SPACE-TIME VARIABILITY OF HEAVY OROGRAPHIC RAINFALL

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1. INTRODUCTION

Heavy rainfall is often the result of slow-moving or quasi-stationary storm systems, or storm cells repeatedly tracking over the same area. High rain rates produced by ample moisture supply, combined with a significant residence time, are the recipe for extreme rainfall accumulations (e.g., Doswell et al. 1996; Smith et al. 1996). Topographic barriers often act to generate heavy rainfall and focus it locally. The study of the detailed mechanisms of this orographic forcing, and how it affects the dynamics and microphysics of heavy precipitation-producing storm systems, was the focus of the Mesoscale Alpine Program (MAP), which entailed a Special Observing Period (SOP) on the south side of the European Alps that lasted from September through November 1999 (Bougeault et al. 2001).

Several heavy rainfall events were observed during the MAP SOP. The hydrologic response at the land surface to the intense rainfall was significant, resulting in local flooding and debris flows. The events earlier in the SOP, especially the Intensive Observing Periods (IOPs) 2, 3, and 5 were characterized by moist, potentially unstable air being lifted at the Alpine barrier, triggering convection that resulted in short-term, local rainfall accumulations in excess of 200 mm.

The heavy rainfall event of 19-21 September 1999 (IOP 2b) is used to assess the spatial and temporal variability of rainfall, particularly over the western side of the Lago Maggiore region, and to shed light on the dynamics and microphysics of the rain-generating mechanisms.

2. SYNOPTIC OVERVIEW

The trough that affected northern Italy on 20 September 1999 extended far south into northern Africa, placing the southwesterly jet ahead of the trough directly over the Lago Maggiore region. The flow into this region, as revealed by the dual-Doppler winds computed from the French RONSARD and Swiss Monte Lema radar data, was generally from the south throughout the period of precipitation, but turned cyclonically as it approached the mountains, thereby lifting air almost perpendicularly over the barrier. Rainfall was heavy throughout the region, but the rain accumulation on the windward slopes of the mountains on the western side of the Lago Maggiore region was particularly large.

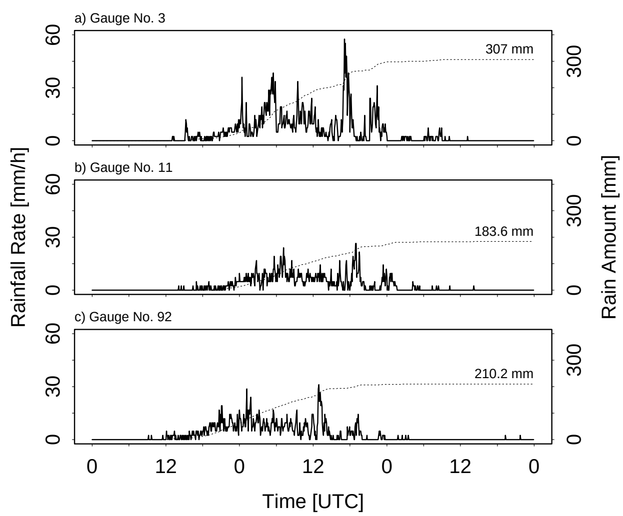

Figure 1. Rainfall rate and accumulation traces recorded during the 19-21 September 1999 heavy rainfall event by three gauges (placed within 2 km) near the outlet of the Anza river valley (see Fig. 2).

3. RAIN GAUGE ANALYSES

The accumulations revealed by the Swiss and Italian rain gauge network data show rainfall in excess of 100 mm (peaking around 300 mm) over the mountain slopes on the western side of the Lago Maggiore, while the Po valley received generally less than 50 mm of rain during that event. This overall rainfall pattern, however, exhibited great variability in space.

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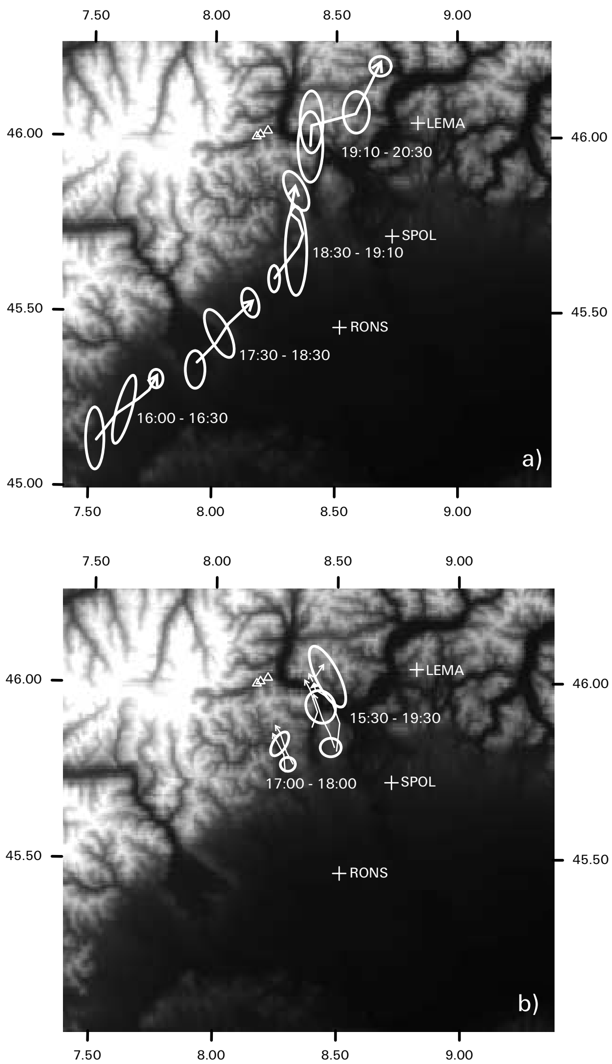

Figure 2. Tracking analyses based on Mt. Lema radar data for storms occurring on 20 September 1999. Shown are examples of two types of tracks: **a)** northeastward, along-barrier propagating cells from 16:00-20:30 UTC and **b)** quasi-stationary cells from 15:30-19:30 UTC. The 3 triangles (Δ) indicate the location of the special gauges (Fig. 1).

Data collected by a special rain gauge network installed in the Anza river valley (a tributary to the Toce river) for the duration of the MAP SOP demonstrate the extreme variability of rainfall on very small time and space scales (Fig. 1). The rain gauges No. 3 and 11, for example, are spaced only 1 km apart, yet the storm total rainfall accumulations differ by approximately 120 mm! Moreover, the rainfall traces recorded by the three gauges exhibit significantly different temporal variability. Gauge siting and exposure to wind etc. may be reasons for significant differences in rainfall accumulations. However, for other heavy rainfall events (e.g., IOP 8), the rainfall totals recorded by these gauges are within 10% or less of each other. We thus believe that this extreme spatial rainfall gradient of approximately 100 mm/km may be real and the result of a particular rainfall pattern to be discussed next.

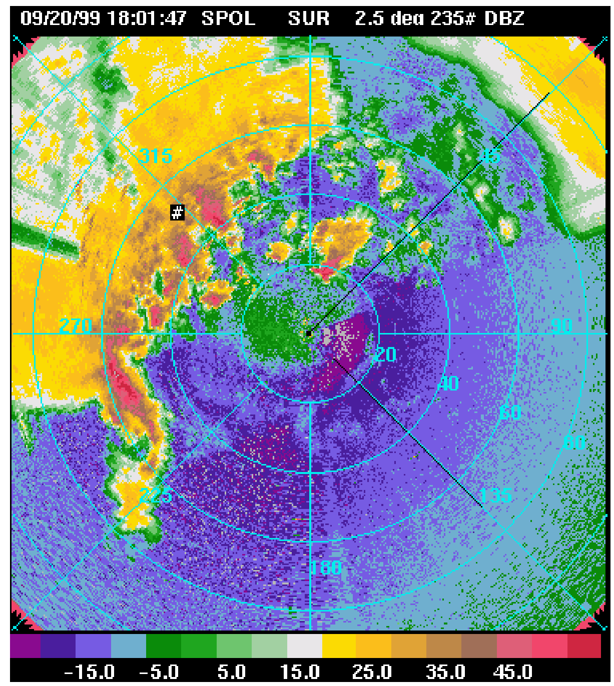

Figure 3. Radar reflectivity observation of the heavy rainfall on 20 September 1999 at 18:00 UTC made the NCAR S-Pol radar located at the southern end of the Lago Maggiore near Vergiate, Italy (see Fig. 2). Range rings are 20 km apart. The # indicates the approximate location of the special gauges.

4. STORM CHARACTERISTICS

Rainfall for the 19-21 September 1999 event over the windward slopes of the mountains on the western side of the Lago Maggiore was composed of mostly broad-scale widespread precipitation with moderate to intense embedded convection (Fig. 3).

The storm cell tracking analyses of Steiner et al. (2000) showed that the most intense pockets of rainfall were either moving rapidly along the Alpine barrier (Fig. 2a) or quasi-stationary (Fig. 2b). New cells forming repeatedly over the foothills of the Alps and intensifying while slowly being lifted onto the barrier caused the quasi-stationary and persistent pattern seen in the northwestern quadrant of the S-Pol radar umbrella (Fig. 3). This process was particularly pronounced in the region of the Toce river feeding into the Lago Maggiore, where the largest point rainfall accumulations were observed (see location of # in Fig. 3).

During the evening hours of 20 September 1999, an intense line of convection moved rapidly along the Alpine barrier (see approaching squall line approximately 60 km to the west of the S-Pol radar in Fig. 3 and storm tracks shown in Fig. 2a). This fast-moving storm behaved dynamically and microphysically different than the quasi-stationary storms: It was more intense, exhibiting stronger updrafts that resulted in the production of heavy rain, graupel, and possibly small hail (Fig. 4). The dynamic and microphysical differences between the fast-moving and quasi-stationary storms were also reflected in storm electrification. The rapidly moving storm was associated with significantly more lightning flashes (recorded by the Alpine lightning detection network), indicating a more active mixed-phase region above the freezing level, where rimed particles (graupel) and low-density ice crystals (dendrites) interacted in an environment of ample moisture.

As the squall line moved rapidly along the Alpine barrier, it merged with the quasi-stationary storms. After the passage of the squall line, however, the quasi-stationary storm pattern didn't reestablish itself again. The squall line, therefore, was likely associated with the passage of the surface cold front, leaving a significantly changed storm environment behind, essentially switching the heavy rainfall off.

5. SUMMARY AND CONCLUSIONS

The heavy rainfall event of 19-21 September 1999 (IOP 2b) falls in the category of major rain events owing to a broad-scale ascent of moist flow over the Alpine barrier ahead of a major baroclinic trough. Heavy rainfall occurred on the Maritime side of the Alps as long as the low-level frontal structure remained on the continental side of the Alps. The frontal passage on the south side of the Alps eventually turned the heavy rainfall off.

Data from a special rain gauge network installed near the Toce river valley demonstrated a significant temporal variability in rainfall intensity and extreme spatial gradients in rain accumulation (100 mm/km). Objective storm cell tracking analyses showed that this heavy rainfall event was composed of embedded storm cells that were either quasi-stationary or fast-moving, with the largest point-rainfall accumulations produced by the former. The analyses of lightning flash data and multiple polarization radar data point towards differences in storm microphysics (thus implicitly also storm dynamics), with the observed fast-moving storm cells generating significantly more lightning flashes as a result of more active mixed-phase processes (supported by stronger updrafts), involving higher-density, rimed ice particles.

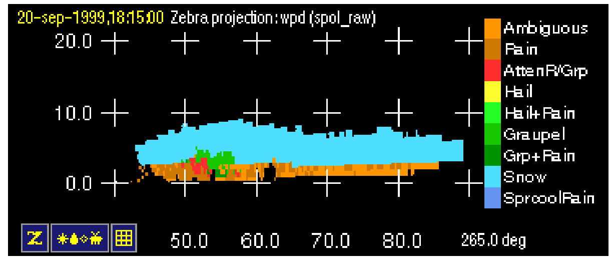

Figure 4. Precipitation particle types identified by the Zeng et al. (2001) algorithm based on a vertical cross section (RHI) scan made by the multiple-polarization S-Pol radar on 20 September 1999 at 18:15 UTC in the direction 265 azimuth.

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