Improved Goddard Microphysics in the Simulation of Typhoon Morakot 2009

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1. INTRODUCTION

In recent years, heavy rainfall associated with severe weather events (e.g., typhoons, local heavy precipitation events) has caused significant damage to the economy and loss of human life throughout Taiwan. For example, Typhoon Morakot struck Taiwan on the night of Friday August 7th, 2009 as a Category 2 storm with sustained winds of 85 knots (92 mph). Although the center made landfall in Hualien county along the central east coast of Taiwan and passed over the central northern part of the island, it was southern Taiwan that received the worst effects of the storm where locally as much as 2400 mm of rain were reported, resulting in the worst flooding there in 50 years. The enormous amount of rain resulted in massive flooding and devastating mudslides. More than 600 people were confirmed dead (including hundreds of people in Shiao Lin Village, which was buried by a large mudslide).

However, Taiwan's geographic features pose a major challenge when it comes to predicting heavy rains associated with the Mei-Yu, MCSs and typhoons. For example, two-thirds of Taiwan is mountainous; the most prominent feature is the Central Mountain Range (CRM), which is oriented in a north-south direction with an average terrain height of 2000 m and a peak of 4000 m. This unique orography cannot only generate its own local circulation but also interact with large-scale and mesoscale weather phenomena such as the Mei-Yu front, MCSs and typhoons. In addition, Taiwan is an island with a major source of moisture provided by southwesterly winds flowing from the South China Sea; it also feels the dynamic and thermodynamic influence of the Asian continent.

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Advances in computing power allow atmospheric prediction models to be run at progressively finer scales of resolution, using increasingly more sophisticated physical parameterizations and numerical methods. A report to the United States Weather Research Program (USWRP) Science Steering Committee calls for the replacement of implicit cumulus parameterization schemes with explicit bulk microphysical schemes to improve Quantitative Precipitation Forecasts (QPF) using non-hydrostatic high-resolution numerical forecast models. The keys to these high resolution modeling systems include the accuracy of the parameterization of complex physical processes (including their interactions), notably moist convective processes and land/ocean interaction with the atmosphere, and the understanding of the resolution-dependence of the parameterized physical processes.

2. Typhoon Morakot (2009)

Analyses by Hong et al. (2009) and Huang-Hsiung Hsu (personal communications) indicated that Typhoon Morakot originated in a large-scale monsoon gyre in the northwestern Pacific where moist southwesterly monsoonal flow meets southeasterlies at the western end of the subtropical Pacific high. Morakot was embedded in a large-scale cyclonic circulation associated with the cyclonic phase of the 40-50-day oscillation and a 10-30-day wave pattern. The latter is consistent with climatological features of quasi-biweekly oscillations over the northwestern Pacific (e.g. Chen and Sui 2010) . It is suggested that the multiscale interaction between the typhoon and large-scale circulation and the topographic effect of the steep terrain in southern Taiwan were the key factors leading to this extreme event.

Morakot began as a tropical depression on the morning of the 4th of August (local time) in the central

Philippine Sea about midway between the Northern Mariana Islands and Taiwan. The system strengthened into a tropical storm later on the 4th and became a typhoon on the morning of the 5th as is tracked due westward toward Taiwan. Morakot maintained Category 1 intensity on the 6th with sustained winds estimated at 80 knots (~92 mph) by the Joint Typhoon Warning Center. The storm briefly reached Category 2 intensity with sustained winds of 85 knots (~98 mph) as it neared the coast of Taiwan on the 7th. The Tropical Rainfall Measuring Mission satellite (commonly known as TRMM) was launched back in November of 1997 with the primary objective of measuring rainfall in the Tropics. Besides its own estimates, TRMM can also be used to calibrate rainfall estimates from other satellites for increased coverage. The TRMM-based, near-real time Multi-satellite Precipitation Analysis (TMPA) at the NASA Goddard Space Flight Center is used to monitor rainfall over the global Tropics. TMPA rainfall totals associated with the passage of Morakot are shown here for the period 3 to 10 August 2009. The storm's track is shown by the appropriate tropical cyclone symbols (Fig. 1). The analysis shows extremely heavy amounts of rain over the southern half of Taiwan, which is on the southern side of the storm track. Nearly the entire southern half of the island has in excess of 600 mm (~24 inches, shown in yellow shading) of rain. Within that are two areas in excess of 1000 mm (~40 inches, shown in red) along the western slopes of the CMR.

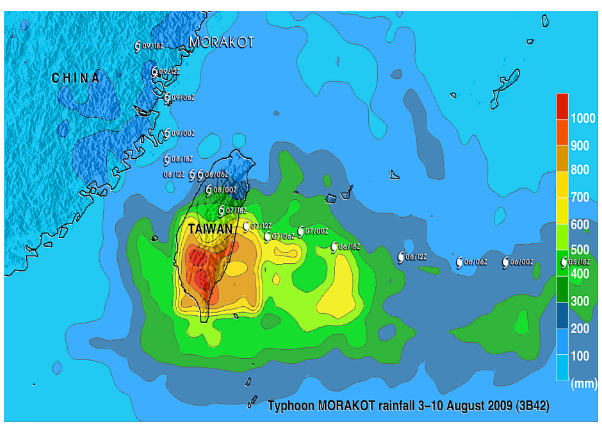


Fig. 1 *Total surface rainfall estimates in mm for the period 3-10 August 2009 from the TRMM-based, near-real time Multi-satellite Precipitation Analysis (i.e., 3B42) associated with Typhoon Morakot. Appropriate tropical cyclone symbols mark the path of the storm.*

After crossing Taiwan, Morakot eventually made landfall in China on the afternoon of the 10th. Eight persons were reported to have died there. And despite its center being nowhere near the islands, Morakot was blamed for 25 deaths in the Philippines (where it was known locally as Kiko) due to flooding and mudslides.

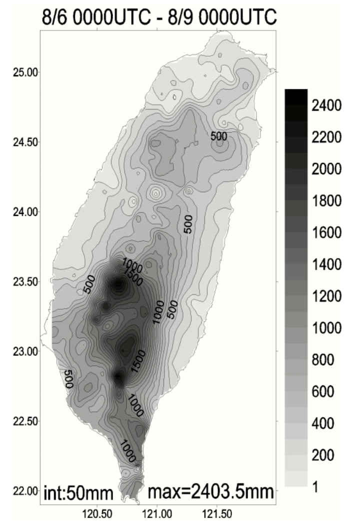


Fig. 2 *Observed accumulated rainfall from August 6 0000UTC to August 9 0000UTC 2009.*

3. Model set-up

3.1 Weather Research and Forecast (WRF) Model

WRF is a next-generation mesoscale forecast model and assimilation system that will be used to advance the understanding and the prediction of mesoscale precipitation systems. The model has incorporated advanced dynamics, numeric and data assimilation techniques, a multiple re-locatable nesting capability, and improved physical packages. WRF can be used for a wide range of applications, from idealized research to operational forecasting, with an emphasis on horizontal grid sizes in the range of 1-10 km. WRF has been widely adopted to replace existing research and forecast models (i.e., MM5, NCEP/ETA).

At Goddard, the Mesoscale Modeling and Dynamics Group has implemented the Goddard ice microphysical scheme with several options (Tao *et al.* 2003a; Lang *et al.* 2007; and Zeng *et al.* 2008) into WRF V2.2.1 and V3.1.1. The Goddard radiation scheme (including explicitly calculated cloud optical properties) was recently implemented into and tested in WRF V3.1. WRF can also be initialized with Goddard Earth Observing System (GEOS) global analyses. This link between GEOS global analyses and WRF allows for many useful regional modeling applications. For example, a series of weeklong WRF simulations were conducted to test the sensitivity of the initial and boundary conditions derived from NCEP, ECMWF, and GEOS on simulations of precipitation and chemistry (for air pollution study) transport over the eastern USA and East Asia.

3.2 *Microphysics scheme*

The Goddard Cumulus Ensemble (GCE) model's (Tao and Simpson 1993) one-moment bulk microphysics were implemented into WRF. The scheme is mainly based on Lin *et al.* (1983) with additional processes from Rutledge and Hobbs (1984). However, the Goddard microphysics scheme has several modifications. First, there is an option to choose either graupel or hail as the third class of ice (McCumber *et al.* 1991). Graupel has a relatively low density and a high intercept value (i.e., more numerous small particles). In contrast, hail has a relative high density and a low intercept value (i.e., more numerous large particles). These differences can affect not only the description of the hydrometeor population and formation of the anvil-stratiform region but also the relative importance of the microphysical-dynamical-radiative processes. Second, a new saturation technique (Tao *et al.* 1989) was added. This saturation technique is basically designed to ensure that super saturation (sub-saturation) cannot exist at a grid point that is clear (cloudy). The saturation scheme is one of the last microphysical processes to be computed. It is only done prior to evaluating the evaporation of rain and deposition or sublimation of snow/graupel/hail. Third, all microphysical processes that do not involve melting, evaporation or sublimation (i.e., transfer rates from one type of hydrometeor to another) are calculated based on one thermodynamic state. This ensures that all of these processes are treated equally. The opposite approach is to have one particular process calculated first modifying the temperature and water vapor content (i.e., through latent heat release) before the next process is computed. Fourth, the sum of all sink processes associated with one species will not exceed its mass. This ensures that the water budget will be balanced in the microphysical calculations.

In addition to the two different 3ICE options (i.e., cloud ice, snow and graupel or cloud ice, snow and hail) implemented into WRF 2.2.1 and 3.1.1, the Goddard microphysics has other two options. The first one is equivalent to a two-class ice (2ICE) scheme having only cloud ice and snow. This option may be needed for coarse resolution simulations (i.e., > 5 km grid size). The 2ICE scheme could also be applied for winter and frontal convection (Tao *et al.* 2009; Shi *et al.* 2010). The second one is warm rain only (cloud water and rain). Recently, the Goddard 3ICE options were modified to reduce over-estimated and unrealistic amounts of cloud water and graupel in the stratiform region (Tao *et al.* 2003a; Lang *et al.* 2007). Various assumptions associated with the saturation technique were also revisited and examined (Tao *et al.* 2003a). A spectral bin microphysics (SBM) scheme was also recently implemented into WRF V3.1. The following are recent modifications to the Goddard scheme that were implemented into WRF.

<u>*(a) An improved rain evaporation process*</u>

By comparing the bulk and SBM, it was found that the evaporation of rain in the bulk scheme is usually too large. An empirical correction factor—$r(qr)$ = $0.11q^{-1.27}r + 0.98$, where q_r is the rain mixing ratio (g kg^{-1})—was developed to correct the overestimation of rain evaporation in the bulk scheme (Li *et al.* 2009). Applying $r(q_r)$ in the bulk scheme produces spatial and temporal variation modes similar to those in sensitivity tests using the mean evaporation reduction factor. However, using $r(q_r)$ consistently results in a larger stratiform area. Similarly, it is possible to modify the ice phase microphysics in the bulk simulation using the bin scheme (see Fig. 1). However, ice phase microphysics has many uncertainties, including ice initiation and multiplication and the density, shape, and terminal fall velocity of various ice species and their interactions with one another. Many fundamental processes in ice microphysics are still being actively researched. Planned future studies include validating the ice microphysics in the bin scheme using both in situ and remote observations. After gaining confidence in the SBM, it will then be used to improve the bulk microphysical scheme.

<u>*(b) A reduced bias in the excessive penetration of 40 dBZ echoes at high altitude*</u>

It is important to continue to examine and improve the performance of the WRF's bulk microphysics schemes. For example, there is a well-known bias in bulk schemes, which tend to generate excessively large reflectivity values (e.g., 40 dBZ) aloft due to graupel (e.g., Lang *et al.* 2007; Li *et al.* 2009). This bias is also related to a bias in excessive simulated ice scattering. The performance of the GCE bulk microphysics scheme was improved by reducing the bias in over penetrating 40-dBZ echoes at higher altitudes (Fig. 1), which is due mainly to excessively large amounts and/or sizes of graupel particles at those altitudes. This also improved the overall model reflectivity probability distribution (i.e., CFADs). These improvements were achieved by systematically evaluating and improving individual ice processes in the bulk scheme such as: (1) accounting for relative humidity and mean cloud ice mass in the Bergeron process for snow, (2) adding a simple Hallett-Mossop rime splintering parameterization, (3) replacing the Fletcher curve, which determines the number of active ice nuclei as a function of temperature, with the Meyers *et al*. (1992) curve, which determines the active ice nuclei as a function of ice supersaturation, in the cloud ice nucleation, depositional growth and Bergeron growth parameterizations, (4) relaxing the saturation scheme to allow for ice supersaturation, (5) adding two additional parameterizations for contact nucleation and immersion freezing, (6) including cloud ice fall speeds, (7) allowing graupel and snow to sublimate (the original R&H scheme only allows graupel and snow deposition but not sublimation, and (8) mapping the snow and graupel intercepts (effectively the mean snow and graupel particle diameters) as functions of temperature and mass.

3.3 WRF set-up for Morakot

WRF V3.1 with improved microphysics is used to simulate Typhoon Morakot. Figure 3 shows the WRF nested domains, with 18, 6 and 2 km resolution and corresponding grid sizes of 391x322x61, 475x427x61, 538x439x61 points, respectively. Time steps of 18, 6 and 2 seconds are used in these nested grids, respectively. The Grell-Devenyi (2002) cumulus parameterization scheme was used for the outer grid (18 km) only. For the inner two domains (6 and 2 km), the Grell-Devenyi parameterization scheme was turned off. The planetary boundary layer parameterization employed the Mellor-Yamada-Janjic (Mellor and Yamada 1992) turbulence closure model. The surface heat and moisture fluxes (from both ocean and land) were computed from similarity theory (Monin and Obukhov 1954). The land surface model is based on Chen and Dudhia (2001). It is a 4-layer soil temperature and moisture model with canopy moisture and snow cover prediction. The Goddard broadband two-stream (upward and downward fluxes) approach was used for the shortwave and longwave radiative flux calculations (Chou and Suarez 1999). The model was initialized from NOAA/NCEP/GFS global analyses (1.0^{o} by 1.0^{o}). Time-varying lateral boundary conditions were provided at 6-h intervals.

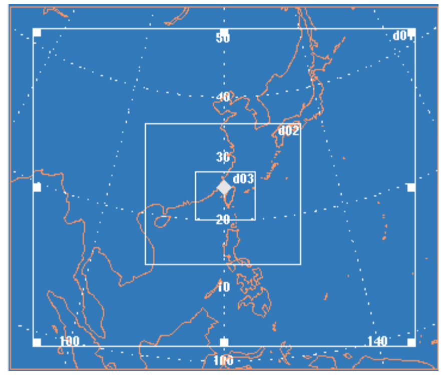
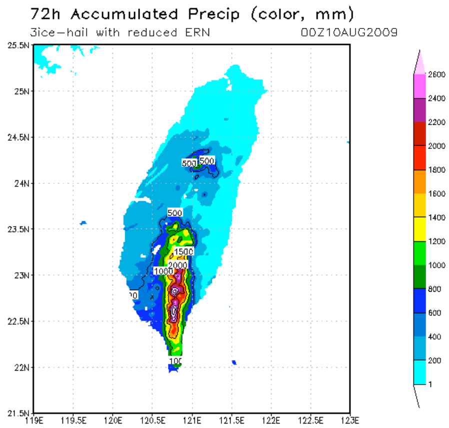


Fig. 3 WRF inter-nesting model configuration used for the Typhoon Moratok case. Horizontal resolutions for the 3 domains are 18, 6 and 2 km, respectively.

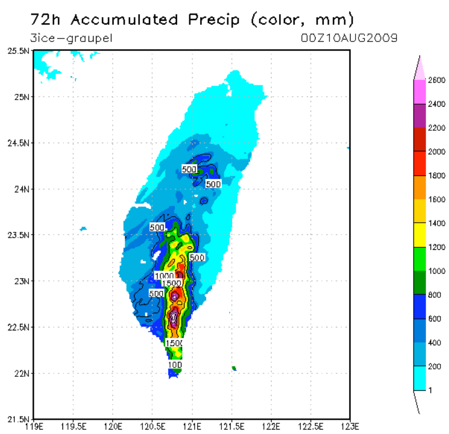
4. Results

Figure 4 shows the WRF-simulated rainfall using two different options (improved and original 3ICE-graupel) in the Goddard microphysical scheme. Generally speaking, WRF produced the right distribution of precipitation for this typhoon case despite using different Goddard microphysical options. For example, in all of the runs the main precipitation event is elongated in the southwest-northeast direction and concentrated in a heavy north-south line over southern Taiwan as observed (Fig. 2). Both options resulted in simulations wherein the main area of precipitation continued over southern Taiwan over the 72-h period. This feature also generally agrees with observations (Fig. 2). The results (with high resolution visualization) show that a persistent (over 48 h) southwesterly flow associated with Morakot and its circulation was able to draw up copious amounts of moisture from the South China Sea into southern Taiwan where it was able to interact with the steep topography in all four microphysical options. These results suggest that the main rainfall distribution in the Morakot case is determined by the large-scale circulation pattern (i.e., the typhoon-induced circulation). The interaction between the terrain and moisture flux was the dominant factor that led to the floods/landslides in this case. However, less rainfall was simulated with the warm rain only option as compared to those options with ice processes (see Table 1) and clearly indicates the importance of ice processes in the production of rainfall in this case. All of the ice options produced more than 2000 mm of accumulated rainfall over southern Taiwan. The improved 3ICE-graupel option simulated a maximum rainfall amount in better agreement with observations than the other two ice options (Table 1). Also, the improved 3ICE-graupel produced more rainfall over northeastern

Taiwan, which may be in better agreement with observations than other schemes (see Figs. 2 and 4).



(a)



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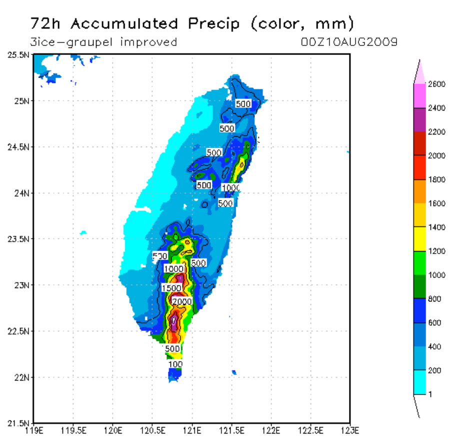

(c)

Fig. 4 WRF-simulated accumulated surface rainfall (mm) from 08Z Aug 7 to 08Z Aug 9, 2009 using the Goddard 3ICE microphysics: (a) 3ICE-hail with reduced evaporation, (b) original 3ICE-graupel, and (c) improved 3ICE-graupel.

	48–hour Maximum Rainfall (mm)	72-hour Maximum Rainfall (mm)
3ICE-hail with reduced evaporation	**2867**	**3307**
3ICE-graupel	**2856**	**3345**
3ICE–graupel improved	**2396**	**2942**
Warm Rain Only	**1589**	**2000**
Observed	**2143**	**2434**

Table 1 Maximum WRF-simulated rainfall amounts using different Goddard microphysical options (including the improved as described in Section 3.2). The observed maximum rainfall is also shown for comparison.

5. REFERENCES

Provided upon request.

6. Acknowledgements

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