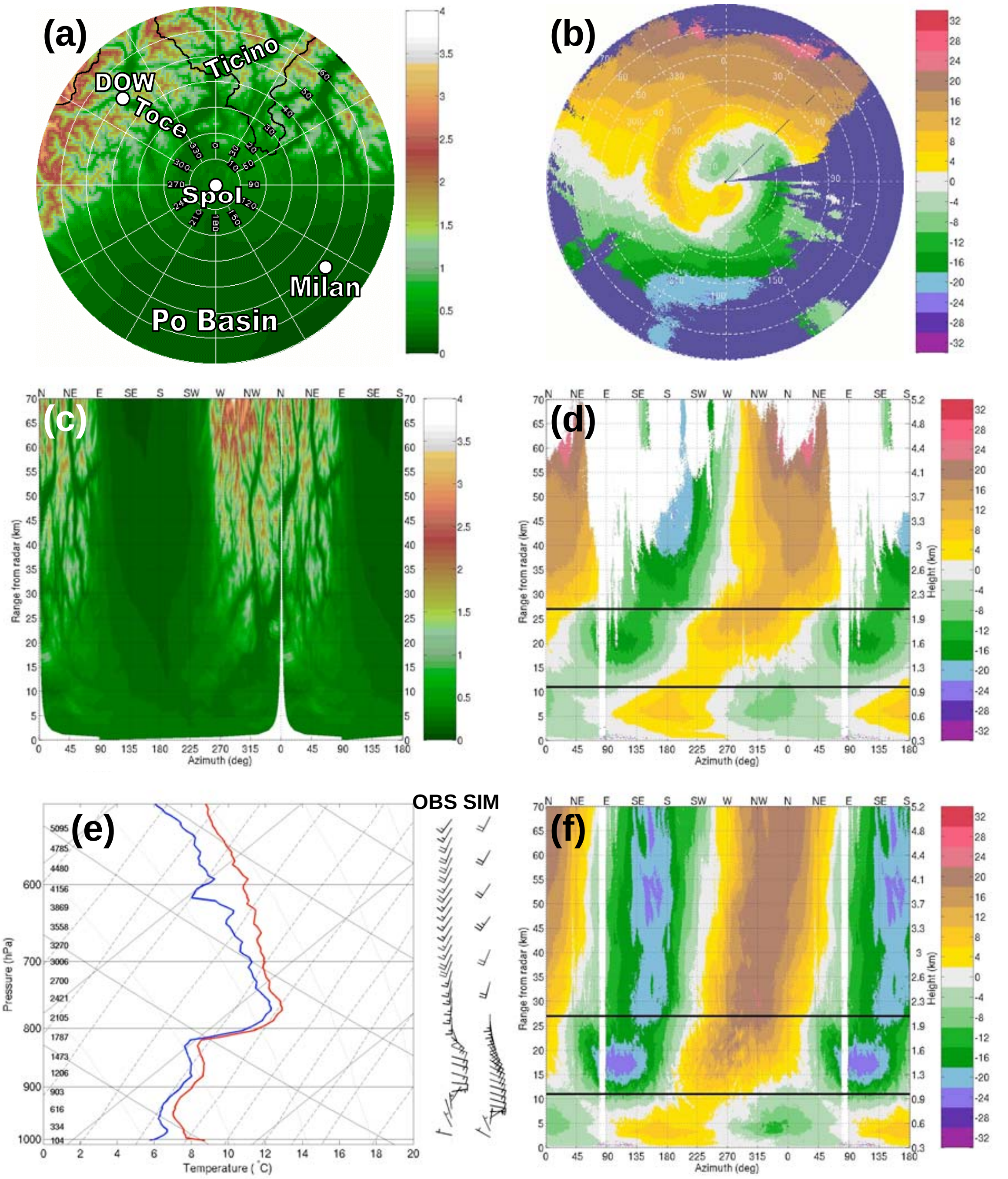

Figure 1: (a) Terrain height (km) in Lago Maggiore and S-Pol radar range rings at 10 km intervals. (b) S-Pol radar radial velocity (m s^{-1}) at 00 UTC 21 October 1999 from 3.8 deg Plan Position Indicator (PPI). (c) As in (a) but displaying azimuth in the x-axis and range in the y-axis. One and a half azimuth cycles are shown for clarity. (d) Range-azimuth display of data shown in (b), with height (km) shown in the right y-axis. The black horizontal lines, at ~1 and ~2 km height, mark the separation between the low-, mid-, and upper-level flows. (e) Skew-T plot of Milan sounding at 00 UTC 21 October 1999. The numbers to the right of the y-axis correspond to height (m). The observed wind profile is labeled 'OBS', while the one labeled 'SIM' is from a Meso-NH mesoscale simulation of IOP8. (f) As in (d) but for 09 UTC 21 October 1999.

Before IOP8, a cold and stable air mass entered the western edge of the Po Basin, preventing the incoming, synoptically driven, SSW flow associated with IOP8 from entering this region (BS03). SSW flow from the Adriatic turned cyclonically and was channelled between the Alps and the Apennines, forming the

ESE flow seen in Fig. 1b (BS06). At higher levels, the synoptic SSW airstream flowed unimpeded by terrain over the region (Fig. 1b). The low-level NNW flow was draining out of the exit of the Toce and Ticino valleys into the Po Basin (Fig. 1a). S03 suggested that this flow formed as diabatic cooling from melting of precipitation drove a drainage flow, since the NNW flow layer coincided with the radar bright band. AS06 confirmed this hypothesis in a mesoscale simulation of IOP8 and identified the NNW, ESE, and SSW flows described above as valley, regional and synoptic circulations, respectively.

A range-azimuth (RA) plot in rectangular coordinates shows the vertical extent of these flows (Fig 1d). The low-level flow, which was located below ~1 km height (denoted by the lower black horizontal line), had a minimum (toward the radar) at ~330° and a maximum (away from radar) at ~180°, denoting NNW flow. The outline of this flow conforms to the horizontal shape of the Alpine barrier at azimuths between 270° and 30° and ranges between 5-15 km (Fig 1c). The mid-level flow, which was located roughly between 1 and 2 km (corresponding to the black horizontal lines in Fig. 1d), shows a minimum at ~120° and a maximum at ~300°, indicating ESE. The upper-level flow, located above ~2 km, was SSW.

3. MESOSCALE SIMULATION OF OROGRAPHIC FLOWS

Simulated winds at Milan from the Meso-NH simulation of AS06 are shown in Fig. 1e (wind profile labelled 'SIM'). The simulation captured well the overall behaviour of the flows. The altitude of the top edge of the simulated low-level and mid-level flows was slightly lower than in the observations. AS06 state that these two flows contributed to the flow reversal and blocked configuration seen during IOP8. The underestimation in the altitude of these flows in the simulation (and hence of the blocking) may have been responsible for the overestimation of the accumulated precipitation on the Lago Maggiore slopes (Fig. 8 of AS06).

4. EVIDENCE OF TURBULENCE

Figure 1f shows a RA plot of radial velocity at ~0900 UTC 21 October, a time when high rain-rates and echo-tops were measured within the Toce Valley (Fig. 6c,d of S03). At this time, the mid-level flow had a strongly negative (inbound) jet at ~90-120° (ESE) at 1.3 km height. At higher levels, the inbound flow consisted of a south-southeasterly minimum extending upward from ~2 km height. The outbound flow also exhibited an extremum above ~2 km. However, at midlevels (1-2 km) there was no outbound counterpart to the inbound ESE jet, and the outbound flow between 1-2 km height exhibited large spatial standard deviation, consistent with the presence of turbulence (Newsom et al. 2000). Houze and Medina (2005) presented evidence from high-resolution vertically pointing Doppler radar data that during IOP8 and other statically stable orographic cases, turbulence-induced cellular updrafts form in a shear layer over the windward slopes of the barrier. They suggested that the persistent layer of intermittent strong updrafts enhances the precipitation over the windward slope by quickly removing the orographically generated condensate before it is advected to the lee side of the barrier.

The high shear (Fig. 1b,d,f) and stable static stability (Fig. 1e) observed during this case were consistent with the occurrence of shear-induced turbulence (Richardson number < ¼). Figure 2 shows an example of Kevin-Helmholtz (KH) billows observed by the X-band scanning Doppler on Wheels (DOW) radar (S03), located inside the Toce Valley (Fig. 1a), in a range-height indicator (RHI) collected in the down-valley direction. Evidence of cellular overturning is seen in the radial velocity perturbations of vertical and horizontal scales of ~1 km and 4 km, respectively (Fig. 2a). Previous investigators (e.g., Chapman and Browning 1997, 1999) have noted that KH billows located in a shear layer exhibit a "braided" or shear-splitting structure such as that seen in Fig. 2b, which shows the radial velocity shear[2].

5. CONCLUSIONS

The complex, moist, and orographically modified flows observed in Lago Maggiore region during IOP8 were documented using detailed radar observations collected during MAP. Three flows were clearly evident

[2] The billows were observed at close ranges and at low elevation angles, hence the shear was calculated as the difference in the radial velocities between gates adjacent in elevation divided by the vertical distance separating the gates. Since the jet seen in Fig. 2a is less than zero, the negative of the radial was used in the calculation.

in this region: a synoptically driven south-southwesterly upper-level flow above ~2 km, a barrier-scale ESE mid-level flow between ~1-2 km and a smaller-scale north-northwesterly low-level flow out of river valleys below 1 km. A mesoscale simulation of IOP8 captures the three flows described above; however, the altitude of the low- and mid-level flows is too low, which evidently reduced the amount of flow blocking and hence produced more upslope precipitation.

The observations show that the easterly component of the mid-level flow was consistently stronger upstream than downstream of the radar throughout IOP8. The fine scale features of the flow suggest that momentum was being dissipated in the mid-level jet by turbulence. Houze and Medina (2005) found evidence of turbulent motions in the shear layer and suggested that the turbulent updrafts may be important in hastening the enhancement of the windward precipitation fallout. The DOW radar data analyzed in this study show the turbulent cells to have the structure of KH waves in the shear layer.

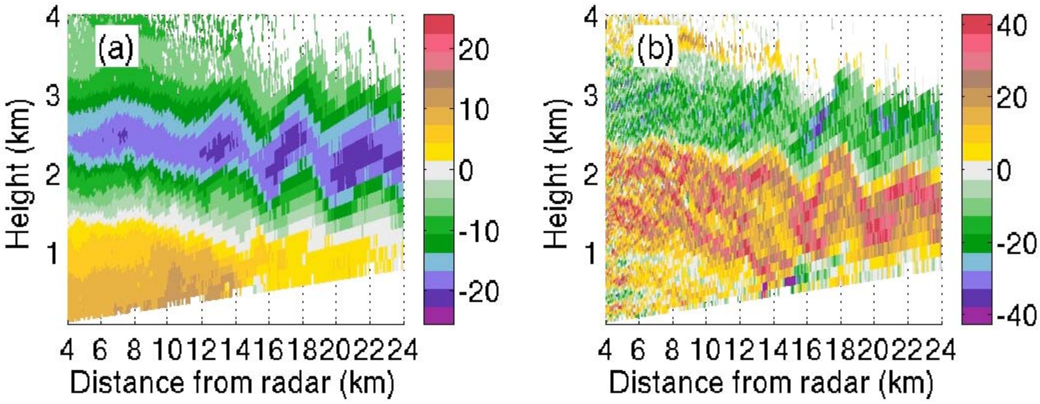

Figure 2: DOW radar RHI collected at 0728 UTC 21 October 1999 looking in the down-valley direction showing (a) radial velocity and (b) vertical wind shear (m s^{-1} km^{-1}). See text for details on shear calculation.

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