LESSONS ON OROGRAPHIC PRECIPITATION FROM MAP

Richard Rotunno [1], Robert A. Houze [2]

[1] National Center for Atmospheric Research, P. O. Box 3000, Boulder, CO, 80307-3000, USA
[2] Atmospheric Sciences, University of Washington, Box 351640, Seattle, WA, 98195-1640, USA
E-mail: *rotunno@ucar.edu*

Abstract: Although moisture-laden airflow towards a mountain is a necessary ingredient, the results from MAP taught us that detailed knowledge of the orographically modified flow is crucial for predicting the intensity, location and duration of orographic precipitation. Understanding the orographically modified flow as it occurs in the Alps was difficult since it depends on the static stability of the flow, which is heavily influenced by the complex effects of latent heating, and the mountain shape, which has important and complicated variations on scales ranging from a few to 100's of kilometers. Central themes in all the wet-MAP studies are the ways the complex Alpine orography influenced the moist, stratified airflow to produce the observed precipitation patterns, by determining the location and rate of upward air motion and triggering fine-scale motions and microphysical processes that locally enhance the growth and fallout of precipitation. In this presentation will review the major findings from the MAP observations, along with related theoretical developments

Keywords *– MAP, Precipitation, Orography, Rain, Clouds, Ice*

1. INTRODUCTION

This summary of lessons learned from MAP regarding orographic precipitation was the result of our polling the wet-MAP community and condensing the information collected into numbered lists. The lessons were divided into four categories: pre-SOP (Special Observation Period, Fall 1999), SOP (QJRMS Special MAP Issue), SOP (other publications) and post-SOP work.

2. LESSONS ON OROGRAPHIC PRECIPITATION FROM MAP

2.1. Pre-SOP

1) Doswell et al. (1998), Buzzi and Foschini (2000), Lin et al. (2001) summarize "ingredients" for heavy orographic precipitation in the Western Mediterranean. For example, heavy rain events associated with slowly eastward -moving, north-south-elongated troughs (Massacand et al. 1998) imply moist, southerly (Alps-directed) airflow. N.B. in any particular case not all "ingredients" are required, as illustrated by the following two items.
2) Conditional instability of air rising over the Alps was a critical ingredient for the Vaison-La-Romaine flood (Senesi et al. 1996).
3) However for the 1994 Piedmont flood, the thermodynamic stability was close to moist neutral (Doswell et al. 1998).
4) Simulations demonstrate the critical importance of latent heating for flow over (rather than around) the Alps (Buzzi et al. 1998; Ferretti et al. 2000).
5) The shape of the Alps has been suggested as contributor to enhance rain in "concavities" such as the LMTA (Schneidereit and Schar 2000)
6) Along-Alps gradient of moist stability has been suggested as possible contributor to low-level horizontal convergence (Schneidereit and Schär 2000; Rotunno and Ferretti 2001).
7) MAP triggered the development and implementation of a novel radar data processing for the estimation of the wind profile above the radar station (Germann 1999, Tabary et al. 2000). The radar

wind profile proved to be very useful in nowcasting the onset and let-up of heavy rainfall both in the northern and southern Alps (personal communication from forecasters of Zurich and Locarno).

2.2. SOP (*QJRMS* special MAP issue 2003)

1) In spite of the fact that both IOP2b and IOP8 had a slowly eastward -moving, north-south-elongated trough, the presence of a low-level stable layer in the Po Valley during IOP8 produced a very different rainfall pattern(Medina and Houze, Rotunno and Ferretti).
2) The stable layer in the Po Valley during IOP8 had the effect of triggering convection upstream (over the Gulf of Genoa) and allowing only relatively weak stratiform precipitation over the LMTA (Bousquet and Smull , Medina and Houze, Rotunno and Ferretti).
3) The stable layer in the Po Valley during IOP8 also seemed to be related to the DOW-observed down-valley flow in the Toce Valley which was unexpected (the large-scale flow was up-valley/upslope). (Bousquet and Smull (a) , Steiner et al.).
4) In a case of heavy rain in the LTMA (IOP2b) convergence of the synoptic-scale southerly flow with orographically induced easterly flow in the Po Valley was identified as a key ingredient in producing the location and intensity of rainfall (Asencio et al., Georgis et al., Rotunno and Ferretti).
5) The moist southerly air stream over the Alps can lose a large portion of its moisture in traversing the Alps. The scale dependence of the precipitation had a complex dependence on horizontal topographic scales (some features were locked to the terrain, while others formed upstream and then drifted toward the terrain), which was not easily explainable in terms of simple model (Smith et al.) Latent heat addition associated with upwind precipitation during IOP2 tuned the atmosphere for a nonlinear resonance that leads to strong descent in the lee and reinforcement of the lee waves (Doyle and Smith).
6) Embedded small-scale vertical motion cells played an important role in the heavy rain events. The small-scale updrafts enhanced growth by coalescence and riming thus hastening the fallout of precipitation particles (reduction of the time scale of the precipitation fallout). The more rapid growth and fallout of precipitation caused the rain to fall farther upstream and over the lower windward slopes as opposed to the crest of the mountain barrier. (Medina and Houze, Yuter and Houze).
7) The hydrology of the LMTA is difficult because of the problems associated with making radar and rain gauge measurements in the rugged terrain. This difficulty complicates model verification. Limited hydrological studies in MAP indicate that intensive rain gauge networks can estimate runoff. Such networks are not practical operationally. Radar techniques show promise. The uncertainty in radar measurement was estimated and the sources of uncertainty identified. Drop-size distribution variations are not a significant source of error in radar rain estimation; efforts to improve radar measurements need to focus instead on calibration biases and corrections for blocking by mountains, which requires technique for extrapolation of observations made aloft to the ground (Hagen and Yuter, Ranzi et al.)

2.3. SOP (other publications)

1) The strength of the low-level flow, in combination with the static stability, correlates with rainfall in LMTA (Houze, James and Medina, 2001).
2) Ekman-layer turning is a non-negligible contributor to the low-level easterly flow in the Po Valley during IOP2b (Chiao et al. 2004).
3) Complex effects on convection of the Alps-modified frontal flow were seen in Friuli during IOP5 (Pradier et al. 2002; Ivancan-Picek et al 2003)
4) Storms in which the strong cross barrier flow in an upper layer is separated by strong shear from a slower moving lower layer of air manifest cellular overturning in the shear layer, likely (at least in part) as a turbulent response to the shear. The cells associated with the shear layer accelerate the growth of particles by riming and coalescence, thus reducing the time scales of growth and fallout of precipitation over the windward slope of the mountain barrier. This turbulent mechanism suggests that cellular overturning can accelerate the microphysical growth even in the absence of thermodynamics instability (Houze and Medina 2004).
5) Further investigation of both freely ascending up-valley (IOP2b) and subsiding down-valley (IOP8) flow [Bousquet and Smull (b)].

6) The occurrence of (embedded) convection can greatly affect the predictability of precipitation amounts (Walser et al. 2004; Walser and Schär 2004). However, in some cases convection appears rather predictable and thus determined by the larger-scale flow.
7) Stimulated by the MAP community, large efforts were made to improve quantitative precipitation estimates from radar. The main challenge was to further reduce the amount of residual ground clutter (Germann and Joss 2004) and the correction for blocking by mountains (Vignal et al. 2000, Germann and Joss 2002). An objective large-scale verification reveals a significant reduction of the bias, the scatter and the rate of false alarms (Germann et al 2004).

2.3. Post-SOP

Given the importance of orographic flow modification a number of studies have appeared (or are in progress) that address various idealizations of the ambient flow, moist stability, Alpine topography, and the role of "secondary" upstream topography, especially the Appenines, in determining the flow impinging on the Alps. (Chen and Lin, 2004, 2005; Gheusi and Stein 2003; Gheusi and Davies 2004; Jiang, 2003; Lin et al. 2005; Migletta and Buzzi 2001,2004; Miglietta and Rotunno, 2005; Rakovec et al. 2004; Stein 2004; Vrhovec et al. 2004a,b). MAP findings motivated R. Smith and collaborators to develop and apply linear models of orographic precipitation to the Alps and other mountains ranges (Jiang and Smith 2003; Smith 2003; Smith and Barstad 2004; Smith et al. 2004; Barstad and Smith 2005; Smith 2005). The close relation between low-level flow, static stability and rainfall in LMTA found in MAP motivated MeteoSwiss to begin development of a novel application for nowcasting heavy precipitation in southern Switzerland.

REFERENCES

Asencio, N., J. Stein, M. Chong and F. Gheusi, 2003: Analysis and simulation of local post-SOP:and regional conditions for the rainfall over the Lago Maggiore Target Area during MAPIOP2b, *Q. J. R. Meteorol. Soc.,* **129**, 565-586.

Barstad, I. and R.B. Smith, 2005, Evaluation of an orographic precipitation model. *Journal of Hydrometeorology*, to appear.

Bousquet, O. and B. Smull, 2003a: Observations and impacts of upstream blocking during a widespread orographic precipitation event. *Q. J. R. Meteorol. Soc*., **129**, 391-410.

Bousquet, O., and B. Smull, 2003b: Airflow and precipitation fields within deep Alpine valleys observed by airborne Doppler radars. *J. Appl. Meteorol*., **42**, 1497-1513.

Buzzi, A., N. Tartaglione, and P. Malguzzi, 1998: Numerical simulations of the 1994 Piedmont flood: Role of orography and moist processes. *Mon. Wea. Rev*., **126**, 2369-2383.

Buzzi, A., and L. Foschini, 2000: Mesoscale meteorological features associated with heavy precipitation in Southern Alpine Region. *Meteorol. Atmos. Phys.,* **72**, 131-146.

Chen, S.-H. and Y.-L. Lin, 2004 Orographic effects on a conditionally unstable flow over an idealized three-dimensional mountain. *Meteorol. Atmos. Phys*. , to appear.

Chen, S.-H. and Y.-L. Lin, 2005: Effects of moist Froude number and CAPE on a conditionally unstable flow over a mesoscale mountain ridge. *J. Atmos. Sci*., to appear.

Chiao, S., Y.-L. Lin, and M. L. Kaplan, 2004: Numerical study of orographic forcing of heavy Orographic precipitation during MAP-IOP-2B. *Mon. Wea. Rev*., **132**, 2184-2203.

Doswell, C.A. III, C. Ramis, R. Romero, and S. Alonso, 1998:A diagnostic study of three heavy precipitation episodes in the western Mediterranean. *Wea. Forecasting*, **13**, 102-124.

Doyle, J. and R.B.Smith, 2003: Periodic gravity waves over the Hohe Tauern, *Q. J. R. Meteorol. Soc*., **128** (588), 799-823.

Ferretti, R., S. Low-Nam, and R. Rotunno, 2000: Numerical simulations of the 1994 Piedmont flood of 4-6 November. *Tellus,* **52A**, 162-180.

Germann, U. and J. Joss, 2002: Mesobeta Profiles to Extrapolate Radar Precipitation Measurements above the Alps to the Ground Level. *J. Appl. Meteorol.,* **41**, 542-557.

Germann, U. and J. Joss, 2004: Operational measurement of precipitation in mountainous terrain. In P. Meischner, editor, *Weather Radar: Principles and Advanced Applications,* **vol XVII** of *Physics of Earth and Space Environment*, chap. 2, 52-77, Springer Verlag.

Germann, U., G. Galli, M. Boscacci, M. Bolliger, and M. Gabella, 2004: Quantitative precipitation estimation in the Alps: where do we stand? *Proc. European Radar Conference*, Visby, Sweden, 2-6.

Germann, U., 1999: Vertical wind profile by Doppler radars. *MAP Newsletter,* **11**, 6-7. Available from MeteoSwiss, Kraehbuehlstrasse 58, CH-8044 Zuerich.

Georgis, J.-F., F. Roux, M. Chong, and S. Pradier, 2003: Triple-Doppler radar analysis of the heavy rain event observed in the Lago Maggiore region during MAP IOP2b.*Q. J. R. Meteorol. Soc*. **129**, 495-522.

Gheusi, F. and J. Stein, 2003: Small-scale rainfall mechanisms for an idealized convective southerly flow over the Alps. *Q. J. R. Meteorol. Soc*. **129**, 1819-1839.

Gheusi, F. and Davies, 2004: Autumnal precipitation distribution on the southern flank of the Alps: A numerical-model study of the mechanisms. *Q. J. R. Meteorol. Soc*., **130**, 2125-2152.

Hagen, M., and S. E. Yuter, 2003: Relations between radar reflectivity, liquid water content, and rainfall rate during the MAP-SOP. *Q. J. R. Meteor. Soc.*, **129**, 477-493.

Houze, R. A., Jr., and S. Medina, 2004: Turbulence as a mechanism for orographic precipitation enhancement. *J. Atmos. Sci.,* to appear.

Houze, R. A., C.N. James, and S. Medina, 2001: Radar observations of precipitation and airflow on the Mediterranean side of the Alps: Autumn 1998 and 1999. *Q. J. R. Meteorol. Soc*., **127**, 2537-2558.

Ivančan-Picek, D. Glasnović and V. Jurčec, 2003: Analysis and Aladin prediction of a heavy precipitation event on the eastern side of the Alps during MAP IOP5. *Meteorol. Z*., **12**,103-112.

Jiang, Q., 2003: Moist dynamics and orographic precipitation. *Tellus A*, **55**, 301-316.

Jiang, Q., and R. B. Smith, 2003: Cloud timescales and orographic precipitation. *J. Atmos. Sci.*, **60**, 1543–1559.

Lin, Y.-L., S. Chiao, T.-A.Wang, and M. L. Kaplan, 2001: Some common ingredients for heavy orographic rainfall. *Wea. Forecasting*, **16**, 633-660.

Lin, Y.-L., H. D. Reeves, S.-Y. Chen, and S. Chiao, 2005: Synoptic and mesoscale environments and the formation of convection over the Ligurian Sea during IOP8. *Mon. Wea. Rev*., to appear.

Medina, S., and R. A. Jr. Houze, 2003: Air motions and precipitation growth in Alpine storms. *Q. J. R. Meteorol. Soc.,* **129**, 345-372.

Miglietta, M. M., and A. Buzzi, 2001: A numerical study of moist stratified flows over isolated topography. *Tellus*, **53A**, 481-499.

Miglietta, M. M., and A. Buzzi, 2004: A numerical study of moist stratified flow regimes over isolated topography. *Q. J. R. Meteorol. Soc.*., **130**, 1749-1770.

Miglietta, M.M., and R. Rotunno, 2005: Numerical simulations of moist nearly neutral flow. *J. Atmos. Sci.*, to appear.

Pradier, S., M. Chong, and F. Roux, 2002: Radar observations and numerical modeling of a precipitating line during MAP IOP5. *Mon. Wea. Rev*., **130**, 2533-2553.

Rakovec J., Gaberšek S., Vrhovec T., 2004: Relief shapes and precipitation at the south side of the Alps - Relief characteristics and dry sensitivity simulations, *Meteorol. Z* , **13**, 83-90.

Ranzi R., B. Bacchi, G. Grossi, 2003: Runoff measurements and hydrological modelling for the estimation of rainfall volumes in an Alpine basin *Q. J. R. Meteorol. Soc.*, **129**, 653-672.

Rotunno, R., and R. Ferretti, 2001: Mechanisms of intense alpine rainfall. *J. Atmos. Sci.*, **58**, 1732-1749.

Rotunno, R., and R. Ferretti, 2003: Orographic effects on rainfall in MAP cases IOP2b and IOP 8. *Q. J. R. Meteorol. Soc.* , **129**, 373-390.

Schneidereit, M. and C. Schär, 2000: Idealised numerical experiments of alpine flow regimes and south side precipitation events. *Meteor. and Atmos. Phys*., **72**, 233-250.

Smith, R.B., 2003: A linear time-delay model of orographic precipitation. *J. of Hydrology,* **282**, 2-9.

Smith, R. B., Q. Jiang, M.G. Fearon, P. Tabary, M. Dorninger, J. D. Doyle, and R. Benoit, 2003:Orographic precipitation and air mass transformation: An Alpine example. *Q. J. R. Meteotol. Soc*., **129**, 433-454.

Smith, R. B., and I. Barstad, 2004: A Linear Theory of Orographic Precipitation. *J. Atmos. Sci.,* **61**, 1377–1391.

Smith, R.B., L. Bonneau, and I. Barstad, 2004: Orographic precipitation and Oregon's climate transition. *J. Atmos. Sci*., to appear.

Smith, R.B., 2005: Progress on the theory of orographic precipitation, Chapter in *GSA Special Paper, Tectonics, Climate and Landscape Evolution*, to appear.

Stein, J., 2004: Exploration of some convective regimes over Alpine orography. *Q. J. R. Meteorol. Soc.,* **130**, 481-502.

Steiner, M., O. Bousquet, R. A. Houze Jr., B. F. Smull, and M. Mancini, 2003: Airflow within major Alpine river valleys under heavy rainfall. *Q. J. R. Meteorol. Soc*. **129**, 411-432.

Tabary, P., G. Scialom, and U. Germann, 2000: Real-time Retrieval of the Wind from Aliased Velocities Measured by Doppler Radars. *J. Atmos. Oceanic. Technol.,* **18**, 875-882.

Vignal, B., G. Galli, J. Joss, and U. Germann, 2000: Three Methods to Determine Profiles of Reflectivity from Volumetric Radar Data to Correct Precipitation Estimates. *J. Appl. Meteorol.,* **39**, 1715-1726.

Vrhovec, T., G. Gregorič, J. Rakovec, and M. Žagar, 2001: Observed versus forecasted precipitation in the South-east Alps. *Meteorol. Z.*, **10**, 17-27

Vrhovec, T., J. Rakovec, G. Gregorič, 2004a: Mesoscale diagnostics of prefrontal and frontal precipitation in the Southeast Alps during MAP IOP 5. *Meteorol. Atmos. Phys*., **86**, 15 – 30.

Vrhovec, T., J. Rakovec, S. Gaberšek, G. Skok, R. Žabkar and G. Gregorič, 2004b: Relief shapes and precipitation on the south side of the Alps – Part II: Heavy-rain cases during MAP and sensitivity to topography modifications. *Meteorol. Z.* , **13**, 1-8 .

Walser, A., D. Lüthi and C. Schär, 2004: Predictability of Precipitation in a Cloud-Resolving Model. *Mon. Wea. Rev.*, **132** (2), 560-577

Walser, A., and C. Schär, 2004: Convection-resolving Precipitation Forecasting and its Predictability in Alpine River Catchments. *J. Hydrol*, **288**, 57-73