WRF Simulations of a TC-Induced Record-Breaking Heavy Rainfall Event over Taiwan

Hiep Van Nguyen and Yi-Leng Chen
Department of Meteorology, University of Hawaii, Honolulu, Hawaii, USA

Abstract

In this work, a model self-bogus vortex is constructed by model cycle runs using the Weather Research and Forecasting Model (WRF) Version 3 to provide high-resolution initial conditions for tropical cyclone simulations. During the cycle runs, only sea level pressure (SLP) is forced at the first time step of each cycle run by an empirical profile. Three separate simulations with three different types of initial conditions including global analysis (CTRL), the bogus package of the WRF (WB) and the new initialization package (NT) are performed for Morakot (2009). The NT initialization scheme shows advantages in generating realistic vortex features including SLP, winds, warm core, and TC size. The NT scheme also shows significant improvements in TC simulations including asymmetric structure, track, intensity, low-level winds, radar reflectivity, and rainfall over the open ocean. Of the three types of initial conditions, only the NT runs simulated the observed TC-induced rainband associated with Morakot reasonable well. For this case, orographic lifting by TC circulations alone may not be adequate to account for the record rainfall over southern Taiwan. In addition to Morakot, Typhoon Goni and another tropical depression were embedded within a moist monsoon gyre. The combined circulations associated with the monsoon gyre and tropical storm circulations helped to bring moist laden flows toward the western slopes of southern Taiwan with a persistent westerly wind component.

Key word: model initialization, heavy rainfall

1. Introduction

Initialization of tropical cyclones (TC) in numerical models has been a challenging problem for many years. To improve the initial conditions for numerical TC forecasts, a vortex specification technique is usually used. The procedures include removing the poorly analyzed-meteorological fields associated with TCs from the global analysis, constructing an empirical vortex, or a bogus vortex, and inserting the bogus vortex into the observed TC location. A bogus vortex can be constructed by model integration (Kurihara et al., 1993), by analytic empirical functions (Fujita, 1952; Low-Nam and Davis, 2001; Kwon and Cheong, 2009), or constructed by three- (*3DVAR*) or four-dimensional variational data assimilation (4DVAR) with bogus data as one of the data sources (Zou and Xiao, 2000, Wang et al., 2008). The methods are able to significant improve in track and intensity forecasts as compared to model forecasts without a bogus vortex.

With a height over 3 km, the CMR (Central Mountain Range) of Taiwan plays an important role in the development of heavy rainfall due to the interaction between the TC and the terrain, as the oceanic moisture-laden air is forced upslope by TC circulations (Wu et al., 2002). Strong orographic lifting is accompanied by significant latent heating in the low atmosphere above the slopes (Wu et al., 2002). Heavy rainfall can be more severe if TCs hit Taiwan and interact with the East Asian winter monsoon, as the convergence is enhanced by monsoon circulations (Wu et al., 2009).

In this work, a TC-initialization technique is constructed using the Weather Research and Forecasting Model (WRF) (Skamarock et al., 2005) cycle runs and applied to Hurricane Morakot (2009). Model outputs with the new TC-initialization package and global analysis data are then used to investigate the mechanism for a record-breaking rainfall event associated with Morakot (2009). The TC-initialization is described in Section 2. The model and data description are given in Section 3. Preliminary results are presented in Sections 4. Large-scale factors contributing to the heavy rainfall related to Morakot are discussed in Section 5. Summary and discussion are given in Section 6.

2. Vortex initialization

In this study, a model self-bogus vortex is constructed by the WRF model cycle runs. During the cycle runs, only SLP is forced at the first time step of each cycle run by an empirical profile. We assume that (1) in a short period of time (<1 hour), the TC moves but its structure does not change significantly; and (2) a TC's structure at the model initial time is a function of environmental conditions. The model is first integrated for a period of time, dt (dt < 1 h), with the prescribed SLP at model initial time, t_0. Three parameters are used to construct a modified Fujita's surface pressure including minimum pressure, radius of maximum wind, and radius R beyond which the value of all variables are kept as in the global analysis. Secondly, the vortex structure after dt integration is used to construct a new vortex at the initial time, t_0, of the next cycle run while the large-scale variables are kept intact. Then the model is integrated again for dt. The above two-step cycle run is repeated until the current TC has the minimum SLP at the initial time + dt, and the maximum wind speed close to the observed values with a pre-set criterion or after a fixed number of cycle runs, N. Usually, N ranges from 30 to 60.

3. Data and model descriptions

The WRF modeling system (Skamarock et al., 2005) is used. The model configuration includes the Ferrier microphysics scheme, a Rapid Radiative Transfer Model scheme for longwave radiation, the Dudhia scheme for shortwave radiation, the Monin-Obukhov Similarity scheme for surface layer physics, the Yonsei University scheme for planetary boundary layer physics, and the Betts-Miller-Janjic scheme for cumulus parameterization. An advanced land surface model is employed using the land surface update procedures introduced by Zhang et al. (2005). The terrain height, landuse, green fraction and vegetation cover data were provided by the Central Weather Bureau (CWB), Taiwan.

Two nested domains are employed in the model with a two-way nesting, with horizontal resolutions of 18 km, 6 km, and horizontal dimensions of 311 x 256 and 505 x 343, respectively. There are 28 vertical levels from the surface to the 50-hPa level. Initial and lateral boundary conditions for the model are from the global reanalysis (FNL). Best track and intensity data are from Japan Meteorological Agency (JMA) at http://agora.ex.nii.ac.jp/digital-typhoon/.

4. Simulations of Typhoon Morakot

Morakot was formed on 2 August, 2009. It reached its peak intensity, with winds of 150 km h-1 (90 mph, a Category 2 hurricane), on early 7 August and made landfall over Taiwan on late 7 August. It stayed over Taiwan for about a day and then moved over the Taiwan Strait for about a day after which it made landfall over the China coast on 9 August. The hurricane weakened and dissipated on 11 August.

3-day simulations of Morakot initialized at 0000 UTC 6 August, about 36 hours before Morakot makes landfall over Taiwan, are first presented. Three different types of initial conditions, including those from global reanalysis data (CTRL), from the bogus package of WRF (WB) and from the new initialization package (NT) are performed for comparison. Other than the differences in the initial conditions, the WRF model is configured as described in Section 3 for all runs. At the model initial time, Morakot reached a minimum sea-level pressure of 965 hPa and had obtained a maximum wind speed of 33.5 m s^{-1} (65 kt). The TC center was located at 23.0^{o}N 127.8^{o}E with the radius for gale wind (wind speed > 17.1 m s^{-1}) at approximately 350 n m (~ 650 km).

The TC intensity from the global analysis is too weak, with a minimum SLP at only about 982 hPa (thin line, Fig. 1a). Although the WB scheme can initialize the vortex with a much lower SLP (open circle, Fig. 1a) as compared to the CTRL run, the value (~ 978 hPa) is still much higher than the observed value of 965 hPa. For the NT run, the initial minimum SLP (cross, Fig. 1a) is close to the best track data with a value of 965 hPa. In addition, both the initial SLP (Figs. 1a) and wind speed (Fig. 1b) in the NT run at a radius larger than about 400 km away from the TC center are consistent with the global analysis. The 10-m wind speed in the NT run reached the observed value of 65 kts (Fig. 1b). In contrast, the maximum speed in the CTRL run is only about 36 kts.

The temperature anomalies from the environment at the same height at the initial time for the CTRL, WB and NT runs are shown in Figure 2. In the CTRL run (Fig. 2a) the analysis vortex shows a warm core, with the warmest temperature anomaly, of over 8 K, at a height of about 12 km. However, the warm core is located about 1 degree away from the observed TC center. For the WB run (Fig. 2b), the altitude of the warm core, at about 5 km above the surface, is too low. The NT run (Fig. 2c) generates a vortex with a warm core at about 12 km, which is about the same height as in the global analysis (Fig. 2a) but about 4 K warmer. And the warm core is located right above the observed TC center.

At 0000 UTC 7 August, after 24 h of simulation, the simulated radar reflectivity in these three runs shows significant differences (Fig. 3). Both the observed (Fig. 3a) and the simulated reflectivity from the NT run (Fig. 3b) show large areas of high radar reflectivity associated with rainbands and the eyewall. In contrast, both the CTRL (Fig. 3c) and WB runs (Fig. 3d) simulated weak and not well-organized radar reflectivity related to Morakot.

Sensitivity tests of 48-h simulations during 5-10 August are performed to investigate the role the NT package on simulations of rainfall, TC track, intensity. When the TC center is located less than 400 km from the nearest coast (from 0000 UTC 7 August), no cycle runs are performed for the NT run. In this case, the simulated vortex at 12 h from the previous NT run, initialized 12 h earlier, is used as a bogus vortex for the current simulation. Prior to 0000 UTC 7 August, the TC initialization described in Section 2 is used. The model is initialized every 12 h from 0000 UTC 5 August to 0000 UTC 8 August for a total of seven 48-h simulations. The last run ended at 0000 UTC 10 August. Seven 48-h simulations are also performed for both the CTRL and WB runs during the same period.

Within 48 h of simulation, the largest track error in the NT run is about 60 nm. Meanwhile the values are 150 nm and 120 nm in the CTRL and WB runs, respectively (Fig. 4a). The mean 24-h track errors for the seven runs are 60 nm, 80 nm, and 40 nm for the CTRL, WB, and NT runs, respectively. The mean 48-h track errors are 150 nm, 120 nm, and 50 nm for the CTRL, WB, and NT runs, respectively (Fig. 4a). The mean 24-h maximum absolute wind speed errors are 15 kts, 13 kts, and 6 kts for the CTRL, WB, and NT runs, respectively (Fig. 4b). The mean 48-h maximum absolute wind speed errors are 14 kts, 11 kts, and 4 kts for the CTRL, WB, and NT runs, respectively (Fig. 4b). After 6 h, the

WB run does not show notable advantages in simulating maximum wind speed compared to the CTRL run (Fig. 4b). This problem may be due to the inconsistency between the bogus vortex from the WB run and the environmental fields at the model initial time. Mean absolute SLP errors at 24 h and 48 h of simulation in the NT run are about 1/3 and 1/2 of that in the CTRL, and WB runs, respectively (Fig. 4c).

Over the open ocean, the NT run produces better rainfall accumulations than the other two runs in comparison with rainfall estimated from the Tropical Rainfall Measuring Mission (TRMM) satellite data (Fig. 5) because the track, intensity and tropical cyclone structure are better simulated by the NT run. Nevertheless, all the runs are able to simulate heavy rainfall over southwest Taiwan with a maximum value over 2500 mm (Fig. 6). It is apparent that, in addition to the simulated TC track and circulation, large-scale conditions and orographic lifting are also crucial for the record breaking rainfall associated with Morakot over Taiwan. This problem will be further investigated in the next section.

5. Large-scale factors contributing to the heavy rainfall associated with Morakot

The FNL data are used to diagnose the large scale patterns of wind, geopotential height, and precipitable water (PW) associated with Morakot. During 5-9 August, Morakot is embedded within a monsoon gyre (Fig. 7), defined as a large monsoon cyclonic vortex, with a size of about 2500 km (Lander, 1994).

During the heavy rainfall period, (7 to 8 August), another TC, Goni, is also embedded within the monsoon gyre southwest of Morakot (Figs. 7). Figure 7 shows that the wind vectors in the southeast section of Goni's circulation and to the southwest of the monsoon gyre circulation are southwesterlies on 7 to 8 August. The strong (30 to 40 m s^{-1}) southwesterly winds, bring the high PW anomaly air (Fig. 8) from low latitudes and from the vicinity of Goni's circulation toward Morakot and Taiwan. It appears that the existence of Goni within the monsoon gyre is important for the presence of higher moisture air in flow toward the island of Taiwan.

During 7-8 August, there is a tropical depression embedded within the monsoon gyre to the east of Morakot (Fig. 7). Strong (> 20 m s^{-1}) southeasterly winds along the east/northeast periphery of the monsoon gyre bring high PW anomaly air toward the south China coast and finally with the northwesterly winds west of the Morakot circulation toward southwest Taiwan (Fig. 8). It is no doubt that orographic lifting of the warm, moist flows by the broad westerly wind components in the monsoon and Morakot's circulation (Figs. 9) is one of the crucial factors for the development of heavy rainfall. However, if the high moisture air associated with Goni as well as the tropical depression embedded within the monsoon gyre did not exist, and if the high moisture air associated with the southwest monsoon flow were not present, the record rainfall over Taiwan probably would not have occurred. A schematic diagram showing circulations of the three tropical storms embedded within the monsoon gyre with elevated PW is given in Figure 9. The flows that help to bring moisture impinging on the western slopes of southern Taiwan along the southwestern quadrant of the Morakot circulations are highlighted by small arrows with waving tails.

6. Summary and discussions

In this work, a model self-bogus vortex is constructed by model cycle runs using the WRF model Version 3 to provide high-resolution initial conditions for tropical cyclone simulations (NT). During the cycle runs, only SLP is forced at the first time step of each cycle run by an empirical profile assuming that in a short period (~1 h), the TC moves, but its structure does not change significantly. The vortex after 1-h of model simulation is used to construct the vortex structure at the initial condition for the next cycle run. After about 30 ~ 60 1-h cycle runs, the tropical cyclone structure is well established under the given large scale conditions.

Three separate runs initialized at 0000 UTC 6 August, 2009 with three different initial conditions including the CTRL, WB, and NT runs were performed for Hurricane Morakot (2009) to investigate the impacts of TC initialization on TC forecasts. Without vortex initialization, the simulated vortex in the CTRL run is too weak. The WRF bogus scheme (WB) can reasonably generate some features of the TC including lower minimum SLP, and stronger winds in the TC core at the model initial time. However, there are several shortcomings in the WRF bogus package including the fact that the altitude of the warm core is too low, and the simulated maximum wind speed is significantly weaker than observed. The NT run shows advantages over both the CTRL and WB runs in generating realistic vortex features at the initial time including SLP, winds, warm core, TC size, and asymmetric rainband structure. The NT run also shows improvements in simulating TC structure, intensity, low-level winds, and radar reflectivity as compared to both the CTRL and WB runs.

Sensitivity tests were performed with error statistics to examine the ability of the CTRL, WB, and NT runs in simulating track, intensity and rainfall for Morakot. With each type of initialization, seven 48-h model runs were performed with initialization at every 12 h from 0000 UTC 5 August to 0000 UTC 8 August. For the Morakot case, track simulations between 24 to 36 hours in the WB run are worse than in the CTRL. The NT run shows significant improvements in track and intensity simulations during the period (0000 UTC 5 - 0000 UTC 10 August) as compared to the other two runs. The mean 24-h track errors for the seven runs are 60 nm, 80 nm, and 40 nm for the CTRL, WB, and NT runs, respectively. The mean 48-h track errors are 150 nm, 120 nm, and 50 nm for the CTRL, WB, and NT runs, respectively. Mean 24-h maximum absolute wind speed errors are 15 kts, 13 kts, and 6 kts for the CTRL, WB, and NT runs, respectively. Mean 48-h maximum absolute wind speed errors are 14 kts, 11 kts, and 4 kts for the CTRL, WB, and NT runs, respectively. Mean absolute SLP errors at 24 h and 48 h of simulation in the NT run are about 1/3 and 1/2 of that in the CTRL and the WB runs, respectively.

The NT run has better rainfall simulation over the open ocean as compared to the other two runs. Over Taiwan, all three different types of model initializations can simulate the location and amount of heavy rainfall related to Morakot reasonable well. It is apparent that the heavy rainfall related to Morakot may not be solely controlled by Morakot's circulation and orographic lifting of TC circulations. In addition to Morakot, typhoon Goni and another tropical depression were embedded in a moist environment within a monsoon gyre. During three days of the heaviest rainfall, 7-8 August, Taiwan is on the southwestern quadrant of Morakot, In addition to TC circulations associated with Morakot, the increase in the southwesterlies associated with the combined circulations of Goni, Morakot, and the monsoon gyre to the southwest of Taiwan and the increase in northwesterlies associated with the combined Morakot/monsoon gyre circulations to the northwest of the Taiwan Strait help to bring a persistent moist laden westerly wind component impinging on the slopes of southern Taiwan.

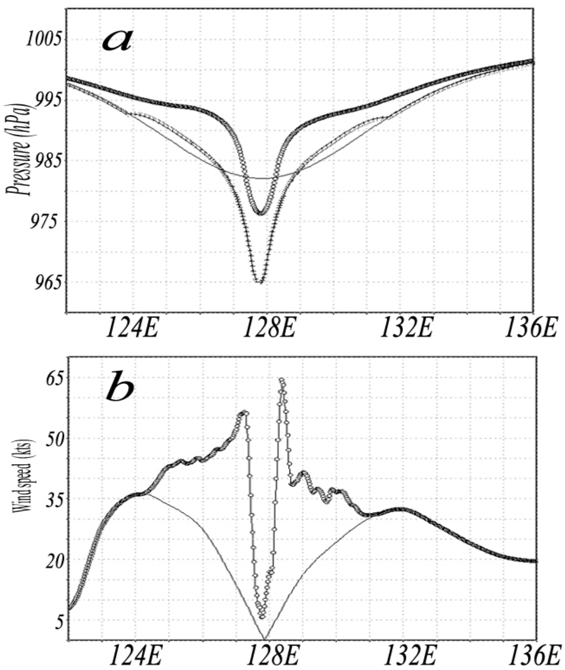

Fig. 1. East-west cross section along TC center (23.0 N) of (a) SLP for the CTRL (thin line), WB (open circle) and NT (cross) runs, (b) 10-m wind speed (kts) for the CTRL (thin line), NT (open circle) runs.

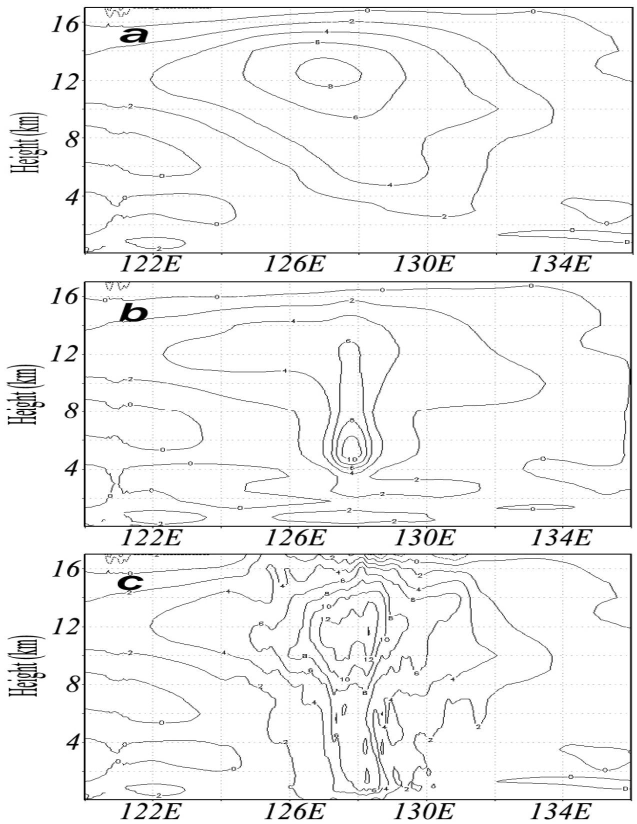

Fig. 2. Vertical cross sections through the TC center of temperature anomalies (K) from the environment at the same height for 0000 UTC 6 August, 2009 for (a) the CTRL, (b) WB, and (c) NT runs.

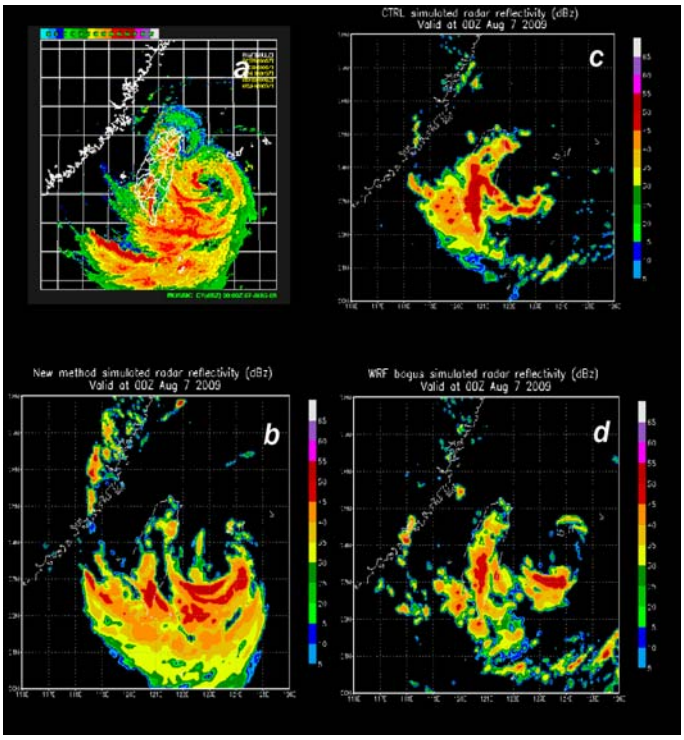

Fig. 3. Horizontal distribution of radar reflectivity at 0000 UTC 7 August, 2009 for (a) observed, (b) the NT, (c) CTRL, and (d) WB runs after 24 h of integrations.

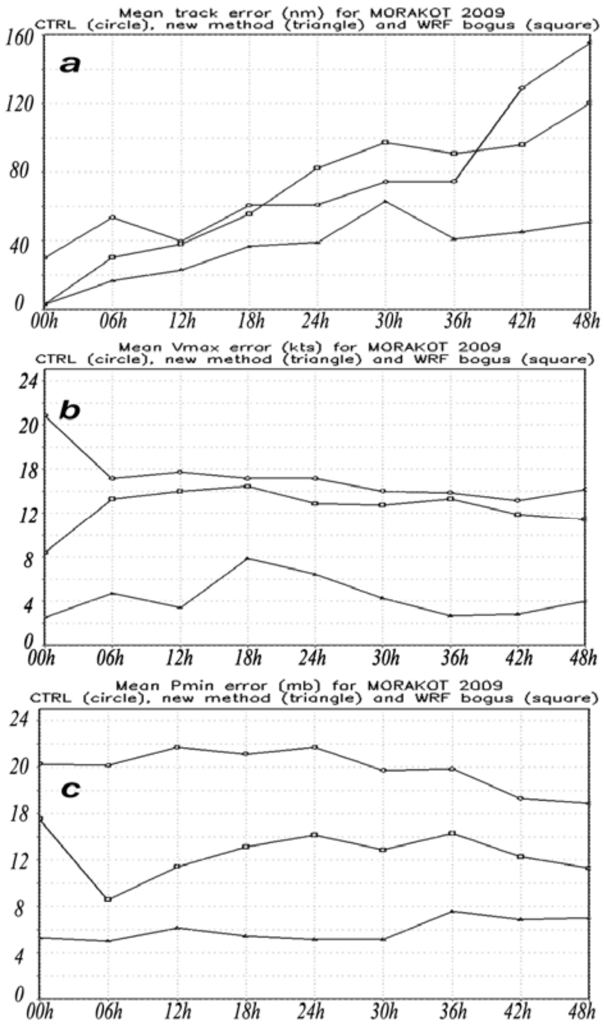

Fig. 4. Mean absolute errors of (a) track, (b) maximum wind speed, and (c) minimum SLP for the CTRL (circle), WB (square), and NT (triangle) runs.

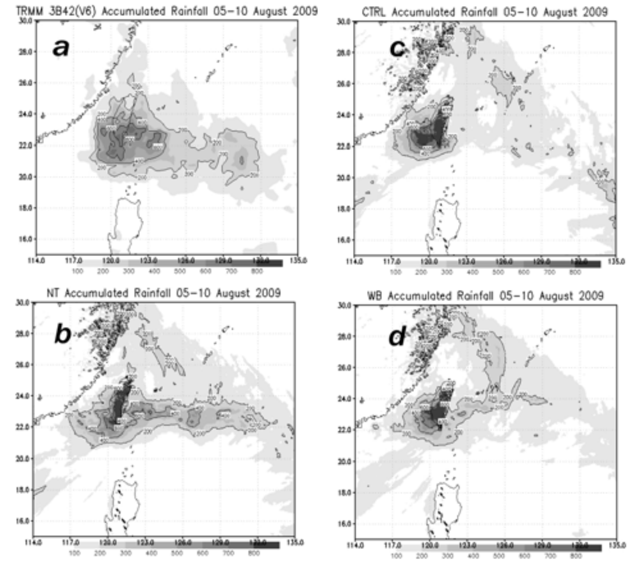

Fig. 5. 5-day rainfall accumulation (mm) from 0000 UTC 5 August, 2009 to 0000 UTC 10 August, 2009 over Taiwan and the adjacent oceans from (a) TRMM satellite observations, and 6-km simulations from (b) the NT, (c) CTRL, and (d) WB runs.

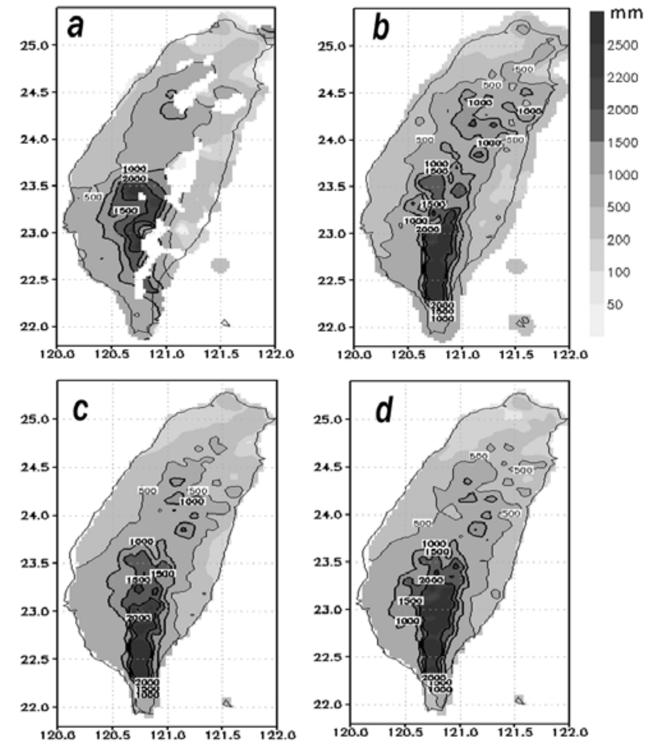

Fig. 6. 5-day rainfall accumulation (mm) from 0000 UTC 5 August to 0000 UTC 10 August, 2009 over Taiwan for (a) observation, and 6-km simulations from (b) the NT, (c) CTRL, and (d) WB runs.

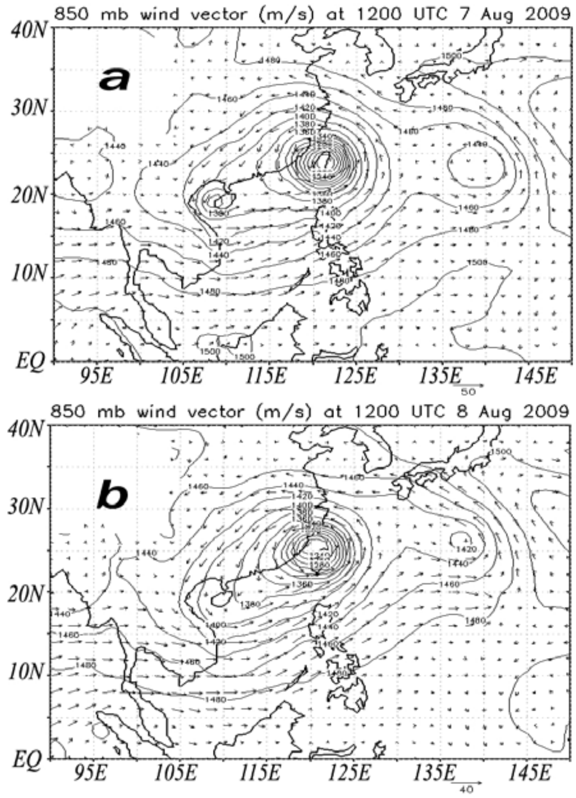

Fig. 7. FNL analysis of 850 hPa winds (m s^{-1}) and geopotential height (m) at 1200 UTC 7 (a), 8 (b) August, 2009.

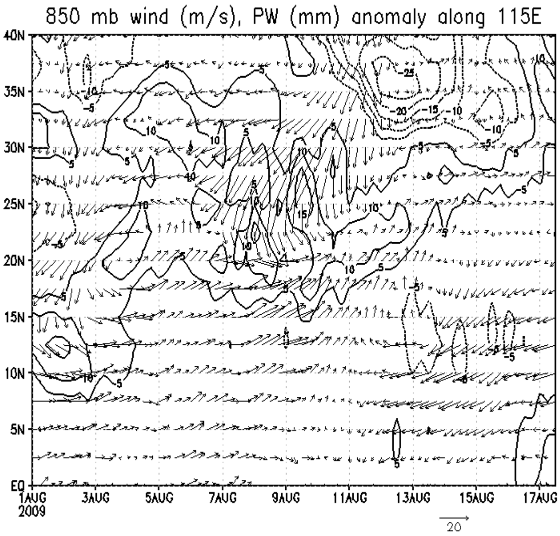

Fig. 8. Time-latitude cross section along 115^{o}E of FNL 850-hPa wind anomalies (m s-1) and precipitable water anomalies (mm) from August long term mean.

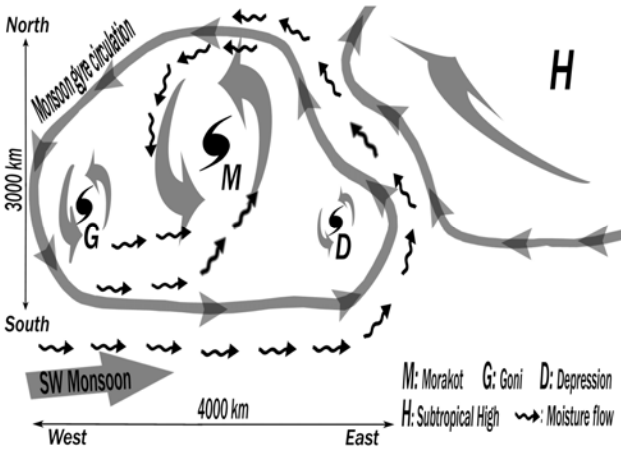

Fig. 9. Schematic diagram of Morakot embedded within a monsoon gyre circulation and the flows of moist laden air (highlighted with small arrows with waving tails) associated with Morakot as the flow with a westerly component impinging on the western slope of southern Taiwan. Southern Taiwan is on the southwestern quadrant of Morakot's circulations during the period with heavy precipitation (7-9 August).

Acknowledgements

This work was supported by the Pacific Disaster Center, Kihei, Hawaii. We would like to acknowledge the USDA Forest Service, the University of Hawaii/Maui High Performance Computing Center (UH/MHPCC) for also funding this research, Profs. F. F. Jin, P-S. Chu, D. E. Stevens, and K. F. Cheung for their comments, and Mei-Yu Chang, Dr. S.-C. Lin Central Weather Bureau, Taiwan for the land surface data and rainfall data used in this research.

References

Fujita, T., 1952: Pressure distribution within typhoon. Geophys. Mag., 23, 437-451.

Kurihara, Y., M. A. Bender, and R. J. Ross, 1993: An Initialization scheme of hurricane models by vortex specification. Mon. Wea. Rev., 121, 2030-2045.

Kwon I.-H., H.-B Cheong, 2009: Tropical cyclone initialization with spherical high-order filter and idealized three-dimensional bogus vortex. Mon. Wea. Rev., in Press.

Lander, M. A., 1994: Description of a monsoon gyre and its effect on the tropical cyclones in the Western North Pacific during August 1991. Wea. Forecasting, 9, 640-654.

Low-Nam, S., and C. Davis, 2001: Development of a tropical cyclone bogusing scheme for the MM5 system. Preprints, 11th PSU/NCAR Mesoscale Model Users' Workshop, Boulder, CO, National Center for Atmospheric Research, 130–134.

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, and J. G. Powers, 2005: A description of the Advanced Research WRF version 2. NCAR Tech. Note TN-468 STR, 88 pp.

Wang, D., X. Liang, Y. Zhao, B. Wang, 2008: A comparison of two tropical cyclone bogussing schemes. Wea. Forecasting, 23, 194-204.

Wu, T.-H. Yen, Y.-H. Kuo, and W. Wang, 2002: Rainfall simulation associated with Typhoon Herb (1996) near Taiwan. Part I: The topographic effect. Wea. Forecasting, 17, 1001–1015.

——, K. K. W. Cheung, and Y. Y. Lo, 2009: Numerical Study of the Rainfall Event due to the Interaction of Typhoon Babs (1998) and the Northeasterly Monsoon. Mon. Wea. Rev., 137, 2049–2064.

Zhang, Y., Y.-L. Chen, S.-Y. Hong, H.-M. H. Juang, and K. Kodama, 2005: Validation of the Coupled NCEP Mesoscale Spectral Model and an Advanced Land Surface Model over the Hawaiian Islands. Part I: Summer trade wind conditions and a heavy rainfall event. Wea. Forecasting. 20, 847-872

Zou, X., and Q. Xiao, 2000: Studies on the initialization and simulation of a mature hurricane using a variational bogus data assimilation scheme. J. Atmos. Sci., 57, 836-860.