Numerical Simulation of Typhoon Herb (1996) Using MM5

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ABSTRACT

Typhoon Herb (1996) is one of the most damaging tropical cyclones in the recent history of Taiwan. The most dramatic aspect of Typhoon Herb is the enormous amount of rain it produced over the Central Mountain Range (CMR). The lifting associated with the upslope motion produced extremely heavey precipitation. Mountain A-Li recorded a 24-h rainfall of 1094.5 mm on 31 July, and 892 mm on 1 August. The total accumulation as a result of Typhoon Herb was 1987 mm over the two day period. The purpose of this paper is to experiment with a high-resolution, nonhydrostatic, mesoscale model on the prediction of Typhoon Herb.

In this study we performed a series of forecast experiments on Typhoon Herb using the MM5 model with variable horizontal resolutions of 60, 20, and 6.7 km. Our primary interest is to examine the ability of the model in predicting the precipitation distribution associated with Typhoon Herb, and to assess the impact of horizontal resolution and topography on rainfll prediction. It was found that the 6.7-km MM5 successfully simulated the mesoscale rainfall distribution associated with this extreme rainfall event. The MM5 also successfully simulated the subsidence-induced meso-low near Hualien. The ability of the model to successfully simulate the observed rainfall declined with the reduction of horizontal grid resolution. Even with a 20-km grid, the model could not reproduce the detailed rainfall distribution, and the model-predicted maximum 24-h rainfall over the CMR and western Taiwan was reduced to 866mm. The ability of the model to capture the heavy precipitation and its associated mesoscale structure was found to be closely tied to its ability to resolve the detailed topography of the CMR. The CMR was found to play a key role by both substantially increasing the total rainfall produced by Typhoon Herb (by almost a factor of 3), and by focusing the heavy rainfall over the western slopes of the mountains.

1. INTRODUCTION

Of all the natural disasters occurring in Taiwan, tropical cyclones are the most serious. Over a 20-year period, Taiwan was hit by an average of 3.7 typhoons per year. These storms can produce heavy rainfall and strong winds, leading to severe damage to agriculture and industry, and serious loss of human life. An outstanding example is Typhoon Herb, which made landfall on Taiwan on 31 July 1996. Typhoon Herb took 70 lives, and caused an estimated 5 billion U. S. dollars of damage to agriculture and property. The most dramatic aspect of Typhoon Herb is the enormous amount of rain it produced over the CMR. A record-breaking total rainfall of 1987 mm between July 30 and August 1 was observed at Mountain A-Li in central Taiwan.

The CMR of Taiwan occupies two-thirds of the island, and has many peaks over 3500 m. It has been observed that during the passage of tropical cyclones, the precipitation distribution, as well as cyclone track and local winds, is strongly influenced by the island topography (Wang 1989). Even though the dynamics of typhoon circulation and its interaction with the Taiwan topography on typhoons has been investigated from various idealized numerical simulations (e.g., Bender et al. 1987), many of the details of such interaction are still not well understood. The track deflection, the development of secondary lows, the changes in intensity, and the mesoscale structure of pressure, wind, and precipitation associated with an approaching typhoon, make the forecasting of a tropical cyclone approaching Taiwan an extremely

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difficult task. The understanding of the dynamics of typhoon circulation and its interaction with the Taiwan terrain, and the forecasting of track, intensity, and mesoscale wind and precipitation distribution are some of the most important scientific and forecasting problems for meteorologists in Taiwan (Wu and Kuo 1998).

Accurate prediction of the track, intensity, precipitation and strong winds for typhoons affecting Taiwan is not an easy task. The lack of meteorological data over the vast Pacific Ocean and the strong interaction between typhoon circulation and Taiwan's mesoscale Central Mountain Range are two major factors that make the forecasting of typhoons in the vicinity of Taiwan highly challenging. Improved understanding of the dynamics of typhoon circulation and its interaction with Taiwan terrain is needed for more accurate prediction.

In this work, We experimented with a high-resolution (6.7 km), nonhydrostatic, mesoscale model (MM5) on the prediction of Typhoon Herb. Our primary interest was to examine the ability of the model to predict the detailed precipitation distribution associated with Typhoon Herb, and to assess the impact of horizontal resolution and detailed topography on rainfall prediction.

2. SYNOPSIS OF HERB (1996)

According to the best track analysis, the central pressure of Herb was about 930 mb during the day of 30 July 1996 as it moved toward northern Taiwan along a northwestward track. The estimated intensity of the storm was reduced to 935 mb at 1200 UTC 31 July. The storm made landfall near I-Lan about 1.5 hour later, with a recorded central pressure of 944.7 mb at the I-Lan station. Prior to landfall, the estimated maximum surface wind was about 100 kts. The WSR-88D located over northestern Taiwan (Wu-Fun Shan radar station) recorded a maximum wind speed of 65 m/s at 1 km above sea level. The center of the storm traversed across northern Taiwan, and eventually moved off to sea again at about 2100 UTC. The Hsin-Chu station, which was directly passed over by the center of the storm, recorded a central pressure of 968.6 mb at that time. The storm weakened by 24 mb during the 7-hour period when its center was over land.

As Thphoon Herb traversed across northern Taiwan, the airflow over the main body of Taiwan changed from northwesterly to westerly, and then to southwesterly. The moisture-laden typhoon circulation was forced to move over the CMR. The lifting associated with the upslope motion produced extremely heavey precipitation. Mountain A-Li recorded a 24-h rainfall of 1094.5 mm on 31 July, and 892 mm on 1 August. The total accumulation as a result of Typhoon Herb was 1987 mm over the two day period. In sharp contrast, downslope flow persisted over eastern Taiwan, and very little precipitation was recorded on the eastern side of Taiwan. The downslpoe flow also produced a topographically induced meso-low near Hualien. The Hualien meso-low was generated at around 1800 UTC. This meso-low then moved northward along the coast of Taiwan.

3. MODEL DESCRIPTION AND EXPERIENT DESIGNS

This study makes use of the Penn State—NCAR mesoscale model version 5,MM5 (Dudhia 1993; Grell et al. 1994). The MM5 model is a nonhydrostatic, primitive-equation model, and can be used with a wide range of grid sizes (from 1 km to 200 km). A suite of model physical parameterization schemes are available for subgrid-scale convection, grid-resolvable scale microphysical parameterization, the planetary boundary layer forcing, and radiation. The particular version of MM5 used here includes the following physics options: (1) the Kain-Fritsch cumulus parameterization, (2) the Blackadar PBL, (3) the atmospheric radiation scheme of Dudhia (1989), and (4) the simple ice physics scheme of Dudhia (1989). The initial condition was based on the ECMWF global analysis. We first performed a 60-km/20-km/6.7-km MM5 simulation staring at 1200 UTC 30 July with a bogus vortex according to the characteristics of the storm estimated by the best-track analysis. The typhoon vortex was well developed in 12 h (0000 UTC 31 July). The fully developed typhoon vortex was (with a radius of 760 km) then lifted from the model simulation to merge with the ECMWF analysis at 0000 31 July. The spun-up typhoon was placed at the observed storm location according to the best track analysis. Very little adjustment is needed for the typhoon vortex to reach a balance with the ECMWF analysis. The forward model prediction then commenced at 0000 UTC 30 July.

A series of experiments were conducted. All the experiments used the same radiation, and cumulus parameterization scheme. Experiment E60 and E20 were the control experiment with two meshes at 60 and 20 km run in two-way mode. Experiment E6.7 had a horizontal grid size of 6.7 km, and run in one-way mode with initial and boundary conditions from E20 staring at 0000 UTC 31 July. The final experiment, E6.7NT, is similar to E6.7 except that the topography of Taiwan was set to ocean value. The purpose of this experiment was to show the impact of the CMR on the rainfall prediction and wind field distribution.

4. RESULT

Figure 1 shows the daily rainfall prediction and the corresponding model terrain (from 0000 UTC 31 July to 0000 UTC 1 August) from three experiments with resolutions of 6.7 (E6.7), 20 (E20), and 60 km (E60), respectively. The daily rainfall in E6.7 captured the two rainfall maxima, one over northern Taiwan with a peak amount of 929 mm, and the other over A-Li Mountain with 450 mm. The model also predicted a band of precipitation over the southern CMR with an amount exceeding 682 mm, which is also found in the observation. The model is very successful in capturing the rain shadow over eastern Taiwan.

The differences between these rainfall forecasts can be attributed to differences in the model topography with different grid resolution. The 6.7-km model is able to provide a realistic depiction of the CMR, with two peaks: one over northern Taiwan with an elevation of 2844 m (representing the Snow Mountain), and the other over southern Taiwan with an elevation of 2000 m (representing the A-Li Mountain and the Jade Mountain). The model is also able to preserve the coastal plains around Taiwan. Reducing the model resolution to 20 km, the CMR becomes much fatter and the slope much gentler. The coastal plains are nearly gone on both sides of Taiwan. The 20-km terrain also shows two peaks exceeding 2000 m, however, the southern peak is now located over central Taiwan (instead of southern Taiwan). The 60-km terrain is even worse. With such a low horizontal resolution, the topography of Taiwan can only be represented by a few grid points. As a result only one peak is preserved over northern Taiwan. The terrain slope is even smaller, and the coastal plains on either side of Taiwan are complete gone.

The model typhoon in the E6.7 moved analogous to the observed storm and made landfall at 1400 UTC 31 July. To account for the timing difference, we show in Fig. 2 the surface pressure and airflow prediction from the E6.7 at 1400 UTC and 1700 UTC 31 July. At 1400 UTC, the predicted storm is located near Keelung, a position almost identical to that of Fig.2a. The central pressure of the storm is 940 mb, which is a little lower than the observed value of 944.7mb. The model vortex was spun up according to the "estimated" storm intensity, which may be stronger than the "actual" storm. A pronounced lee trough is simulated immediately to the east of the CMR. The model successfully captured the sudden change of airflow direction from strong westerly and northwesterly immediately to the west of the CMR to sourtherly to the east of the mountains. The southerly flow along the east coast of Taiwan is directedly perpendicular to the isobar, in close agreement with the observations. The ageostrophic nature of the southerly flow is successfully simulated.

A careful comparison of the E6.7 terrain and daily rainfall shows that the rainfall took place mainly along the western slopes of the CMR. The maximum rainfall tends to occur immediately to the west of the mountain peaks. The importance of upslope flow in producing the extreme heavy rainfall over the CMR is quite evident. To extreme the importance of large-scale upslope motion in producing heavy rainfall, we show in Fig.3 east-west vertical cross sections of selected meteorological fields at 1700 UTC 31 July, cutting across the A-Li Mountain. Two-dimensional wind vectors, constructed from along the cross section wind and the vertical motion, show a significant westerly wind component throughout the troposphere to the west of the CMR, especially for the airflow below 500 mb (Fig. 3a). The westerly wind component varies from about 20 m/s near the west coast of Taiwan to 40.8 m/s on the top of the CMR (Fig. 3b). As the airflow impimges upon the CMR, the entire layer from the surface to 500 mb (which is nearly saturated) was lifted above the mountains. It then descended to the lee of the CMR.

The potential temperature field shows the existence of mountain waves. Sizeable subsidence warming is found in the lower troposphere (between 400 mb and surface) in the lee (Fig. 3a). The subsidence has also produced significant drying. The entire troposphere along the cross section, under the influence of the typhoon, has a relative humidity (RH) close to 100%, except localized drying due the subsidence in the upper troposphere above the mountain (minimum RH of 53.1 %), and in the lee of the CMR (minimum RH of 62.6 %)(Fig.3c). The horizontal wind barbs along the cross section (Fig.3b) show that the deep cyclonic circulation associated with the typhoon dominates the entire troposphere, with its trough line nearly perfectly aligned with the CMR. As the deep trough slowly moves past Taiwan, the strong westerly wind component continued to force a deep layer of up-slope motion, which can easily produce cloud and rain water in a nearly saturated typhoon environment.

Figure 3d shows the cloud water and rain water fields along the cross section. Indeed, we see a deep layer of cloud water and rain water with a width of about 200 km, extending from the peak of the mountains to the west coast of Taiwan. Immediately to the east of the mountain, there is a distinct clear zone as a result of sinking motion associated with the downslope flow. Another band of cloud and rain water (with a width less than 50 km) exists off the east coast of Taiwan. This band, most likely produced by the mountain wave, did not produce very much precipitation at the ground. A possible explanation is the evaporation of rainwater in the dry subsiding air coming off the mountains.

5. SUMMARY

In this study we performed a series of forecast experiments on Typhoon Herb using the MM5 model with variable horizontal resolutions of 60, 20, and 6.7 km. The highlights of their results are summarized as follows:

1) The 6.7-km MM5 successfully simulated the mesoscale rainfall distribution associated with this extreme rainfall event. The MM5 also successfully simulated the subsidence-induced meso-low near Hualien.

2) The ability of the model to successfully simulate the observed rainfall declined with the reduction of horizontal grid resolution (as shown by a comparison of Figs. 1a,1b and1c). Even with a 20-km grid (Fig.1b), the model could not reproduce the detailed rainfall distribution, and the model-predicted maximum 24-h rainfall over the CMR and western Taiwan was reduced to 866mm. The ability of the model to capture the heavy precipitation and its associated mesoscale structure was found to be closely tied to its ability to resolve the detailed topography of the CMR.

3) The CMR was found to play a key role by both substantially increasing the total rainfall produced by Typhoon Herb (by almost a factor of 3), and by focusing the heavy rainfall over the western slopes of the mountains.

The results presented above show that a high-resolution mesoscale model, such as MM5, can be a very useful tool for Taiwan in forecasting the detailed mesoscale precipitation and wind distribution associated with an approaching typhoon. Additional research is required to access the potential of such high resolution mesoscale or typhoon models in order to improve the detailed wind and rainfall forecasts for typhoons near Taiwan.

REFERENCE

Bender, M. A., R. E. Tuleya, and Y. Kurihara, 1987: A numerical study of the effect of island terrain on tropical cyclones. *Mon. Wea. Rev.*, **115**, 130-155.

Dudhia, J., 1989: Numerical study of convection observed during the Winter Monsoon Experiment using a mesoscale two-dimensional model. *J. Atmos. Sci.*, **46**, 3077-3107.

Grell, G. A. Dudhia, D. R. Stauffer, 1994: A description of the fifth generation Penn State/NCAR mesoscale model (MM5). NCAR Tech. Note, NCAR/TN-398+STR,138 pp.

Tsay, C.-Y. and C. C. Wu, 1997: Typhoon Herb. Preprints, *Workshop on Typhoon Research in the Taiwan Area*. Boulder, CO, May 17-18, 1997.

Wu, C.-C., and Y. H. Kuo, 1998: Typhoons Affecting Taiwan – Current Understanding and Future Challenges. Bulleton of Amer. Meteor. Soc. (in press).

Wang, S.-T., 1989: Track,intensity, structure, wind and precipitation characteristics of typhoon affecting Taiwan. Disaster Mitigation Res. Report 80-73, National Science Council, NSC 80-04140-P052-02B, 285 pp.

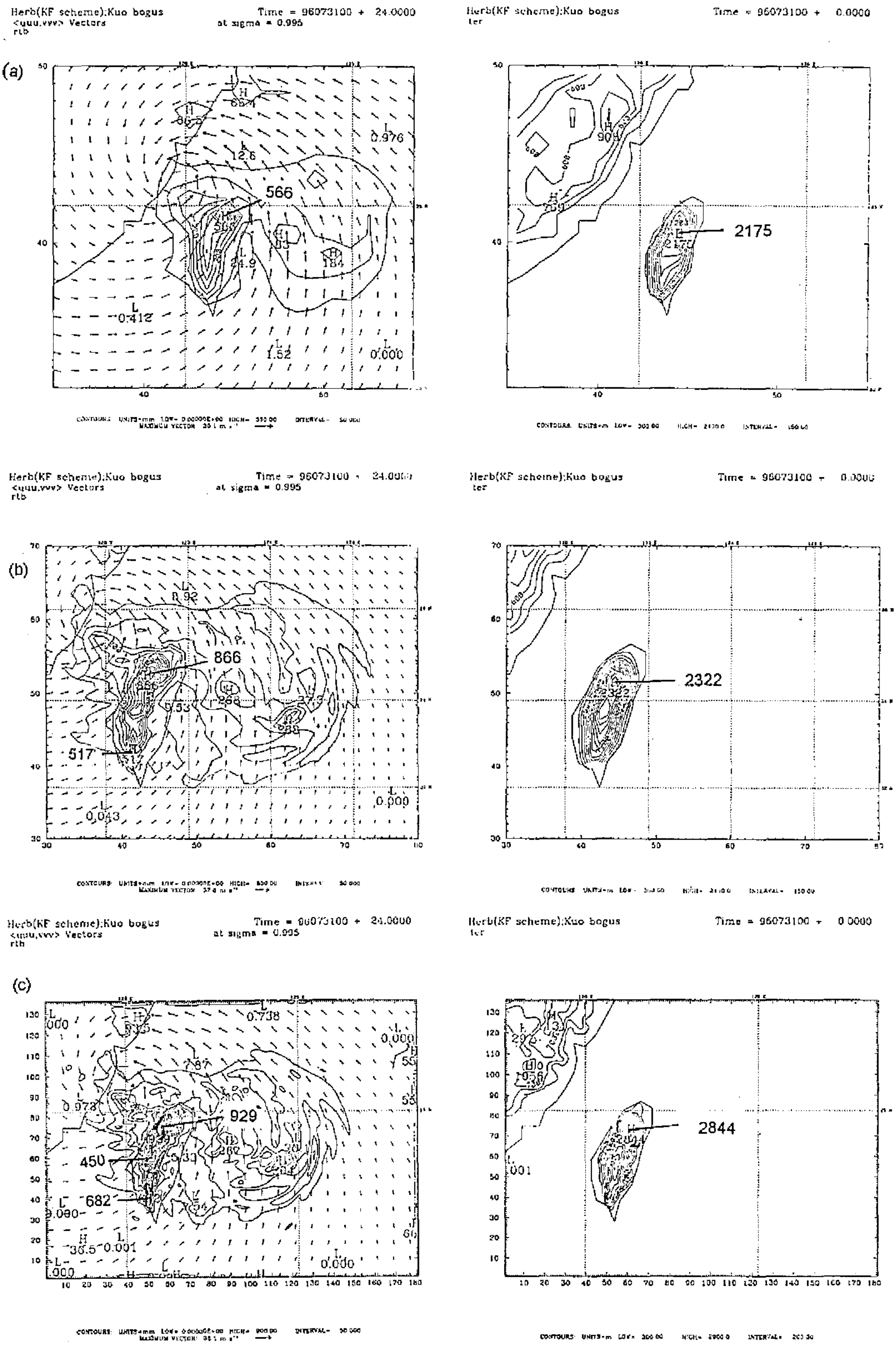

Figure 1 Simulated 24-h rainfall (in mm) ending at 0000 UTC August 1 1996 and the corresponding model terrain from (a) E60, (b) E20, (c) E6.7.

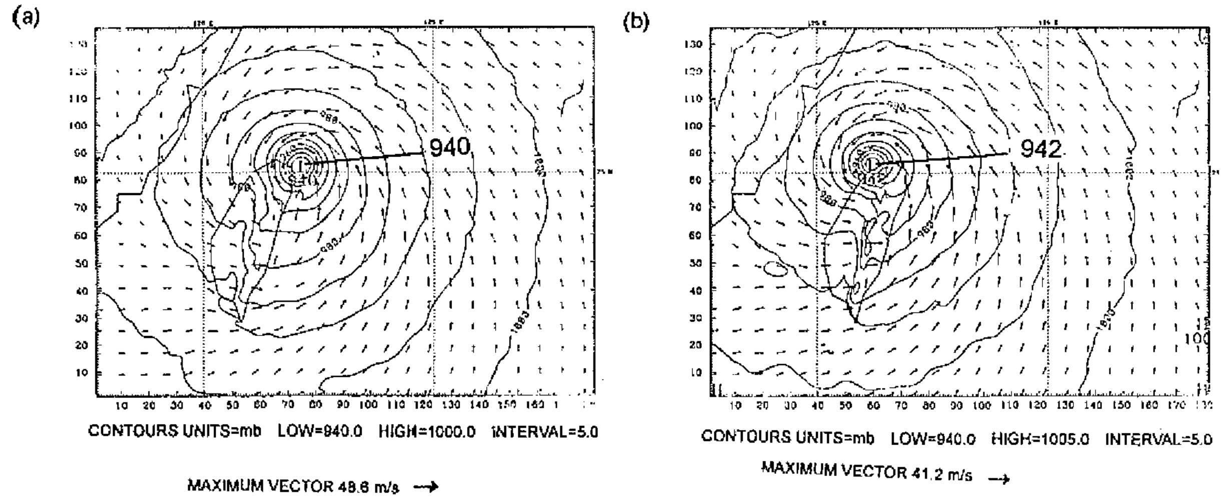

Figure 2 Simulated sea-level pressure and lowest model level winds valid at 1400 UTC, and (b) 1700 UTC July 31 1996 from experiment E6.7.

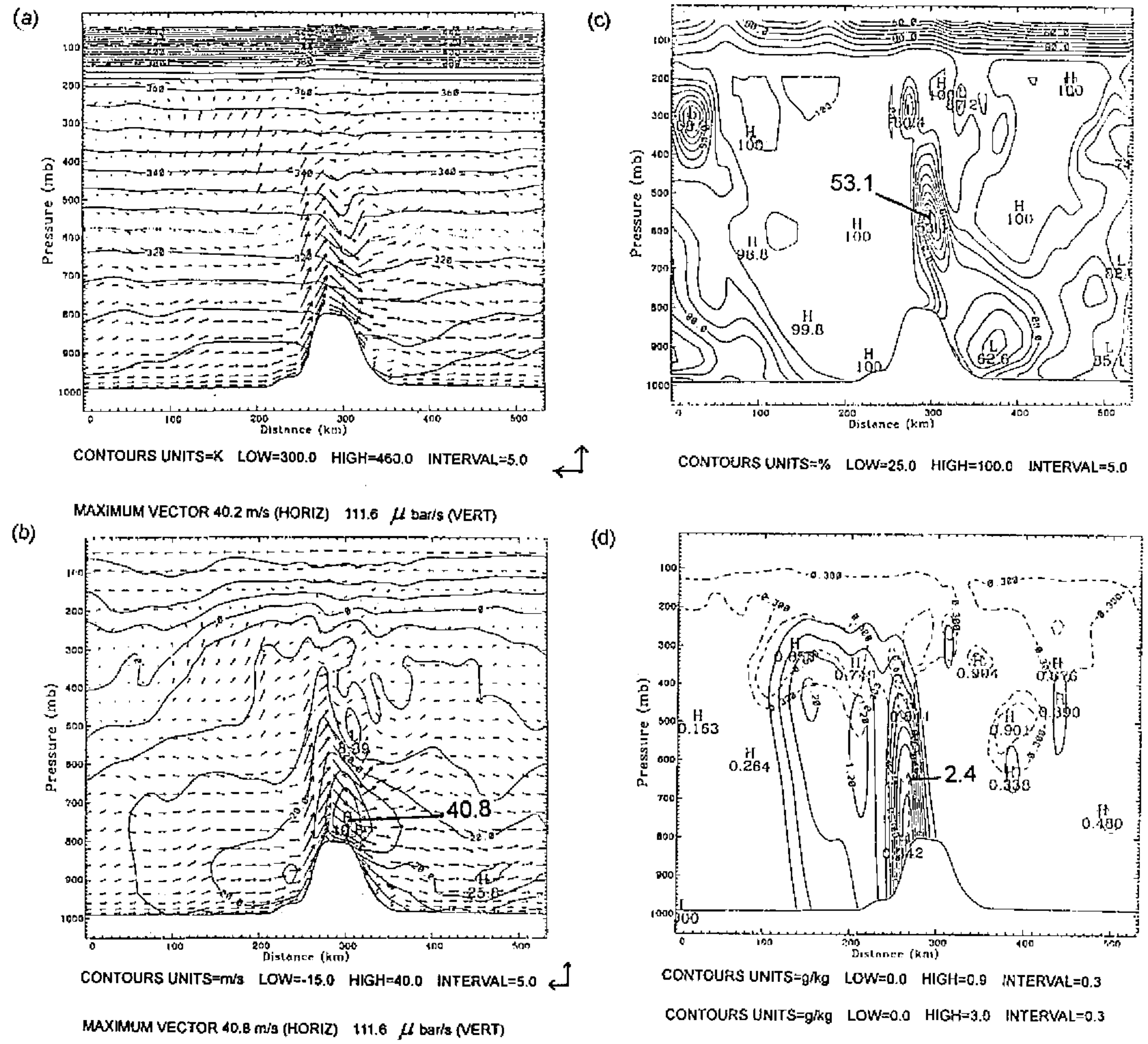

Figure 3 Vertical cross-sections from E6.7 valid at 1700 UTC July 31 1996. Potential temperature (contour interval 5 k) and two-dimensional wind vector along the cross section; (b) Horizontal winds and wind speed along the cross section (contour interval 5 m/s); (c) Realtive humidity (contour interval 5 %); and (d) Rain water (solid) and cloud water (dashed, contour interval 0.3 g/kg). The location of the cross section is 23.6° N.