6.6 EFFECTS OF OROGRAPHICALLY-INDUCED LOCAL CIRCULATIONS ON THE FORMATION OF HEAVY RAINFALL

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1. INTRODUCTION

Orographic rainfall over Alpine regions occurs under a variety of conditions. (e.g., Bougeault et al. 2001). The strong influence of the Alps on the flow has been demonstrated in the numerical work of Chen and Lin (2001). They concluded that a relatively large amount of rainfall can be produced over the upwind slope under the presence of an impinging low-level jet (LLJ). In addition, idealized experiments by Rotunno and Ferretti (2001) show that in the 1994 Piedmont heavy rainfall event, the western moist part of the airstream (saturated) flows over the mountains, while the eastern drier branch (unsaturated) is deflected westward around the obstacle. Thus, a convergence of air is produced between the airstreams, and heavy precipitation is produced. The influence of terrain on the flow and precipitation has also been demonstrated in the idealized simulation by Schneidereit and Schär (2000). They conjuncture that the Coriolis effect and a pronounced moist low-level jet provided a suitable environment for heavy condensation and precipitation. In addition, Lin et al. (2002) also found that a vortex was produced near the Lago Maggiore area due to the interaction of the LLJ and the concave geometry of the Alps. It appears that local circulations as well as the rainfall distribution in either the upstream mountains or western flank of the Alps are not clear and deserve further study. This study will focus on IOP-2B by performing fine-scale and idealized topography simulations.

2. EXPERIMENTS DESIGN

Numerical simulations were performed by using the PSU/NCAR MM5 model. Three nested domains were constructed with the grid spacing of 45 km, 15 km, 5 km, and 1.67 km horizontal resolutions, respectively. The corresponding numbers of grid points are 91 × 85, 121 × 121, 121 × 121, and 271 × 271. The model contains 1-km resolution terrain data that are mapped to the grid spacing of 5 km and 1.67 km horizontal resolutions. All the simulations used the same initial and lateral boundary conditions, which are generated from the NCAR/NCEP Reanalysis with $2.5^o \times 2.5^o$ resolution. A total of 46 unequally spaced levels in the vertical with the lowest model level beginning approximately 20 m above ground are used. Forty-eight hour simulations were run from 0000 UTC 19 to 0000 UTC 21 September 1999. Our discussions are based on the results of the 5-km grid domain.

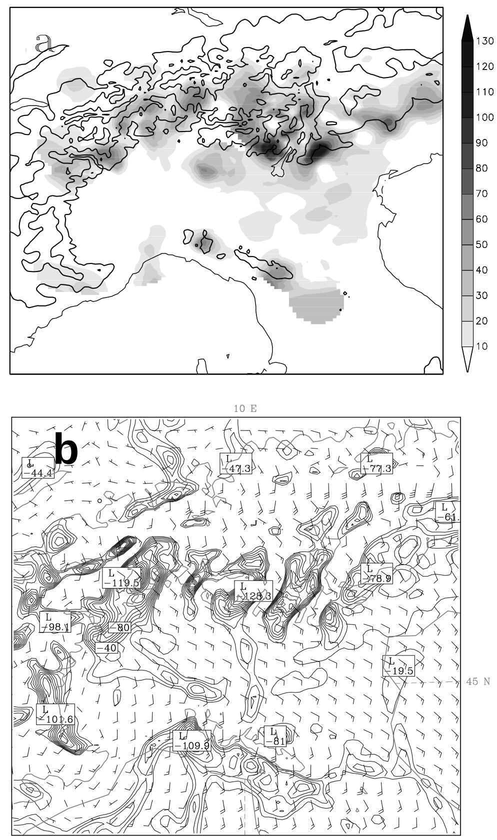

Figure 1: (a) Objectively analyzed 6-h accumulated rainfall ending at 1200 UTC 20 September 1999. (b) Simulated 1000 hPa convergence (contour interval $10{\times}10^{-5}$ s^{-1}) and winds (one full barb = 10 ms^{-1}) from the 5 km resolution domain CTRL case at 1200 UTC 20 September 1999.

3. EVOLUTION OF OROGRAPHICALLY-INDUCED CIRCULATION AND PRECIPITATION

Beginning in the late afternoon of 19 September (local time), light rain initiated along the steep

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southward-facing slopes of the Maritime Alps and the southeastward-facing slopes of Alps in between 45N and 46N, i.e. the concave topography area. By 0000 UTC 20 September, a clear easterly jet had developed along the south side of the Alps, which is often referred to as a barrier jet. This barrier jet was formed by the westward turning of the low-level southeasterly flow. In the afternoon (local time) of 20 September (i.e., 0600 to 1200 UTC 20), the observed analysis showed the precipitation area broadened on the windward slopes of the eastern side of the Alps and moved toward the east along with the trough (Fig. 1a). Light rain was still observed in the Lago Maggiore area at 1800 UTC 20 September. The 5 km resolution simulation started at 0600 UTC 19 September 1999, which was about 12 hours prior to the formation of heavy rainfall over the south side of Alps. By 1200 UTC 20 September, the control simulation (CTRL) results indicated that there were several significant convergence zones along the mountain slopes (Fig. 1b), even though the trough has moved to the east. These convergence zones were consistent with the westward turning of the southerly flow near the south side of the Alps.

Sensitivity experiments on the upstream topography (i.e., Ligurian Apennines Mountains) demonstrated that orographically-induced local circulation is qualitatively similar to the control simulation (not shown). However, a feature worthy of note is that a broad-scale area of rainfall ($\sim$ 20 mm in 6 h) fell on the Po Valley, which was caused by the absence of upstream mountain blocking. Evidence supporting this result was that the precipitation on the windward slopes of the Ligurian Apennines mountains was due to the coastal blocking in the CTRL, which results in the shallow convection along the coastal windward slopes. In addition, this coastal blocking also suggested a rain shadow effect which resulted from downslope wind as the southerly flow developed over the crest of the Ligurian Apennines mountains. The experiment on the western flank of the Alps (NWAP) effects (i.e., concave area) demonstrated that the precipitation distributions appear to be correlated with the slopes of the modified mountains. By 1200 UTC 20 September, a clear cyclonic vortex existed along the left end of the modified mountains, where strong convergence was formed by the westerly and southeasterly flows (Fig. 2a). The 6-h simulated accumulated rainfall ($\sim$ 160 mm) was about 30 mm higher than the control simulation near the Lago Maggiore area from 0600 to 1200 UTC 20 September. This result suggests that the French Alps do not play a significant role in the formation of heavy rainfall near the Lago Maggiore area.

Unlike the real topography simulations, the accumulated rainfall was much lower in both idealized arc-sharped (AALP) and elongated barrier-like (BALP) obstacle experiments. For instance, from 0600 UTC to 1200 UTC 20 September (Fig. 2b), a similar banded precipitation occurred in association with the low-level westerly flow that moved into the domain as in NWAP simulation. The major rainfall during this period fell on the left end of the barrier. The lower precipitation amounts in these two idealized topography simulations

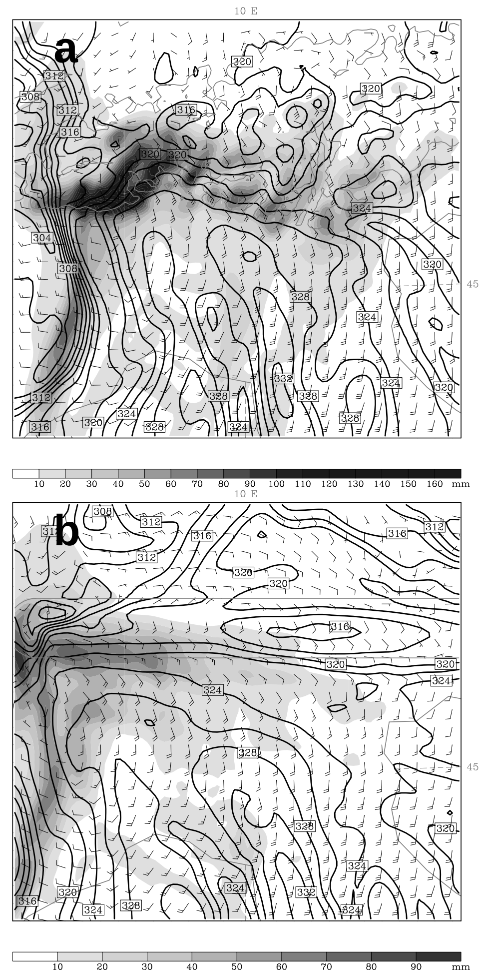

Figure 2: Simulated 850 hPa wind field, equivalent potential temperatures and 6-h accumulated precipitation (shaded) ending at 1200 UTC 20 September 1999 in (a) NWAP, and (b) BALP.

were partly the result of the smoother topography (i.e., decreased roughness length) that reduced the strength of orographic uplift, and partly due to the simplicity of the barrier, including the mountain height and width. The simulation results from the 1.67 km grid resolution domain (FALP) indicated that the accumulated rainfall was over-predicted on the windward slopes of the Alps as well as the Maritime Alps. As shown in Fig. 3a, valid at 1200 UTC 20 September, the rainfall was around 50% increased as compared to the control simulation. A comparison of the time evolution of the hourly precipitation from the rain gauges over the 15 km, 5 km , and 1.67 km resolution domains at Cimetta (46.2N, 8.8E, station height: 1672 m) is shown in Fig. 3b. Clearly, the increase in resolution has drastically changed the precipitation patterns and magnitudes, and leads to an increase in precipitation, especially over the mountains. The results imply that the vertical motion increases rapidly as resolution increases, transitioning from less-than to greater-than particle fall speeds and allowing more variety of microphysical processes over complex topography.

4. CONCLUSIONS

This study investigates the local circulation associated with an orographic rainfall event occurred during 19-21 September 1999 (MAP IOP-2B). The near-surface flow was dominated by an easterly jet originally from the Adriatic Sea and a southerly jet from the Gulf of Genoa. A significant westward turning occurred when the southeasterly and southerly flow approached the south side of the Alps. Precipitation was mainly concentrated on the windward slopes, especially near the Lago Maggiore area. This event was simulated by MM5 model with a 5-km horizontal grid spacing in the inner nested domain. The MM5 simulation reproduced the basic features such as the timing and location of the deep trough and the associated precipitation evolution, though the total amount of precipitation is slightly higher than that measured by rain gauges. The results demonstrate that the low-level convergence and the orographic uplifting of a potentially unstable impinging flow were the major causes of the heavy rainfall. Sensitivity experiments have been conducted to investigate the effects of upstream orography, western flank of the Alps, and model horizontal resolution. The precipitation distribution and amount over the southern upslopes of the Alps were not directly related to either coastal Apennines Mountains or the western flank of the Alps. The 1.67 km horizontal grid spacing simulation indicates that heavy rainfall tended to concentrate in the vicinity of individual mountain peaks. The total amount of rainfall was over-predicted along the windward slopes due to the strong upward motion that occurred over the upslopes. The results imply that the dynamical forcing manifested as vertical motion increases rapidly as resolution increases. It is speculated that the rainfall over-prediction problem might be caused by the inaccurate or unrealistic microphysical processes over complex topography.

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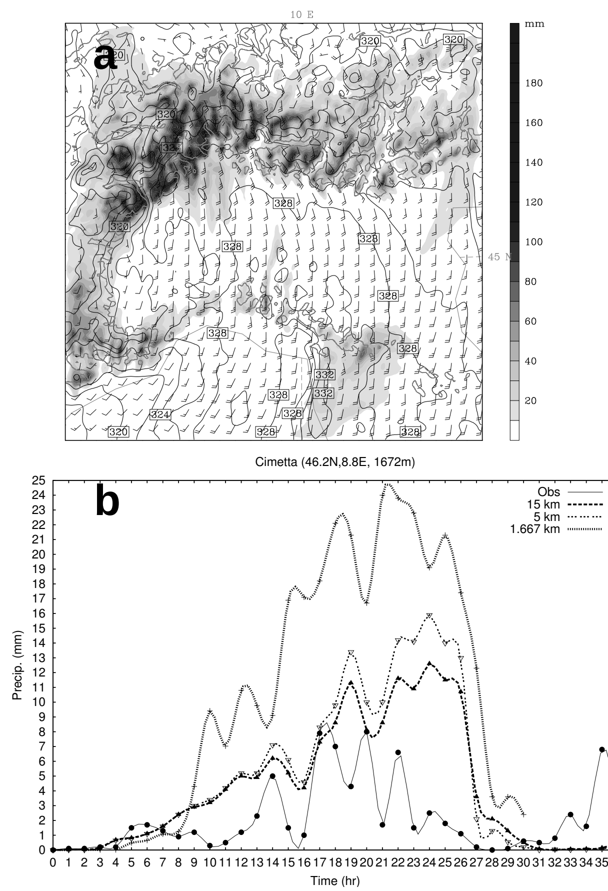

Figure 3: (a) Simulated 850 hPa wind field, equivalent potential temperatures and 6-h accumulated precipitation (shaded) from the 1.67 km resolution FALP case ending at 1200 UTC 20 September 1999. (b) Time evolution of the hourly precipitation by the rain gauge, 15 km, 5 km and 1.67 km domain at Cimetta (46.2N, 8.8E, 1672 m).