

Orographic Control of Precipitation: What are We Learning from MAP?

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The first four words of the title of this article match the title of Section 4 of Ron Smith's (1979) review, "The Influence of Mountains on the Atmosphere". Via a comprehensive survey of the literature available 25 years ago, Smith identified the key ways in which mountains potentially can affect precipitation. Little has changed regarding his conclusions. However, little factual information was then available to confirm, refute, or assess quantitatively the relative importance of different potential orographic influences on precipitation.

MAP was designed to answer some of the most basic questions posed by Smith's (1979) review. These answers will come slowly, as it takes years to reach a point of diminishing returns in analyzing data collected in a field project as large and comprehensive as MAP. LeMone (1983) found that this peak of productivity comes about six years after a large field project, at least in descriptive studies. More fundamental results inspired by field work tend to come even later. So, we are still at an early stage in the analysis of MAP data. Nonetheless, some of the more exciting avenues to results are becoming apparent. In this short article, I hope to point out some of the areas in which we are beginning to see progress.

MAP does not address all the orographic precipitation processes reviewed by Smith (1979). Most notably, MAP does not address deep intense cumulonimbus convection triggered by flow over terrain. One MAP case of this type occurred (IOP 2a), but it was not intensively observed other than by ground-based radar¹. Though interesting in its own right, this single case cannot be a basis for generalization. MAP also cannot deal extensively with terrain-frontal interaction as an influence on precipitation enhancement. This restriction arises because the Wet MAP intensive observations, by ground-based and airborne radars, were almost exclusively made on the Mediterranean side of the Alps in regions shielded from advancing fronts by the broadly curved Alpine range, while precipitation enhancement by fronts encountering the mountain barrier occurred primarily on the continental side of the Alps. Several fronts eventually passed over the Alps during Wet

MAP (most spectacularly in IOP 15²). However, on the Mediterranean side of the range, these events were primarily the switches that turned off the heavy precipitation.

A particularly instructive group of events for answering Smith's (1979) open questions about orographic precipitation are IOP 2b, 3, 5, and 8—with the first three, which are rather similar, taken as a group and compared with IOP 8 (quick-look summaries of these cases are on the world wide web³). These four IOPs fall into the category of major rain events owing to broad-scale ascent of moist flow over a high mountain barrier. Within this category lie some of the most fundamental questions raised by Smith's (1979) review.

The broad-scale flow in all four cases occurred ahead of a major baroclinic trough with its low-level frontal structure remaining on the continental side of the Alps. In each case, strong persistent low-level moist flow from the Mediterranean Sea impinged on the Alpine barrier in the mountainous backdrop of the Lago Maggiore region—the location of the Wet MAP ground-based radar array. IOP 8 was colder and more stable than IOP 2b, 3, and 5 (e.g., Houze et al. 2000). In IOP 8 the boundary layer flow had an easterly to northeasterly component, i. e. parallel and away from the mountains. This was different from IOP 2b, 3, and 5, which had boundary-layer flow toward the barrier.

In IOP 8, the precipitation over the Lago Maggiore region was almost entirely stratiform (for an example of the radar echo, see Figs. 17-24 on the IOP summary on the web⁴). Rainfall accumulations in the foothills and mountains surrounding the Lago Maggiore region were ~0-90 mm⁵. The radar echoes seen by all the ground-based and airborne radars in the Lago Maggiore region exhibited a distinct bright band and no embedded cellular structure. In individual river valleys the wind flow was strongly down-slope, feeding cold air into the broad valley of the Lago Maggiore and out over the Po Valley. The down-valley flow was evi-

¹http://www.atmos.washington.edu/gcg/MG/MAP/summ/02/IOP_2A.991104.POC_sci_sumUW6A.html

²http://www.atmos.washington.edu/gcg/MG/MAP/summ/15/IOP_15.991106.POC_sci_sum.html

³http://www.atmos.washington.edu/gcg/MG/MAP/iop_summ.html

⁴http://www.atmos.washington.edu/gcg/MG/MAP/summ/08/IOP_08.991021.POC_sci_sum.html

⁵<http://www.atmos.washington.edu/~soco/ro/research/pcp8n.gif>

dent in data from both the Doppler on Wheels (DOW) and the P3 airborne Doppler radar (Steiner et al. 2000, Smull et al. 2000). This outpouring of air from the river valleys was evidently at least in part a manifestation of blocking of the broad-scale flow. The stable air was dammed up against the greater Alpine barrier and sought a return path down the deep valley gorges. Inside the individual river valleys, the down-valley flow may have been accelerated by the cooling effects of melting and evaporation of precipitation. The cold air running out of the valleys and out over the upwind plain effectively moved the forced lifting effect of the mountains upstream, as has been seen in other mountain ranges (e. g. the Western Ghats, Grossman and Durran 1984). The P3 aircraft data in IOP 8 also suggested a maximum of rainfall over the central Po Valley upstream of the mountains, evidently where the moist current at low levels met the cold blocked flow coming out of the mountains (B. Smull, personal communication). Evidently boundary-layer moisture was condensed upstream of the main Alpine barrier as it was lifted over this cold blocked air in the boundary layer. Farther upstream, over the Ligurian Sea, the P3 aircraft radar detected precipitation of a convective nature. Buoyant instability was evidently spent there and near the boundary of the outflowing blocked air so that by the time the Mediterranean air arrived in the Lago Maggiore region it had already risen over the blocked flow in the boundary layer and had lost all its instability, with the result of highly stratiform precipitation occurring in the Lago Maggiore region. Blocking by the Alpine barrier evidently did not just occur in this particular rainstorm. Seasonal composite reflectivity data for 1998 and 1999 stratified by Froude number show that blocking conditions on average move the maximum of precipitation upstream of the mountain range (James et al. 2001).

IOP 2b, 3, and 5 exhibited cellularity embedded in the widespread precipitation associated with the upslope flow. Cellularity refers to small to moderate convective cells embedded in the broad-scale precipitation layer over the windward slopes. As pointed out by Smith (1979) the convective dynamics producing cellularity can make the precipitation process quicker and more efficient in broad-scale upslope flow. A deeper layer of moisture can be tapped if the cells are deep enough. Probably more importantly the cells produce pockets of increased cloud liquid water content, which the growing precipitation particles can collect. Thus, more water is in the form of rapidly falling graupel and rain that quickly reaches the surface of the terrain.

In IOP2b, the rain amounts reached ~90-270 millimeters (~10+ inches!) at various stations in the foothills and mountains surrounding the Lago Maggiore region⁶. The storm bore some similarity to the Piedmont flood of 1994

(Buzzi et al. 1998, Ferretti et al. 2000), and it affected the whole Alpine barrier. Most of the upstream water vapor evidently condensed and fell out over the slopes. IOP 3 and 5 had upslope flow of a similar character to that in IOP 2b although it was more localized to the Lago Maggiore region. Local heavy rain was so severe in mountains on the north-east side of the Lago Maggiore region during IOP 5 that it caused one fatality.

Radar echoes in IOP 2b, 3, and 5 exhibited distinctly cellular structure, with maximum reflectivity at low altitudes, especially over peaks and ridges of the terrain in the lower windward regions of the Alpine barrier. The air impinging on the Alps from the southeast from the surface up through ~800 mb was warmer, more moist, and less stable than in IOP 8. With the lower stability in IOP 2b the moisture-laden air approaching the Alpine barrier was not substantially blocked but rather rose easily over the terrain. The moisture in the boundary layer was all condensed over the windward slopes (as opposed to being blocked and turned away from the barrier, as in IOP 8), and instability was released.

The MAP radar data further indicate microphysical aspects of the cellularity in the heavy rainfall cases. The dual-polarization S-Pol radar in the Lago Maggiore region showed that in the heavy precipitation cells rimed particles (graupel and small hail) occurred near and just above the melting layer in IOP 2b, 3, and 5⁷. These microphysical observations suggest that the small embedded convective cells released as the slightly unstable broad-scale upstream flow rises over the lower peaks and ridges of the Alpine barrier produce substantial amounts of supercooled water, which rimes onto ice particles, thus forming graupel and/or small hail. Since graupel and hail have higher fall velocity than snow, the moisture condensed in the small cells quickly reaches the mountain sides. Smith's (1979) review of studies done in the 1970's and earlier suggests that ice microphysics might increase the efficiency of orographic precipitation; however, that idea probably arose more from Bergeron's (1950, 1968) seeder-feeder concept than from consideration of the efficacy of riming in orographically triggered convective cells.

So, what are we learning from MAP to answer the outstanding questions identified by Smith (1979)? I think we are confirming that:

- The degree to which blocking occurs can have a major impact on the amount of rain on windward slopes. It

⁶<http://www.atmos.washington.edu/~socorro/research/pcp2n.gif>

⁷http://www.atmos.washington.edu/gcg/MG/MAP/iop_summ.html

can greatly reduce the potential of flooding on the windward slopes, as much of the rain is moved upwind over the plains.

- Slight instability of the flow impinging on the mountain barrier can dramatically increase the precipitation on the windward slopes by producing pockets of concentrated cloud liquid water, extending above the 0 deg level. The collection of this cloud water by precipitation particles, such as ice particles just above the melting level and coalescence of drops at below the melting level, produces heavier particles that fallout out more quickly. These processes may greatly increase the potential of flooding on the windward slopes.

Analysis of the MAP data over the next few years will allow us to quantify these effects. The goal should be to quantify them in such a way that they can serve as constraints for testing of fine-scale numerical models, which ultimately will be the basis of forecasting heavy rain over the Alps and other mountain ranges. The models now seem capable of producing aspects of the flow conditions in heavy rain situations. For example, Rotunno and Ferretti (2001) have simulated IOP 2b and 8 with the MM5⁸. These simulations have not yet addressed detailed understanding of the interaction of the broad-scale flow, the convective cellularity, and the microphysics of the convective cells. Theoretical modeling studies are underway to understand better the convective cell formation in relation to the prevailing large-scale flow (Durran, personal communication). Several groups will undoubtedly be examining the microphysical parameterizations.

Smith (1979) presented an ultra-simple orographic precipitation model in which the amount of moisture condensed is controlled by the surface absolute humidity and the water condensed in upslope flow (for the sake of simplicity) falls out immediately. The modeling work of Ferretti et al. (2001) and Rotunno and Ferretti (2001) suggest that the control by surface humidity is strong. The dynamic cellularity and the microphysics of riming and graupel production in MAP heavy rain cases over the Lago Maggiore region suggests that a quick and highly efficient precipitation release occurs there. Perhaps Smith's simple model may work fairly well in this environment. The MAP data will

tell us, one way or the other. But the analysis of the data will further indicate the factors leading to this simple result and provide a basis for understanding how these results may or may not extend to other mountain precipitation regimes.

■ References:

- Bergeron, T., 1950: Über den Mechanismus der ausgiebigen Niederschläge. *Ber. Deut. Wetterd.*, 12, 225-232.
- Bergeron, T., 1968: On the low-level redistribution of atmospheric water caused by orography. *Proceedings, International Cloud Physics Conference, Toronto.*
- 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.
- Ferretti, R., S. Low-Nam, and R. Rotunno, 2000: Numerical simulations of the Piedmont flood of 4-6 November 1994. *Tellus*, 52A, 162-180.
- Grossman, R. L., and D. R. Durran, 1984: Interaction of low-level flow with the western Ghat Mountains and offshore convection in the summer monsoon. *Mon. Wea. Rev.*, 112, 652-672.
- Houze, R., S. Medina, and M. Steiner, 2000: Two cases of Heavy Rain on the Mediterranean side of the Alps in MAP, Ninth Conf. on Mountain. Meteorology, Aspen, publ. by Amer. Meteor. Soc., Boston, pp. 1-5.
- James, C., R. Houze, and S. Medina, 2001: Radar observations of precipitation and airflow on the Mediterranean side of the Alps. Submitted for publication (available from the authors).
- LeMone, M. A., 1983: The time between a field experiment and its published results. *Bull. Amer. Meteor. Soc.*, 64, 614-615.
- Rotunno, R., and R. Ferretti, 2001: Mechanisms of Intense Alpine Rainfall. *J. Atmos. Sci.*, in press.
- Smith, R. B., 1979: The influence of mountains on the atmosphere. *Adv. Geophys.*, 21, 87-230.
- Smull, B., O. Bousquet, and M. Steiner, 2000: Contrasting stratification and mesoscale airflow in two heavy precipitation events observed during MAP, Ninth Conf. on Mountain. Meteorology, Aspen, publ. by Amer. Meteor. Soc., Boston, pp. 15-18.
- Steiner, M., J. Smith, B. Smull, and R. Houze, 2000: Airflow within major river valleys on the south side of the Alps as observed during the MAP Special Observing Period, Ninth Conf. on Mountain. Meteorology, Aspen, publ. by Amer. Meteor. Soc., Boston, pp. 11-14.

⁸<http://www.mmm.ucar.edu/individual/rotunno/rotunno.html>