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AIRFLOW WITHIN MAJOR ALPINE RIVER VALLEYS: THE CONCEPT OF WET DRAINAGE FLOW

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1. INTRODUCTION

Analyses of the airflow within the Toce River valley (Fig. 1) using ground-based and airborne Doppler radar, surface, and upper-air data taken in the fall of 1999 during the Mesoscale Alpine Program (MAP) Special Observing Period (SOP; Bougeault et al. 2001) show that precipitation can strongly modify the airflow within valleys (Steiner et al. 2000, 2002). Based on these analyses, a new concept of wet drainage flow is proposed.

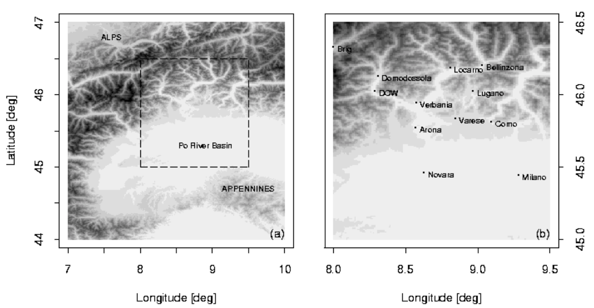

Figure 1. Geographical setting of the Lago Maggiore study area. Shown are the northwestern corner of the Po River basin and the embracing Alpine barrier (the grayscale ranges from 0 to 4000 m) with its major river valleys. The dashed box, outlined in the larger scale perspective of the left panel, is shown in more detail in the right panel. The Toce River feeds into the Lago Maggiore near Verbania. The L-shaped valley has an approximately east-west oriented lower and a north-south oriented upper part. Domodossola is the largest city in the Toce River valley. The location of the hydrometeorological surface station and the mobile Doppler radar deployment near Pieve Vergonte is marked by “DOW”.

Melting and evaporation of precipitation particles result in cooling of air that in turn causes subsidence. In complex terrain and the absence of other forces than gravity, the subsiding air concentrates in river valleys, which act as air drainage. Down-valley flow generated this way is driven by gravitational force and may thus be termed *drainage flow*, similar to the nocturnal drainage flow under clear sky and weak synoptic conditions. The difference between the *wet* and *dry* drainage flows is the mechanism causing the air to subside, namely cooling by melting and evaporation during wet conditions and cooling by long-wave radiation under dry conditions, respectively. The wet drainage flow is in sharp contrast to a nocturnal drainage flow under clear sky conditions (Fig. 2). While a dry drainage flow may occur at nighttime during weak synoptic forcing, the wet drainage flow is not bound to a particular time of day. Moreover, because the cooling rates from melting and evaporation (Leary and Houze 1979) typically exceed those resulting from nocturnal, clear sky radiational cooling (Orgill et al. 1992), a wet drainage flow may develop against moderate synoptic forcing.

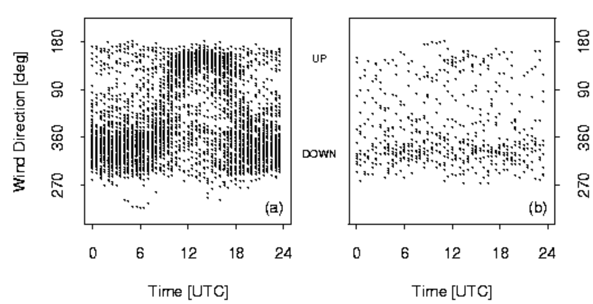

Figure 2. Wind direction analyses for the Toce River valley as a function of daytime for the period 29 June through 10 November 1999, separated into non-raining **(a)** and raining **(b)** conditions.

The precipitation-driven drainage flow may reach a maximum depth limited primarily by the height of the melting layer or cloud base

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(whichever is at a higher altitude) and secondarily by the valley confines (Steiner et al. 2002). The drainage flow strength and depth are related to the rainfall amount. Typical examples of a wet drainage flow documented in the Toce River valley during the MAP SOP are IOPs 8, 9, 10, and 14.

2. OBSERVATIONS AT THE VALLEY SCALE

Ground-based single-Doppler (Doppler-on-Wheels [DOW]; Wurman et al. 1997) and airborne dual-Doppler (NOAA WP-3D [P-3]; Jorgensen et al. 1996) radar and surface data collected during the MAP SOP revealed the formation of significant flow of air down major Alpine river valleys during persistent periods of rainfall. The down-valley flow was typically directed opposite the flow of moist air that was lifted onto the topographic barrier (Figs. 3a and 4d). Flow down the valley occurred in situations, where the lowest boundary layer air remained blocked and only air from layers above 1-2 km was able to rise over the barrier (Bousquet and Smull 2002; Medina and Houze 2002). In the absence of atmospheric instability, this resulted in widespread upslope (orographic) precipitation, where particles formed in the air ascending the slope of the terrain (Figs. 3b and 4b).

Although the results presented here are from the Toce River valley, this phenomenon of down-valley flow under sustained periods of rainfall was not limited to the Toce valley, but also seen in other major Alpine river valleys during MAP (Steiner et al. 2000; Bousquet and Smull 2002).

The down-valley flow typically deepened throughout a rainfall event, yet it never exceeded the height of the melting layer (radar bright band), which presented a thermodynamic limit on the potential depth of the drainage flow. (The cloud base was typically below the altitude of the radar bright band.) Dynamically, the melting layer was marked by a layer of convergence (Fig. 5) that tended to separate the upward motion above from the downward motion below it. The processes generating subsidence of air by cooling from melting and evaporation of precipitation particles are thus somewhat similar to the production of a mesoscale downdraft in the stratiform anvil region of a mesoscale convective system.

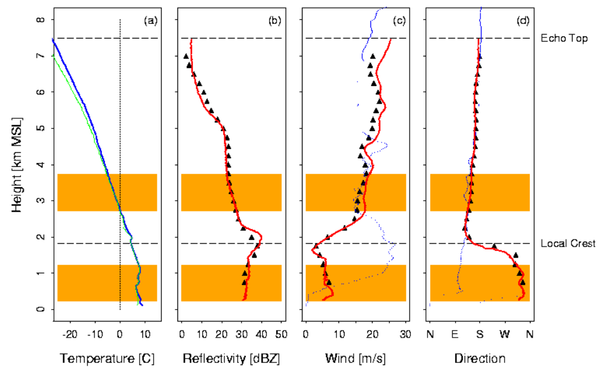

Figure 4. Vertical profiles of sounding-based temperature and dew point **(a)**, and radar reflectivity **(b)**, wind speed **(c)** and direction **(d)** from mobile Doppler radar. The solid line corresponds to the ground-based DOW radar deployed within the Toce River valley, the solid triangles show the airborne P-3 data, and the dotted line highlights the sounding-based wind speed and direction. The shaded altitude ranges indicate the profile averages used in Fig. 6 for the "within valley" and "above local crest line" conditions, avoiding the zone of transitioning winds.

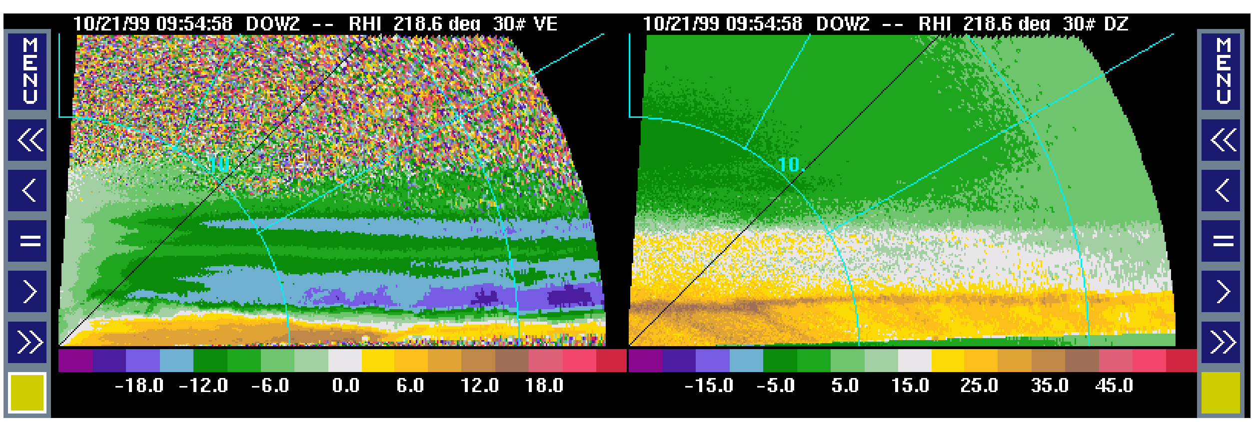

Figure 3. Vertical cross section (RHI) collected at 0954 UTC on 21 October 1999 in the direction down the Toce River valley towards the Lago Maggiore. The DOW radar was located at the Pieve Vergonte site (left corner in the panels). Radial Doppler velocity is shown in the left panel **(a)** and radar reflectivity in the right panel **(b)**. Range rings are indicated every 10 km.

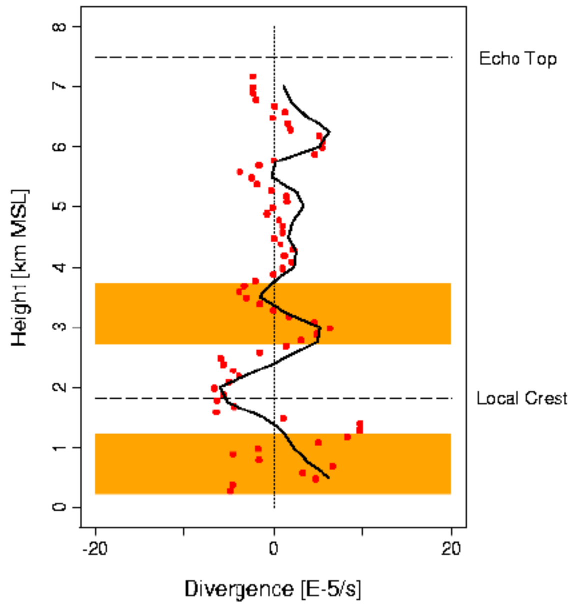

Figure 5. Profile of horizontal divergence based on airborne and ground-based Doppler radar analyses at about 0950 UTC on 21 October 1999. The DOW analysis (shown by the dots) is based on using the extended VAD technique developed by Matejka and Srivastava (1991). The airborne P-3 dual-Doppler analysis (solid line) is detailed in Smull et al. (2000).

The flow within a valley may initially be up the valley when rain starts (Figs. 6b and 6d). The time delay of flow reversal after the onset of rain depends on the precipitation intensity, the degree of subsaturation below cloud base, and the strength of the ambient up-valley pressure gradient. However, the effect of cooling-induced subsidence may not be strong enough to result in a reversal of an up-valley flow into a down-valley flow under strong dynamic forcing conditions, unless the synoptic-scale pressure gradient along the valley axis weakens with time. Moreover, atmospheric instability may provide for enough vertical overturning of air to prohibit development of flow within the valley to be disconnected from the flow above the valley confines. An example for that is IOP 2b (not shown).

In IOP 8, the air motion within the valley reversed from up-valley to down-valley flow after a few hours of rain (notably *before* the upslope wind direction changed markedly) and eventually began to switch back after the rainfall turned off (Figs. 6b and 6d). The few hours of weak rainfall in the early morning hours of 22 October 1999 appear to have caused some additional flow down the valley.

Combined, these observation strongly indicate that moist processes play a key role in driving the down-valley flow.

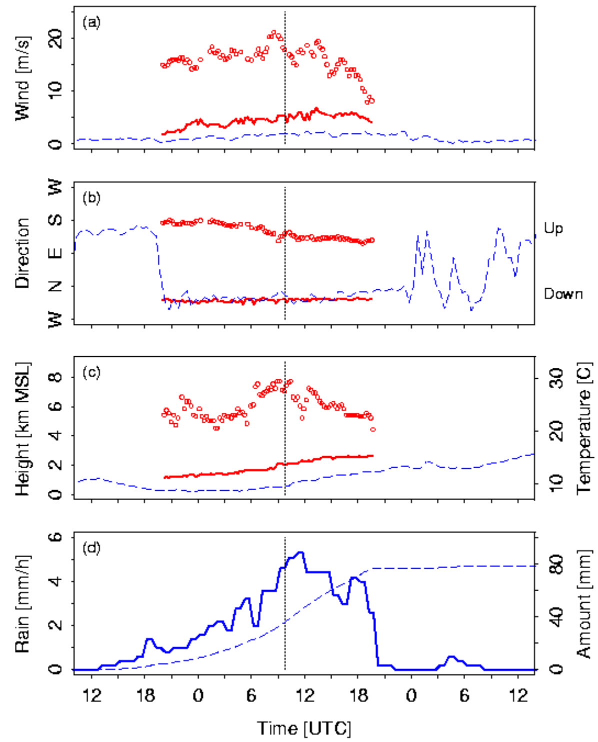

Figure 6. Time series of wind speed (a) and direction (b), precipitation echo structure and surface temperature (c), and surface rainfall traces (d) for the major rainfall event of 20-22 October 1999 (IOP 8). Shown are the wind speed and direction above the crest line (circles) and within the valley confines (bold line) as seen by the DOW radar (see Fig. 4 for corresponding altitude ranges), together with the surface wind observations (dashed lines). The precipitation echo top (circles) and bright band (bold line) height are based on radar observations. The surface temperature is indicated by the dashed line (right axis). The vertical dotted line at 0950 UTC on 21 October 1999 indicates the time of vertical profiles shown in Figs. 4 and 5.

3. CONCLUSIONS

Precipitation can strongly modify the airflow within valleys. Sustained orographic precipitation will be accompanied by subsiding air, cooled by melting and evaporation of precipitation particles, that gets concentrated in valleys and may result in a down-valley flow. Such a precipitation-driven drainage flow can reach a maximum depth limited primarily by the height of the melting layer (or cloud base) and secondarily by the valley confines

(Steiner et al. 2002). The drainage flow strength and depth are related to the rainfall amount. A wet drainage flow can develop when the lowest boundary layer air is blocked and only air from layers above that may rise over the topographic barrier. Under these circumstances, the flow of air within the valley appears to be disconnected from the larger-scale upslope flow.

In contrast, during conditions of atmospheric instability the boundary layer air may not be blocked and able to rise over the barrier (Medina and Houze 2002). In addition, vertical overturning of air prohibits the development of flow within a valley to be disconnected from the flow above the valley confines. In this situation the flow of air is going up the valley in concert with the approaching moist air directed up the slope of the terrain. Precipitation may still generally be widespread but also contain embedded convective cells that are triggered by the passage of the low-level flow over topographic features in the lower reaches of the Alpine terrain (Medina and Houze 2002).

There is a need to further elaborate on the concept of wet drainage flow to better understand and quantify the physical processes involved, and to gage under what conditions this may occur by means of data analysis and numerical simulation experiments. Moreover, we need to evaluate a potential feedback of wet drainage flows to orographic precipitation formation and assess the relevance of this phenomenon to dynamic and microphysical processes ranging from the local (valley) scale to the topographic barrier and larger scales.

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REFERENCES

Bougeault, P., P. Binder, A. Buzzi, R. Dirks, R. Houze, J. Kuettner, R. B. 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 orographic blocking during MAP IOP 8. *Quart. J. Roy. Meteor. Soc*., (submitted).

Jorgensen, D. P., T. Matejka, and J. D. DuGranrut, 1996: Multi-beam techniques for deriving wind fields from airborne Doppler radars. *Meteor. Atmos. Phys*., **59**, 83-104.

Leary, C. A., and R. A. Houze Jr., 1979: Melting and evaporation of hydrometeors in precipitation from the anvil clouds of deep tropical convection. *J. Atmos. Sci*., 36, 669-679.

Matejka, T. J., and R. C. Srivastava, 1991: An improved version of the extended velocity-azimuth display analysis of single-Doppler radar data. *J. Atmos. Oceanic Technol*., **8**, 453-466.

Medina, S., and R. A. Houze Jr., 2002: Air motions and precipitation growth in Alpine storms. *Quart. J. Roy. Meteor. Soc*., (submitted).

Orgill, M. M., J. D. Kincheloe, and R. A. Sutherland, 1992: Mesoscale influences on nocturnal valley drainage winds in western Colorado valleys. *J. Appl. Meteor*., **31**, 121-141.

Smull, B., O. Bousquet, and M. Steiner, 2000: Contrasting stratification and mesoscale airflow in two heavy precipitation events observed during MAP. *Preprints, 9th Conference on Mountain Meteorology*, Aspen, Colorado, Amer. Meteor. Soc., 15-18.

Steiner, M., J. A. Smith, B. F. Smull, and R. A. Houze Jr., 2000: Airflow within major river valleys on the south side of the Alps as observed during the MAP Special Observing Period. *Preprints, 9th Conference on Mountain Meteorology*, Aspen, Colorado, Amer. Meteor. Soc., 11-14.

Steiner, M., O. Bousquet, R. A. Houze Jr., B. F. Smull, and M. Mancini, 2002: Airflow within major Alpine river valleys under heavy rainfall. Quart. J. Roy. Meteor. Soc., (submitted).

Wurman, J., J. Straka, E. Rasmussen, M. Randall, and A. Zahrai, 1997: Design and deployment of a portable, pencil-beam, pulsed, 3-cm Doppler radar. *J. Atmos. Oceanic Technol*., **14**, 1502-1512.