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NUMERICAL SIMULATIONS OF AN OROGRAPHIC RAINFALL EVENT ASSOCIATED WITH THE PASSAGE OF A TROPICAL STORM OVER A MESOSCALE MOUNTAIN

Sen Chiao and Yuh-Lang Lin*
North Carolina State University, Raleigh, North Carolina

1. INTRODUCTION

In this study, we considered a heavy orographic rainfall event associated with a tropical storm over Taiwan. During early August 1999, tropical storm Rachel made landfall on the southwest side of Taiwan island. The operational numerical guidance and forecasts were not adequate in this case, which did not alert the general public of the potential heavy rainfall. Although the Central Mountain Range (CMR) destroyed this tropical storm at landfall, it also provided a favorable condition for moist airstream to be lifted to release instabilities and resulted in heavy orographic rainfall. Additionally, the mesoscale forcing associated with this weather system may also play some important roles in producing heavy rainfall during that period. Lin et al. (2001) suggested some essential ingredients for producing heavy orographic rainfall, including high precipitation efficiency within an incoming airstream, low-level jet, steep mountain, favorable mountain geometry and confluence flow field, strong synoptically forced upward motion, high moisture upstream, large convective system, slow movement of the convective system and a low-level flow with high θ_e tends to be potentially (convectively) unstable, which may trigger orographic convective systems. In this study, we investigate (a) the effects of synoptic and mesoscale environments on the formation of orographic heavy rainfall, (b) the vertical moisture flux from the model output as a potential index for predicting orographic rainfall, and (c) orographic effects on the generation, propagation, and redistribution of the rainfall.

2. NUMERICAL EXPERIMENTS DESIGN

The numerical modeling system used in this study is the atmospheric component of the Naval Research Laboratory's Coupled Ocean/Atmospheric Mesoscale Prediction System (NRL/COAMPS)(Hodur 1997). The fully compressible, nonhydrostatic governing equations with terrain-following vertical coordinate

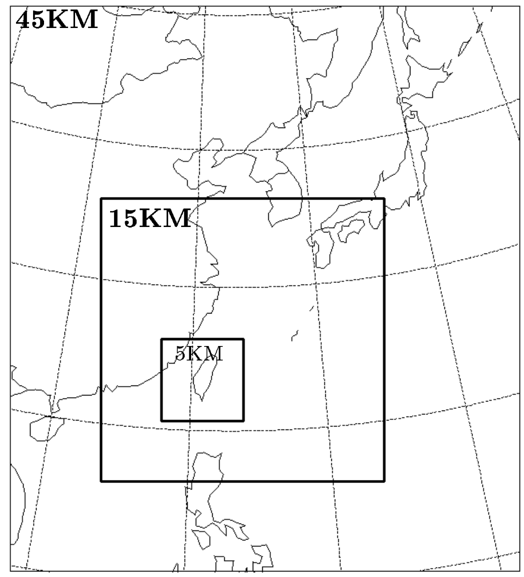

FIG. 1. Numerical model computational domain for TS Rachel. The grid increments for the three nested meshed are 45km, 15km and 5km.

are solved by using second order accuracy finite difference scheme. Physical parameterizations include short and longwave radiation, subgrid-scale moist convective, explicit mixed phase cloud microphysics processes.

A 48-hour simulation, starting at 00UTC 6, August 1999, utilized the incremental update data assimilation procedure. The initial fields were created from multivariate optimum interpolation (MVOI) analyses of surface, upper-air sounding, aircraft, and satellite data that were quality controlled and blended with 1^o resolution first-guess fields from the U.S. Navy Operational Global Analysis and Predication System (NOGAPS). Time dependent lateral boundary conditions also made use of NOGAPS forecast fields. The computational domain for the present study was configured on a Lambert conformal projection with three horizontally nested grids of 91 x 101, 151 x 151 and 133 x 133 points. The grid-point spacing of the computational meshes were 45 km, 15 km and 5 km, respectively (Fig. 1). A total of 30 layers in the vertical were used. The model contains the 1-km resolution terrain data that is mapped to the COAMPS model

* *Corresponding author address:* Yuh-Lang Lin, Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27695-8208; e-mail: yl_lin@ncsu.edu

grid resolution to better account for the effects of topography on mesoscale phenomena.

3. SYNOPTIC ENVIRONMENTS

An orographic rainfall event occurred on 6-7 August 1999 during the passage of tropical storm (TS) Rachel over Taiwan. The first spell of the heavy rainfall episode started in the southwestern concave region of the CMR, at about 15UTC on August 6, when TS Rachel was still in far upstream of Taiwan. The southwesterly monsoon was enhanced by the circulation of TS Rachel during that time. During 18UTC August 6 to 00UTC August 7, the heavy rainfall was recorded at the windward side of the southern part of Taiwan. The rain amount reached ~ 150 mm within 9 hours (from 15UTC August 6 to 00UTC August 7) in both the foothills and the concave region of the southern Taiwan. The rainfall then weakened significantly and resumed at the same location at about 03UTC 7 August when TS Rachel moved inland and filled in the mountains. The continuously moist impinging flow (high θ_e) was forced to rise over elevated terrain. As a result, the total precipitation increased while TS Rachel moved in Taiwan during 00UTC to 06UTC on August 7. Figure 2 shows the distribution of the 3-hr accumulated precipitation from 03UTC to 06UTC August 7. The precipitation could be found along the slope of the concave region and the coastal area during TS Rachel's move inland. We hypothesize that mountain geometry (concave region) induces confluent flow and generate density current which trigger new convective systems and propagate upstream.

4. RESULTS

The 5 km model domain results demonstrate that during 18UTC to 21UTC August 6, the precipitation could be found at the peninsula. The strong southwesterly flow ($\sim$ 18 m/s) dominated during that time, which led to heavy orographic precipitation around the southern Taiwan. Apparently, when TS Rachel had not made landfall, the CMR played an important role in redistribution of precipitation during this stage. During 03UTC to 06 UTC August 7, the result shows more significant precipitation was over the southern part of Taiwan and some local rain cells found over the northern part of Taiwan (Fig. 3). It appears that the precipitation was associated with TS Rachel landfall, however, the concave geometry at southwest Taiwan and blocking effects of CMR did provide favorable conditions for producing heavy orographic rainfall. Compared with observed results (Fig. 2), the model did very well in predicting the location of heavy rain, although the total rainfall amount was slight overpredicted. In general, the heavy rain area was found at the slopes of the concave region as well as the southwestern part of Taiwan during 00UTC to 06UTC August 7. It is suspected the complex topography could induce the smaller-scale convective cells in the model that would affect the disorganized and localized precipitation patterns. The high θ_e may have played an important role in producing heavy rainfall. Figure 4 shows the θ_e distribution at 950 hPa in 03UTC August 7, with shaded area indicating the θ_e higher than 335K. High θ_e associated with the impinging southwesterly flow covered southern Taiwan, noticeably at the concave region, which was consistent with the heavy rain area.

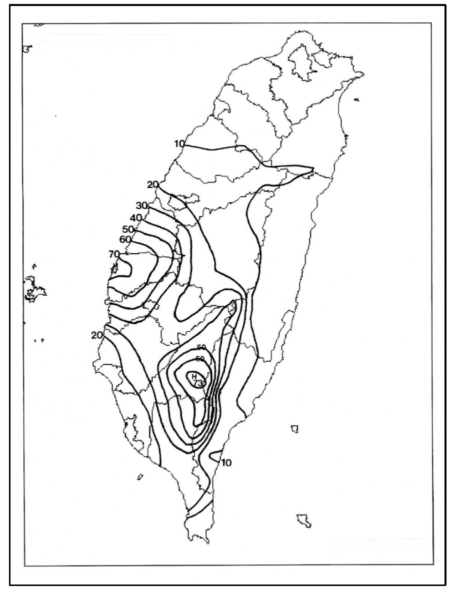

FIG. 2. Analysis of the observed rainfall (mm) in Taiwan area valid at 03-06UTC August 7, 1999.

It appears that the high moisture airstream would be more vigorous at the windward side due to the blocking effects of high mountains. Besides, the upward motion forced by the CMR that induce strong convection over southwest Taiwan could also lift up the moist air to the level of free convection (LFC), and then release the instability. We conclude that the high θ_e is essential for producing a heavy rainfall event, nevertheless, the θ_e effects must make the impinging flow more unstable by the direct orographic lifting with the low-level jet, such as the strong impinging southwesterly flow. Figure 5 shows the cross-section of θ_e from southwest (21.8°N, 119.5°E) to northeast (24.0°N, 122.3°E) at 03UTC August 7, 1999. It is clearly shown that the disturbance of θ_e indicates a very unstable layer caused by the convection of TS

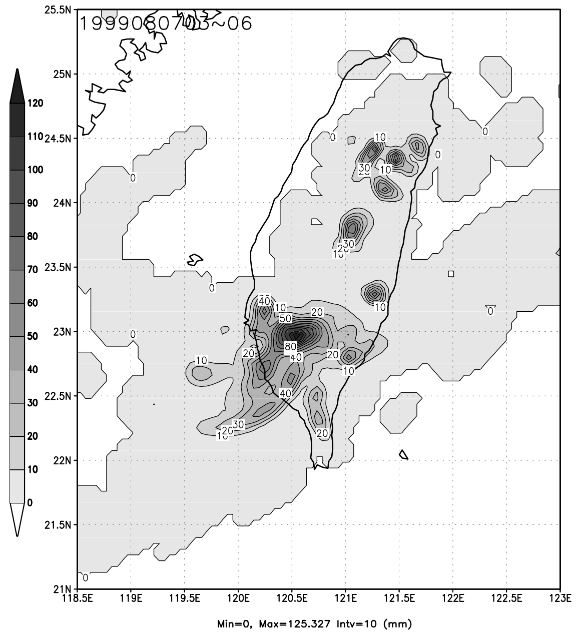

FIG. 3. 5 km resolution grid forecast rainfall in Taiwan area valid at 03-06 UTC August 7, 1999.

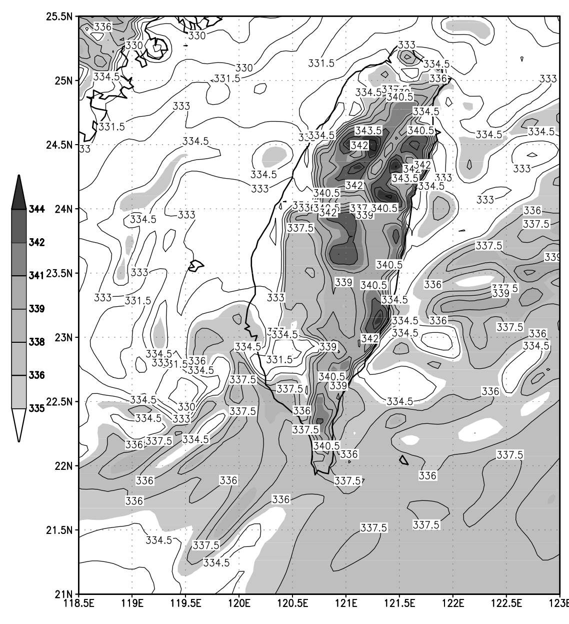

FIG. 4. The simulated equivalent potential temperature at 950 hPa on 03 UTC August 7, 1999.

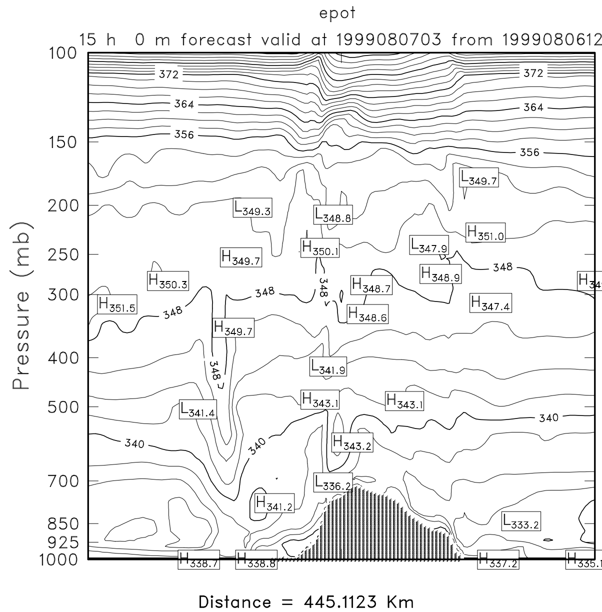

FIG. 5. Cross-section of θ_e from southwest (21.8^{o}N, 119.5^{o}E) to northeast (24.0^{o}N, 122.3^{o}E) valid at 03UTC August 7, 1999.

Rachel and southwesterly impinging flow at the windward side. The strong blocking effects also induce potential instability then trigger convection over the mountain slope. We conclude that the moisture in the lower layer was all condensed over the windward slope and concave region, and instability was released by the terrain-induced uplifting and vertical motion in TS Rachel, which favours the producing of orographic rainfall.

When calculating the orographic vertical moisture fluxes $(V \cdot \nabla h)q$ on 03UTC August 7, at 850 hPa (Fig. 6), we found that positive orographic vertical moisture fluxes tended to be more vigorous at the foothills and the concave region of the CMR as well as the coast region. The rainfall area was consistent with the distribution of orographic vertical moisture fluxes. In addition to $(V \cdot \nabla h)q$, a more general form of vertical moisture flux, wq, may also be used to help predict heavy rainfall. Figure 7 shows the vertical moisture fluxes at 850 hPa on 03UTC August 7. The results did represent the precipitation portion over the ocean. It can be seen that the high value of moisture flux was located at the coast of southern Taiwan, which represent the rainband of TS Rachel. We conclude that the positive area of orographic vertical moisture flux could be used to help predict heavy orographic rainfall. In addition, the synoptically vertical moisture flux can supply the insufficiency of orographic moisture flux. This vertical moisture flux for orographic heavy rainfall could provide weather forecasters with additional information.

5. SUMMARY

This study documents an orographic rainfall event occurred on 6-7 August 1999 during the passage of TS Rachel over Taiwan by using triply-nested, non-hydrostatic numerical simulations. Although the maximum rainfall rate is overpredicted, the model (COAMPS) is able to predict the movement and period of rainfall quite accurately. Examining both observational data and numerical output, we found that during 15UTC 6 to 00UTC 7 August, the southwesterly monsoon flow over southwest Taiwan was strengthened and formed a low-level jet (LLJ) with high θ_e by TS Rachel when it moved closer to Taiwan. Strong orographic lifting of the potentially unstable LLJ triggered convective systems in the concave region of the southwest CMR, which then produced the first spell of the heavy rainfall episode. The second spell of heavy orographic rainfall during 00UTC to 12UTC 7 August was attributed to the modification of TS Rachel's own rainbands by the mountains.

The orographic vertical moisture flux, which is a product of low-level horizontal velocity, mountain steepness, and moisture content (Lin et al. 2001), is calculated based on the fine-resolution model output. The maximum regions of this flux coincide with the heavy rainfall regions over the island (i.e. mountainous area), while the maximum regions of the general vertical moisture flux (wq) coincide with the heavy rainfall regions over the ocean. Therefore, the orographic vertical moisture flux may serve as an index to help predict heavy orographic rainfall.

6. ACKNOWLEDGMENTS

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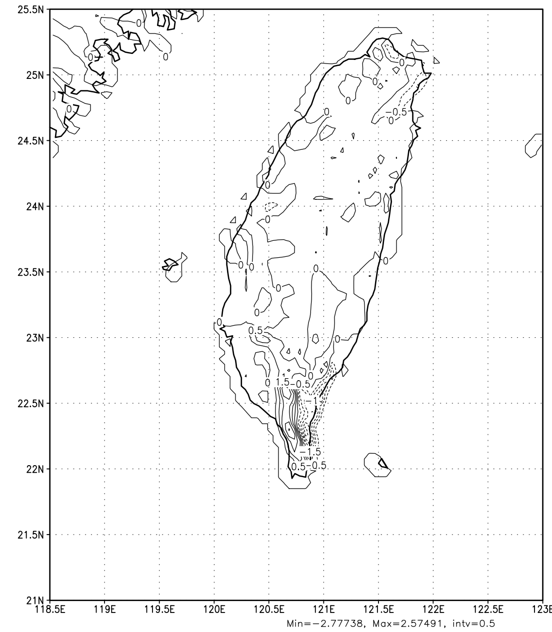

FIG. 6. Orographic moisture flux (kg/kg) at 850 hPa on 03 UTC August 7, 1999.

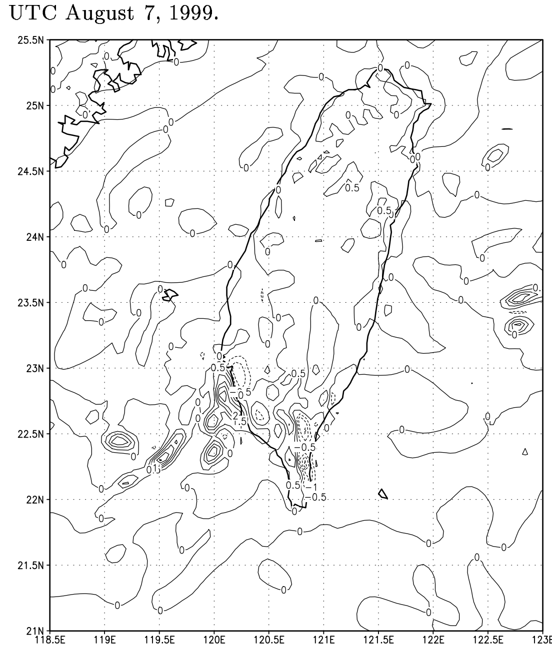

FIG. 7. Total vertical moisture flux (kg/kg) at 850 hPa on 03UTC August 7, 1999.