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區域模式物理參數化方法之改進與研究

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本成果報告包括以下應繳交之附件(或附錄)：See enclosed.

中華民國 100 年 12 月 5 日

政府研究計畫期末報告摘要資料表

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2. Examine and modify the various microphysical processes (i.e., terminal velocity, condensation and evaporation rate) for 2-5 km grid spacing WRF simulations and,
3. Optimize/select a set of WRF's physical processes – a suite (a combination of particular microphysical, cumulus parameterization and planetary boundary layer schemes) for better QPF.</td></tr>
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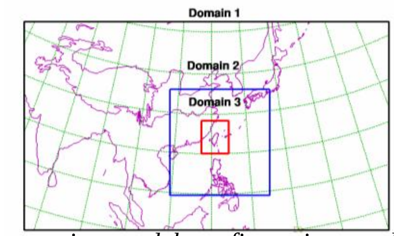
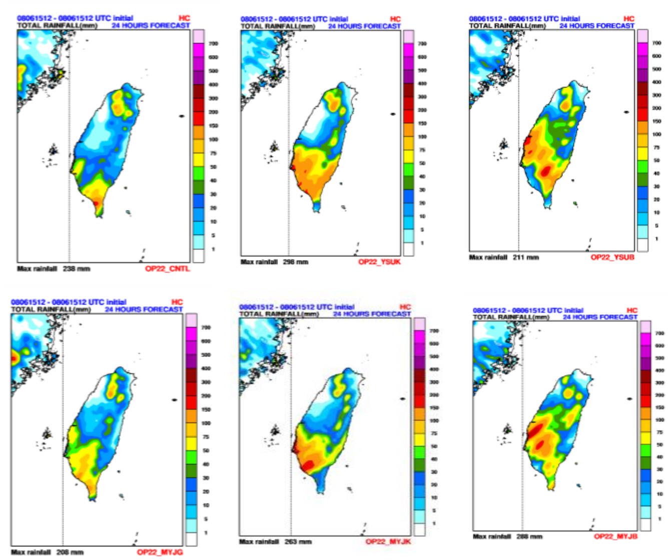


WRF Inter-nesting model configuration used for SoWMEX case. Horizontal resolutions for domains are 45, 15 and 5 km, respectively.

CWB's WRF simulated surface rainfall (mm) WRF simulated accumulated surface rainfall (mm) between 12 Z (UTC) June 15 to 12 Z June 18 2008 using Goddard 3ICE microphysical scheme. Top panel shows the observed rainfall. Middle panels are YK (left), YB (middle) and YG-control (right). Bottom panels are MK (left), MK (middle) and MB (right)
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中文摘要

近年來，台灣地區劇烈天氣系統(如颱風、局部豪大雨系統等)所帶來的強烈降水對於民生及經濟都有很大的損害。舉例來說，2009 年莫拉克颱風帶來的劇烈降水導致山崩，就造成了 600 多人的死亡。因此，改進高解析度模式之定量降水預報(Quantitative Precipitation Forecasts, QPF)便成為氣象局研究之首要需求之一。

本計畫將一個經過改進的雲物理及輻射參數化方法(包含其交互作用)放入目前最先進的數值模式 WRF(Weather and Research Forecast, WRF)之中，藉由模式中成雲過程的改進，使得颱風及其他劇烈天氣系統可以被較真實的模擬、預報及研究。

此項研究委託計畫的主要目標，可總結為三個主要的部份：

(1) 持續改進、測試以及評估 WRF 模式中 microphysical schemes 以及 radiative processes 的效能。此二項物理過程正植入 WRF V3.1.1 及 WRF3.2.1 版本當中。
(2) 針對 WRF 模式 2-5 公里網格之模擬，檢查及修正其微物理過程(即終端速度、凝結與蒸發率)。
(3) 研究 WRF 模式中之物理過程－找出能產生較佳定量降水預報之組合(微物理、積雲參數化以及行星邊界層方法)。

可以預期這些 WRF 模式研究所產生之較佳的降水預報及其他相關資訊應可供作業單位做為有用的參考。

(1) 針對模式中改進之微物理及輻射方法對於地面降水預報的效能，做一詳盡的個案研究
(2) 測試在 WRF 模式中，不同解析度網格之微物理、輻射以及邊界層方法在降水過程中的交互作用
(3) 選取出 WRF 模式中對於降水過程有改善的最佳物理方法之組合(特別是對劇烈系統有改進者)

Summary

In recent years, the heavy rainfall that was associated with severe weather events (e.g., typhoons, local heavy precipitation events) has caused significant damages in the economy and loss of human life throughout Taiwan. For example, more than 600 people were dead due to the heavy rainfall – landslide associated with Typhoon Morakot 2009. An improvement of quantitative precipitation forecasts (QPF) using high-resolution numerical models should be one of the high priorities in CWB research.

An improved cloud microphysics and radiation (including their explicit interaction) parameterization has been implemented into the the-state-of-the-art Weather and Research Forecast (WRF) model. By adding the improved cloud processes in the WRF, the microphysics and their effect on precipitation processes associated with typhoons and other severe weather events can be realistic simulated, forecasted and studied.

The goals of this proposed WRF modeling research are summarized into three major areas:

1. Continue improving, testing and evaluating the performance of the microphysical schemes and radiative processes in WRF. These two physical processes are being implemented into the WRF V 3.1.1 and V3.2.1,
2. Examine and modify the various microphysical processes (i.e., terminal velocity, condensation and evaporation rate) for 2-5 km grid spacing WRF simulations and,
3. Optimize/select a set of WRF's physical processes – a suite (a combination of particular microphysical, cumulus parameterization and planetary boundary layer schemes) for better QPF.

It is expected that these WRF modeling research at CWB can provide better precipitation and rainfall forecast and related information to the operational unit for reference and guidance. It is proposed to:

(1) Conduct the detailed case studies on the evaluating the performance of the improved microphysical and radiation scheme on surface rainfall forecast
(2) Test the interactions between microphysics, PBL and cumulus parameterization for precipitation processes at different grid spacing in WRF
(3) Identify the physical suite for WRF for improving the simulation of precipitation processes (especially for those of associated with impact weather events).

1. Introduction

In recent years, the heavy rainfall that was associated with severe weather events (e.g., typhoons, local heavy precipitation events) has caused significant damages in 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 2000 mm of rain were reported, resulting in the worst flooding there in 50 years. The result of the enormous amount of rain has been massive flooding and devastating mudslides. More than 600 people are confirmed dead (including hundreds of people in Shiao Lin, which was destroyed by a large mudslide). An improvement of quantitative precipitation forecasts (QPF) using numerical models should be one of the highest priorities in CWB research.

However, Taiwan's geographic feature causes a major challenge for predicting/forecasting heavy precipitation and its associated surface rainfall associated with Mei-Yu, MCS and typhoon. For example, two-thirds of Taiwan is mountainous, in particular, the Central Mountain Range (CMR) oriented in a north-south direction with averaged terrain height of 2000 m and a peak of 4000 m. With this unique orography, the mountains could not only generate its own local circulation, but also interact with large and mesoscale weather phenomena, such as Mei-Yu front, MCS and typhoon. In addition, Taiwan is a island with major moisture sources from south-western from South China Sea and dynamic and thermodynamic influences from a major continent (China).

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 an explicit bulk microphysical scheme to improve QPF using the non-hydrostatic high-resolution numerical forecast model. The keys of the high resolution modeling system should also relay on 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 the resolution-dependence of the parameterized physical processes.

A sophisticated cloud microphysics (Lang *et al.* 2011) scheme has been recently implemented into a high-resolution non-hydrostatic weather research and forecast system (WRF). This physical process is being implemented into the WRF V3.1.1 for operational in Spring 2011 a CWB. The improved microphysical process and their interactive processes with PBL and on precipitation and rainfall in the WRF still need to be investigated. Specifically, we will (1) test and improve the performance of the this cloud microphysical processes on severe weather events over Taiwan region, (2) examine the impact of different physical processes (i.e., interactions between cumulus parameterization and planetary boundary layer schemes) on QPF, (3) examine the sensitivity of the strength and evolution of simulated convective systems and hurricanes to vertical and horizontal grid resolution and, (4) select a physical suite (a combination of particular microphysical, cumulus parameterization and planetary boundary layer schemes) for better QPF. It is expected that these WRF modeling research at CWB can provide precipitation and rainfall forecast and related information to the operational unit for reference and guidance.

2. Methodology

The success of numerical modeling at all scales of motion depends on (1) the quality of the initial conditions, (2) the boundary conditions represented at the surface and at the lateral boundaries in limited-area models, (3) the assimilation of diverse data sets into the models, (4) the representation of complex physical processes, (5) the accuracy of finite-difference approximations to the equations of motion, thermodynamic energy, and water continuity, and (6) the evaluation of the model through comparisons with observations. Current limitations in computing technology and in our knowledge of Earth Science prevent us from successfully simulating all diverse manifestations of atmospheric phenomena over all scales of motion. The efforts of this proposed modeling research will focus on (4) and (6), and on improving our understanding and the simulation of precipitation systems.

(2.1) Weather Research and Forecast (WRF) Model

The WRF is a next-generation mesoscale forecast model and assimilation system developed at NCAR along with several NOAA and DOD partners (Michalakes *et al*. 2004),. The model is designed to support research advancing the understanding and prediction of mesoscale precipitation systems. It incorporates advanced numerics and data assimilation techniques and has a multiple re-locatable nesting capability as well as improved physics. WRF will 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.

At Goddard, the modeling and dynamic group has implement several ice schemes (Tao *et al.* 2003a; Lang *et al.* 2007, 2011 and Zeng *et al.* 2008) into WRF V3.1.1 and V3.1.2. The Goddard radiation (including explicitly calculated cloud optical properties) is recently implementing into and testing into WRF. WRF can also be initialized with the Goddard Earth Observing System (GEOS) global analyses. This link between the GEOS global analyses and the WRF models could allow 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. In addition, two other GSFC modeling components have been coupled to the GSFC WRF representing the land surface (i.e., the Land Information System or LIS) and aerosols [i.e., the WRF Chemistry Model and Goddard Chemistry Aerosol Radiation and Transport Model (GOCART)].

The CRM-based packages have improved forecasts (or simulations) of convective systems [e.g., a linear convective system in Oklahoma (International H2O project, IHOP-2002), an Atlantic hurricane (Hurricane Katrina, 2005), high latitude snow events (Canadian CloudSat CALIPSO Validation Project, C3VP 2007), a heavy orographic-related precipitation event in Taiwan (Summer 2007) and Typhoon Morakot (2009)].

(2.2) Microphysics scheme

The Goddard Cumulus Ensemble (GCE) model's (Tao and Simpson 1993) one-moment bulk microphysical schemes were implemented into WRF. These schemes are mainly based on Lin *et al.* (1983) with additional processes from Rutledge and Hobbs (1984). However, the Goddard microphysics schemes have 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 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 schemes (i.e., cloud ice, snow and graupel or cloud ice, snow and hail) implemented into WRF 2.2.1 3.1.1, and 3.1.2, the Goddard microphysics has other two options. The first one is equivalent to a two-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 two-class ice scheme could be applied for winter and frontal convection (Tao *et al.* 2009; Shi *et al.* 2009). The second one is a warm rain only (cloud water and rain). Recently, the Goddard 3ICE schemes 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 Microphysical (SBM) scheme is recently implemented into WRF V3.1.1. The followings are recent modifications of Goddard scheme that was implemented into CWB WRF.

(a) An improved rain evaporation process

By comparing the bulk and spectral bin microphysics, 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})—is 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 study includes validating the ice microphysics in the bin scheme using both in situ and remote observations. After gaining confidence in the bin simulation, it will then be used to improve bulk microphysical schemes.

Note that this modification is only valid for severe thunderstorms (i.e., cloud velocity is over 20 m/s) and for the Goddard 3-ICE scheme with hail option. This modification could be applied for summer thunderstorms occurred in Taiwan.

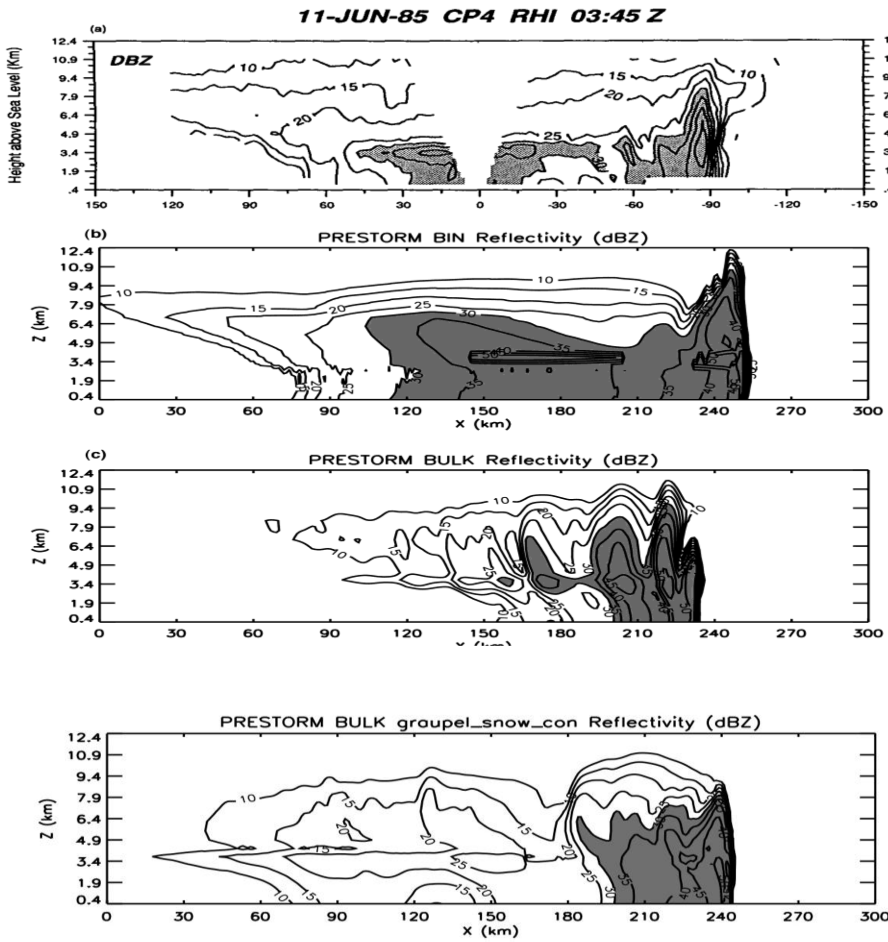


Fig. 1 *Observed (top panel), GCE-spectral bin microphysics (beneath the top panel), GCE-bulk microphysics (above the bottom panel) and GCE-bulk-improved microphysics (bottom panel) simulated instantaneous radar reflectivity (dBZ).*

(b) An improved microphysical scheme to reduce 40dBz at high altitude

There is a well-known bias common to many of the bulk microphysics schemes currently being used in cloud-resolving models. It involves the tendency for these schemes to produce excessively large reflectivity values (e.g., 40 dBZ) in the middle and upper troposphere in simulated convective systems and is primarily due to excessive amounts and/or sizes of graupel (e.g., Lang *et al.* 2007). This bias is also related to a bias in excessive simulated ice scattering. The Rutledge and Hobbs (1983,1984) based bulk microphysics scheme within the GCE model (Lang *et al.* 2011) and WRF (Tao *et al.* 2011) is modified to reduce this bias. Systematic evaluation of the scheme resulted in the following changes to individual processes: the efficiencies for snow and graupel riming and snow accreting cloud ice were lowered or made dependent on collector particle size, thresholds for converting rimed snow to graupel were tightened, snow and graupel were allowed to sublimate out of cloud, simple rime splintering, immersion freezing and contact nucleation parameterizations were added, the Fletcher (1962) curve for the number of activated ice nuclei was replaced with the Meyers *et al.* (1992) formulation throughout, the saturation adjustment scheme was relaxed to allow water saturation at colder temperatures and the presence of ice super saturation, ambient relative humidity and cloud ice size were accounted for in the "Bergeron" growth of cloud ice to snow, cloud ice fall speeds following Hong *et al.* (2004) were added and accounted for in the sweep volumes of processes accreting cloud ice, and the threshold for snow auto-conversion was changed to physical units. In addition, size-mapping schemes for snow and graupel were added whereby the characteristic size (i.e., inverse of the slope parameter for the inverse exponential distributions) was specified based on temperature and mixing ratio, effectively lowering the size of particles at colder temperatures while still allowing particles to become larger near the melting level and at higher mixing ratios. Table 1 gives a summary of all of the changes along with more details. Figure 2 shows time-height cross sections of maximum reflectivity simulated from the model using the new microphysics modifications, the original scheme and observations.

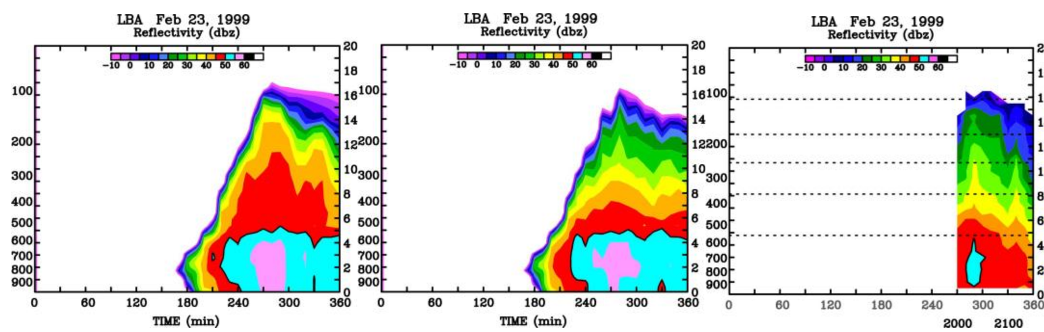


Fig. 2 Time-height cross sections of maximum radar reflectivity obtained from 3D simulations of the 23 February 1999 easterly regime event observed during TRMM LBA (Large Scale Biosphere-Atmosphere Experiment in Amazonia) using the original Rutledge and Hobbs (1984) based bulk microphysics formulation (left panel), an improved version (midde panel) and observed (right panel). Climatologically, 40-dBZ penetrations above 10 km are rare even over land (Zipser et al. 2006; Li et al. 2008). Ground-based radar data for this case indicated 40-dBZ echoes reached to approximately 8 km.

Process	Original	Modified	Reference(s)/Notes
Psaut	Efficiency: f(Tair)	Efficiency fixed, threshold: changed from g/g to g/m^{-3}	
Psaci	Esi = 0.1	Esi is f(snow diameter)	See mapping, Fig. X for size distribution for size distribution
Praci		Accounts for addition of cloud ice fall speed	Cloud ice fall speed follows Hong et al. (2004)
Psfi	Independent of RH	Depends on RH, accounts for cloud ice size via Meyers, which depends on ssi	Meyers et al. (1992)
Dgacs/Dgaci		Turned off	See Lang et al. (2007)
Dgacw	Egc = 1.0	Egc is f(graupel diameter)	See mapping, Fig. X for size distribution
Psacw/Pwacs	Esc = 1.0, Qc0 = 0.5 g/kg	Esc = 0.45, Qc0 = 1.0 g/kg	
Rime splintering	None	Added and applied to Psacw/Pgacw, no f(Vs/g) or f(cloud size)	Hallet and Mossop (1974); f(Tair) and splinter mass follow Ferrier (1994)
Pidw/Pidep	Based on Fletcher	Based on Meyers, which depends on ssi	Fletcher (1962); Meyers et al. (1992)
Pint		Based on Meyers, which depends on ssi, previous ice concentration	Fletcher (1962); Meyers et al. (1992)

	Based on Fletcher	checked	
Immersion Freezing	None	Added based on Diehl	Diehl and Wurzler (2004); Diehl et al. (2006), assumes Bh,i = 1.01 e-2 for pollen
Contact Nucleation	None	Added based on Cotton and Pruppacher for Brownian diffusion only	Cotton et al. (1986); Pruppacher and Klett (1980), 500 active nuclei per cc with radii of 0.1 microns
1444440	Sequential based Tao	Modified sequential, iterative, allows for ssi of up to 10%	Tao et al. (2003)
	None	Allowed if outside cloud and air subsaturated	
Snow/Graupel size	Based on fixed intercepts	Based on intercepts mapped according to snow/graupel mass and temperature	
Cloud ice fall Speed	None or based on Starr and Cox	Based on Hong	Hong et al. (2004); Starr and Cox (1985)

Table 1. Microphysical processes modified or added to the original GCE Rutledge and Hobbs based bulk microphysics scheme. "f( )" indicates "function of". Esi, Egc, and Esc are the collection efficiencies of cloud ice by snow, cloud by graupel and cloud by snow, respectively. Qc0 is the cloud water mixing ratio and ssi, the supersaturation percentage with respect to ice, RH the relative humidity, Vs/g the snow/graupel fall velocity, Bh,i the immersion mode ice nucleating efficiency, and Tair the air temperature. The process nomenclature essentially follows Lin et al. (1983) and Rutledge and Hobbs (1983,1984). Dgacs and Dgaci are the graupel collection of snow and cloud ice for the dry mode, respectively, and Dgacw the graupel collection of cloud at temperature below freezing.

3. Results

3.1 Sensitivity tests on model resolution

WRF was used at high-resolution (2-km horizontal grid spacing and Fig. 3) to both simulate the heavy rainfall associated with Typhoon Morakot (2009) and to conduct sensitivity tests on the impact of microphysics schemes and PBL schemes on the heavy rainfall for this case. The model results are also compared with those from previous modeling studies to assess the impact of microphysics and PBL schemes on hurricane track and intensity. The major highlights are as follows:

1. The results indicate that the high-resolution WRF is capable of simulating the tremendous rainfall (maximum rainfall exceeds 2800 mm over a 72-h integration) observed in this case as well as the elongated rainfall pattern in the southwest-northeast direction and heavy concentrated north-south line over southern Taiwan that was also observed. The good agreement in these features between the model and observations is mainly due to the simulated storm track and intensity being in relatively good agreement with the observed. The typhoon-induced large-scale circulation and Taiwan's unique terrain are the main factors that determine the location of the heavy precipitation.
2. The simulated typhoon intensities are in good agreement with observations after 24 h of model integration when the heavy rainfall occurred over southern Taiwan. The simulated track is in good agreement with the observed before the typhoon moved inland. However, the model-simulated tracks are too far south and their error becomes larger over the high terrain area and after the typhoon re-emerges over the Taiwan Strait.
3. The results also indicate that convective rain areas were initiated over the Taiwan Strait mainly by the typhoon-induced large-scale circulation and a southwest moisture flow. These convective areas were then intensified by orographic lifting as they propagated inland.

4. The improved microphysics does not improve the track forecast but did simulate a stronger storm after 12 h of model integration that was in better agreement with observations. On the other hand, the improved scheme later produces a stronger intensity than the control case and what was observed. The stronger storm resulted in more total rainfall that was in better agreement with observations compared to the control case. Overall, the improved microphysics does not improve the WRF's performance compared to the cases shown in Lang *et al.* (2011). But, it does reduce the amount of graupel and increase the amount of snow and cloud ice as with the cases shown in Lang *et al.* (2011). The stronger storm is a result of less evaporative cooling from cloud droplets and consequently weaker simulated downdrafts. This result is consistent with previous modeling studies (Wang 2002; Zhu and Zhang 2006). Downdrafts are noted to have a negative impact on rapid intensification and the final intensity of simulated storms (Willoughby *et al.* 1984; Wang 2002).
5. Both the MYJ and YSU PBL schemes simulated similar patterns in terms of MSLP, track forecast, and surface rainfall distribution. The YSU PBL scheme simulates 50 W m^{-2} more surface latent heat fluxes over ocean and more total rainfall as well as a higher average rainfall intensity over southern Taiwan than the MYJ scheme. The YSU simulated rainfall intensity is in slightly better agreement with observations. These results are quite different from previous numerical simulations for hurricanes that developed in the Atlantic (i.e., Li and Pu 2008; Nolan *et al.* 2009a,b). The MYJ scheme usually produces a stronger storm in better agreement with observations for hurricanes that develop in the Atlantic. The YSU PBL scheme has been widely evaluated and adjusted for the East Asian summer monsoon system. Results using different PBL schemes have less sensitivity than those due to the ice microphysics for this typhoon case.

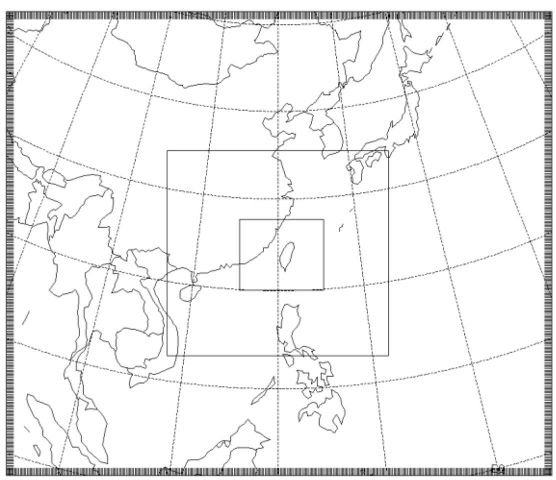


Fig. 3 *WRF Inter-nesting model configuration used for Typhoon Moratok case. Horizontal resolutions for domains are 18, 6 and 2 km, respectively. Time steps of 18, 6 and 2 seconds are used in these nested grids, respectively. . The Grell-Devenyi (2002) cumulus parameterization scheme was used for the outer grid (18 km) only. For the inner two domains (6 and 2 km), the Grell-Devenyi parameterization scheme was turned off.*

For non-hydrostatic cloud resolving models, the choice of horizontal and vertical grid resolutions is always an important issue and can have a major impact on the resolved convective processes (Weisman et al. 1997; Tompkins and Emanuel 2000). Weisman et al. (1997) suggested that a minimum grid length of 4 km is necessary to reasonably simulate the internal structures and mesoscale circulations of a midlatitude squall line. Tompkins and Emanuel (2000) suggested that a high vertical resolution (less than 33 hPa) is needed to develop a high degree of vertical structure in water vapor profiles and stratiform precipitation processes. Olson et al. (2001) used a very high vertical resolution (50 m) in a one-dimensional melting layer (melting band) model to study the precipitation processes in the melting layer. We will investigate the sensitivity of the strength and evolution of simulated mesoscale convective systems and hurricanes to vertical and horizontal grid resolution. For example, will conduct model simulations with 2 and 6 km grid spacing, respectively, in the inner domain (Fig. 4). The 6-km grid spacing run, as expect, under-estimates the maximum rainfall compared to both observed and the run with 2-km grid spacing. Since modeling results indicate that it was the combination of a typhoon-induced circulation, orographic lifting and a moisture-abundant southwest flow that lead to the tremendous rainfall for the Morakot case. The highest terrain within the 2-km domain is 3531 m (Fig. 5). The highest terrain within the 6-km domain is only about 2910 m. We conduct a run using 6-km spacing but with 10% increase of terrain height and its highest terrain is about 3210 m. The results indicate that the 6-km resolution is capable of simulating the maximum rainfall exceeds 2800 mm by just increasing the 10% of terrain height (Fig. 6). We will continue examining the sensitive of model resolution on the microphysics and their impact on surface rainfall intensity and distribution. The results from these sensitivity tests could provide the heavy precipitation and severe rainfall information to the operational unit for reference and guidance.

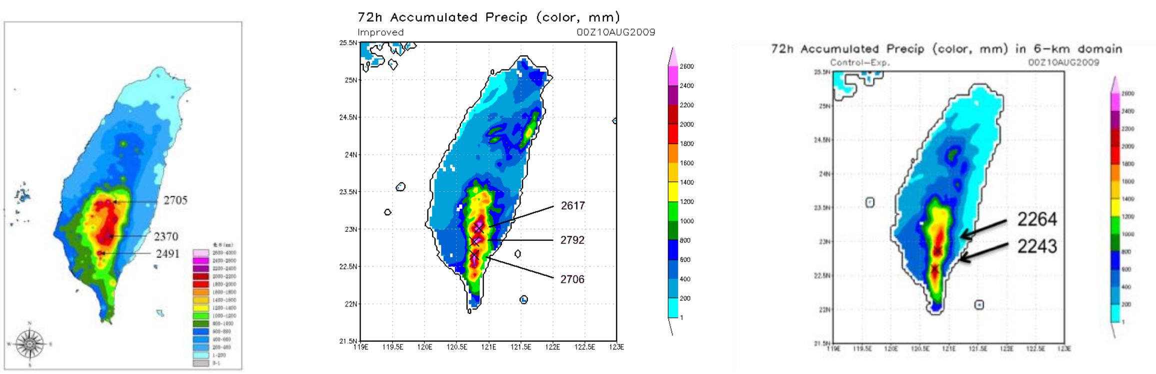


Fig. 4 *Observed (left-top) and model simulated accumulated rainfall from August 6 0000UTC to August 9 0000UTC 2009. The observed (left), improved and 2-km grid spacing (middle) and 6-km grid spacing (right) are shown for comparison.*

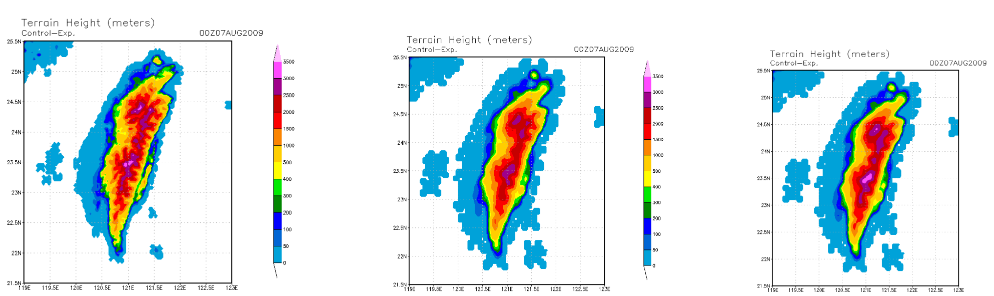


Fig. 5 *Model terrain height for 2 km (left panel – max 3394 m), 6 km (middle - max 2910) and 6 km with 10% increase of terrain height (right – max 3210 m)*

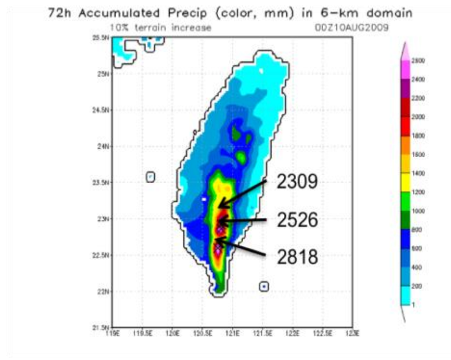


Fig. 6 Same as Fig. 4 except that is for the 6-km grid resolution with 10% increase of terrain height.

3.2 PBL and Cumulus Parameterization and Additional Case study

Note that the local MYJ scheme does not transport the moisture and heat away from the surface as deeply and strongly as the non-local YSU scheme (Holtslag and Boville 1993). Consequently, the MYJ scheme could produce a greater moistening in the PBL, lower cloud base, and larger surface water and heat fluxes. However, the YSU has greater fluxes over Taiwan Strait where convective cells were initiated for Morakot case. We will conduct the sensitivity tests on YSU and MYJ scheme and their impact on high-resolution WRF simulation/forecasting of the impact weather events occurred in Taiwan region.

(a) A case from SoWMEX/TiMREX 2008

The Terrain-influenced Monsoon Rainfall Experiment (TiMREX) during 15 May – 30 June 2008 was a joint US-Taiwan filed campaign, coinciding with Taiwan's Southwest Monsoon Experiment-2008 (SoWMEX-08). The main focus of these field campaigns was to study multiple-scale physical processes leading the development of localized heavy rainfall during the early summer monsoon. Several major precipitation events (i.e., observed during the SoWMEX/TiMREX 2008) that developed over the Taiwan region were selected for examining the performance of the cloud microphysics parameterization on precipitation processes and its predicted rainfall. The selection of these cases will be consulted with CWB operational forecasters and researchers. For example, Ms. Chang of CWB has conducted case study (IOP8 and see Table 2) observed during SoWMEX/TiMREX in 2008. Sensitivity tests will be performed to examine the impact of cumulus parameterization and PBL scheme on simulated rainfall amount and patterns (Table 3). The WRF V3.1 with improved microphysics is used to simulate this typhoon case. For IOP Case 8, the rainfall has a pronounced maximum over the south/southwestern coast. This case is a synoptically disturbed case due to the presence of a weak upper-level trough with warm, moist low-level southerly flow between the Mei-Yu trough over southern China and the Western Pacific High (http://sowmex.cwb.gov.tw/2008/data/report/SGP_Meeting_Summary/20080616/report.SGP_Meeting_Summary.20080616537.SGP_Meeting_Summary.doc). Over northern Taiwan, afternoon heavy rain showers occur over Taipei Basin due to the development of onshore/upslope flow under influence of a weak trough aloft and a conditionally unstable atmosphere.

Figure 7 shows the WRF domain, with 45, 15 and 5 km, respectively.

IOP#	Date	Science objectives
1 (a & b)	06Z May 19 to 00Z May 22	Frontal circulation Upstream environment for orographic convection

		Model verification and data assimilation
2	06Z May 27 to 21Z May 29	Southwest flow interacting with the terrain Upstream condition for mountain convection Lee side vortex/shear zone
3	21Z May 29 to 12Z May 31	Island effects on SW (LLJ) and the Mei- Yu front Upstream condition forheavy precipitation
4	21Z June 1 to15Z June 3	Mesoscale convective systems Shallow surface front Mesoscale convective vortex
5	18Z June 3 to 12Z June 4	Mesoscale convective systems Quasi-stationary front Mesoscale convective vortex
6	18Z June 4 to 12Z June 6	Mesoscale convective systems Quasi-stationary front Mesoscale convective vortex
7	00Z June 12 to 12Z June 13	Convection initiation Orographic convection
8	**00Z June 14 to 12Z June 17**	**Southwesterly flow interacting with the terrain** **Upstream condition for mountain convection, low level jet** **Mesoscale convective systems** **Mesoscale convective vortex**
9	06Z June 23 to 12Z 26 June	Typhoon Fengseng track uncertainty Typhoon induced southwesterly flow and related heavy rain systems

Table 2 The summary of SoWMEX/TiMREX IOP cases (kindly provided by Dr. Pay-Liam Lin). Red indicated the case (IOP8) has been conducted by Ms. Mei-Yu Chang.

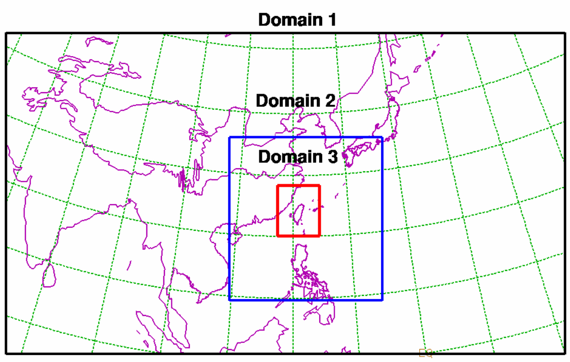


Fig. 7 WRF Inter-nesting model configuration used for SoWMEX case. Horizontal resolutions for domains are 45, 15 and 5 km, respectively.

Case	Microphysics	Radiation	Cumulus Scheme	PBL
1	CWB-Goddard	Old Goddard SW RRTM LW	Grell-Devenyi	YSU
2	New Goddard	Old Goddard SW RRTM LW	Grell-Devenyi	YSU
3	New Goddard	New Goddard	Grell-Devenyi	YSU
4	New Goddard	New Goddard	Kain and Fritsch	YSU
5	New Goddard	New Goddard New	Grell-Devenyi	MYJ
6	New Goddard	New Goddard New	Kain and Fritsch	MYJ

Table 3 The sensitivity tests of the microphysics, PBL and cumulus parameterization schemes for SoWMEX case.

Figures 8, 9, 10 and 11 show the observed and model-simulated rainfall amount and pattern. The difference in simulated rainfall over Taiwan Island is small between Cases 2 (Old Goddard SW and RRTM LW) and 3 (New Goddard Radiation). The difference in these two cases is much smaller than those cases with PBL, microphysics and cumulus parameterization schemes. This result suggests that radiation did not affect the Mei-Yu case. The difference in rainfall between microphysical schemes (Case 1 and 2) are quite large. The old microphysics scheme simulated more rain in southern Taiwan in the early model integration that is in better agreement with observations. On the other hand, in the new microphysics scheme, much more rainfall is simulated between June 00Z June 16 and 12Z June 16. This result is in better agreement with observation. Less snow (slow falling) and more graupel (fast falling) in the old microphysics could be the main reason for early rainfall in Case 1. The Grell and Devenyi cumulus scheme (Case 3 and 5) simulated more rainfall compared to those models using the Kain and Fritsch cumulus scheme (Case 4 and 6). In addition, Case 3 and 5 simulated rainfalls over South Taiwan are in better agreement with observation during the heavy rainfall period (between June 00 Z June 16 and 12Z June 16). For different PBL schemes (Case 3 and 4 using YSU and Case 5 and 6 using MYJ), the difference is not as large as those from using different microphysical and cumulus parameterization schemes except in the later model simulation period.

Overall, Cases 2 and 3 have better simulations for rainfall over South Taiwan during the second 12 h model simulation when the heavy rainfall is occurred. However, these cases simulate more rainfall compared to observation during the decaying stage of system. For Case 4 and 6 (using Kain and Fritsch scheme), the simulated maximum rainfall is over the central – west coast of Taiwan. These two cases cannot simulate correct locations. All cases, except Case 6, over simulated rainfall during the decaying stage of system. In summary, the cases with the Grell and Devenyi cumulus scheme are better than the cases with the Kain and Fritsch scheme. The old microphysics has better simulated rainfall in the early stage of model simulation and new microphysics can capture heavy rainfall in the mature stage of system. The radiation schemes have much less effect on model simulations for the Mei-Yu case..

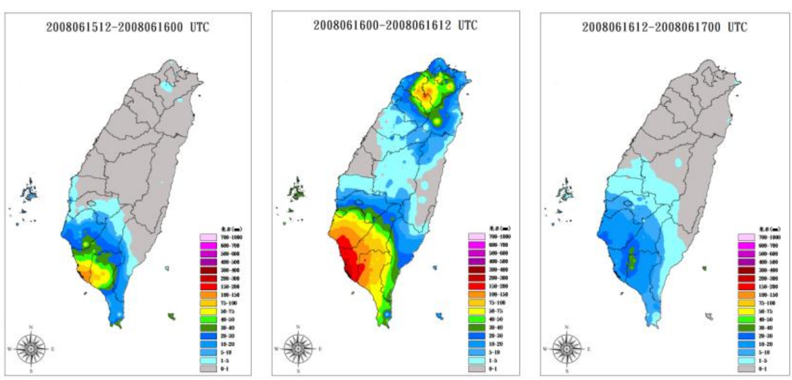


Fig. 8 Observed 12 h accumulated surface rainfall (mm) between 12 Z (UTC) June 15 to 12 Z June 17 2008. Left panel is the rainfall amount between June 12 Z June 15 and 00Z June 16. Middle panel is the rainfall amount between June 00 Z June 16 and 12Z June 16. Right panel is the rainfall amount between June 12 Z June 16 and 00Z June 17.

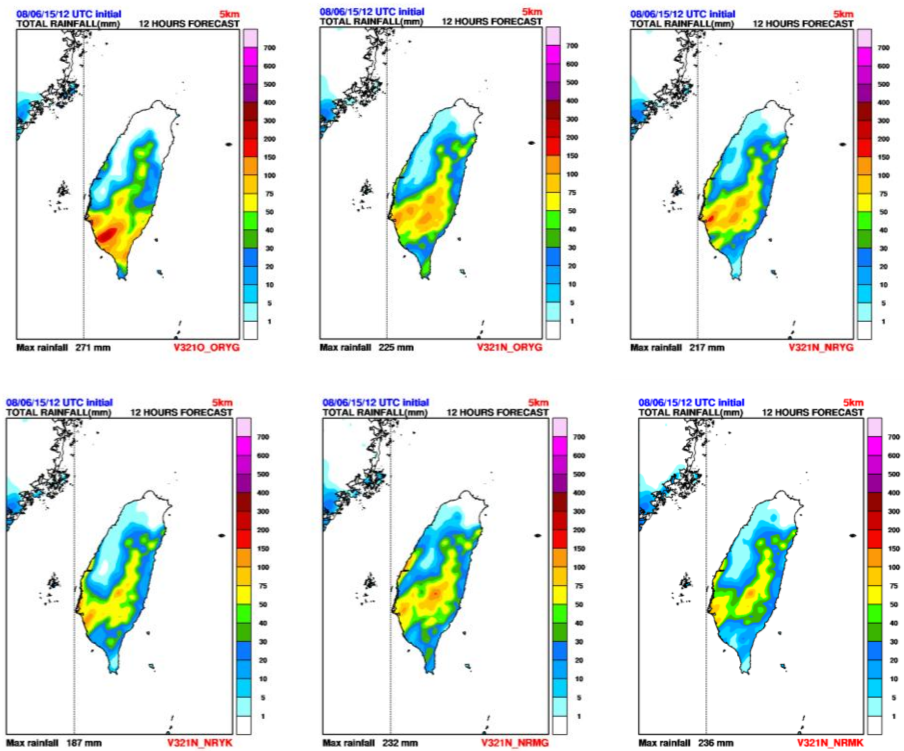


Fig. 9 CWB's WRF simulated surface rainfall (mm) between 12 Z (UTC) June 15 to 00 Z June 16 2008. Top three panels show simulated rain from Case 1 to 3. Bottom panels show simulated rain from Case 4 to 6.

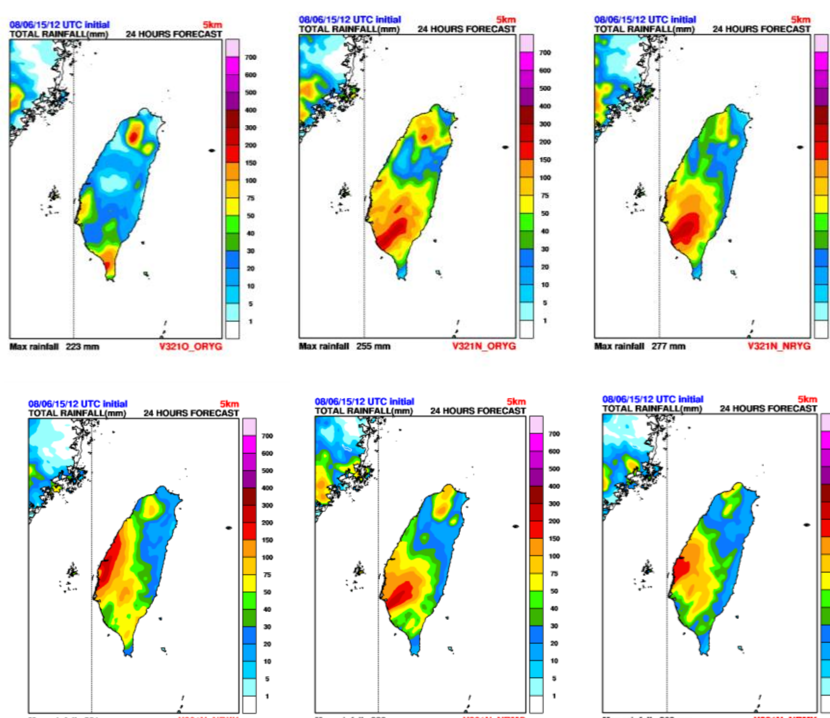


Fig. 10 The same as Fig. 9 except that WRF simulated surface rainfall (mm) are between 12 Z (UTC) June 15 to 00 Z June 16 2008.

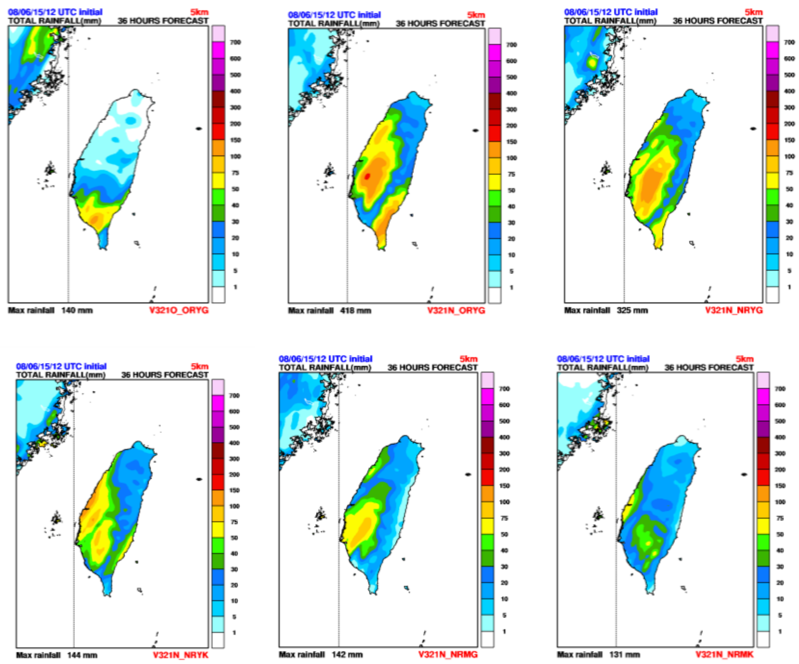


Fig. 11 The same as Fig. 9 except that WRF simulated surface rainfall (mm) are between 12 Z (UTC) June 16 to 00 Z June 17 2008.

(b) Typhoon Fanapi 2010

An additional Typhoon case, (Fig. 12), is also selected for testing and examining the performance of the cloud microphysics, PBL and cumulus parameterization on precipitation processes and its predicted rainfall

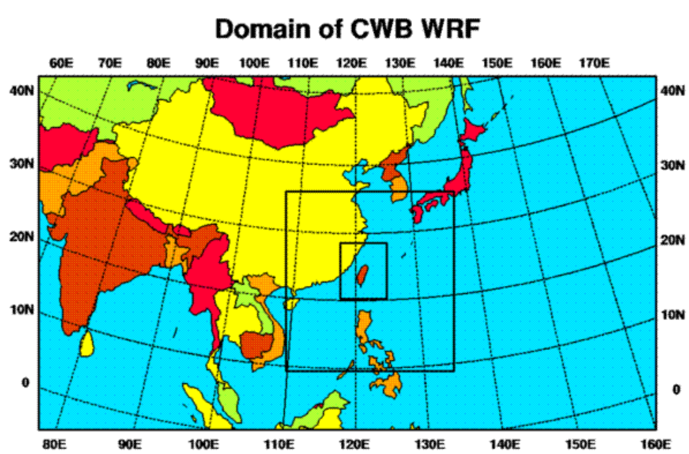


圖1，CWB WRF 積分範圍

Fig. 12 WRF Inter-nesting model configuration used for Typhoon Fanapi 2010 case. Horizontal resolutions for domains are 45, 15 and 5 km, respectively.

Case	Microphysics	Radiation	Cumulus Scheme	PBL
1	CWB-Goddard	CWB-Radiation	Kain and Fritsch	YSU
2	New Goddard	CWB-Radiation	Kain and Fritsch	YSU

3	New Goddard	Goddard New	Kain and Fritsch	YSU
4	New Goddard	Goddard New	Grell-Devenyi	YSU
5	New Goddard	Goddard New	Grell-Devenyi	MYJ
6	New Goddard	Goddard New	Kain and Fritsch	MYJ

Table 4 The same as Table 3 except for the Typhoon Fanapi 2010 case.

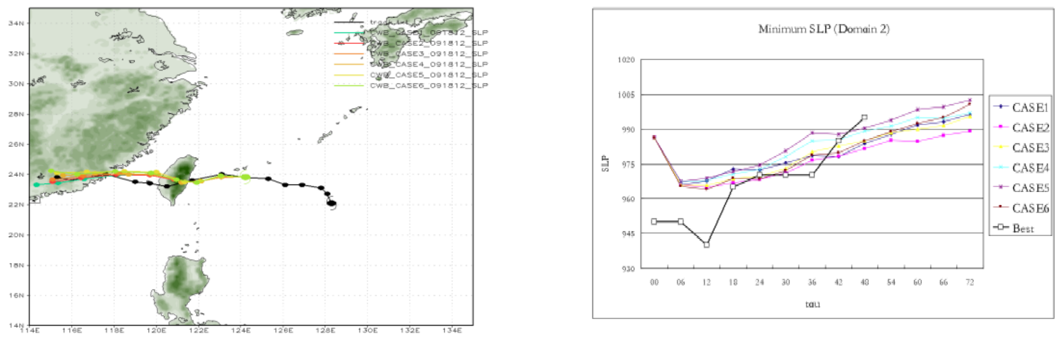
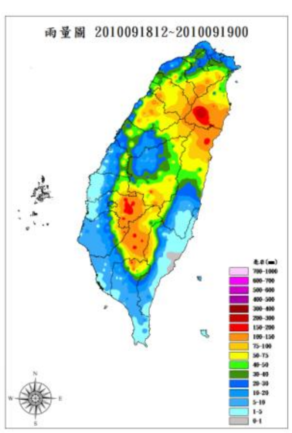


Fig. 13 ***(a)*** *Corresponding typhoon tracks and* ***(b)*** *minimum sea level pressures (hPa) obtained from WRF forecasts for the Typhoon Fanapi case. The observed track and minimum sea level pressure (solid black line) are also shown for comparison.*

The observed and simulated minimum sea level pressure (MSLP) fields and tracks are shown in Fig. 13. The sensitivity tests show no significant difference (or sensitivity) in track among the different microphysical, PBL and cumulus parameterization schemes. The simulated tracks are also very similar to observed track prior to landfall. After landfall, the simulated tracks remain closely packed with the storm center propagating to the east. All the simulations result in landfall farther north than was observed. The simulated typhoon intensities are weaker than observations. The simulated intensities in the early stages of the model simulations have a low bias due to the fact that no initial bogus vortex is used to spin up the model. The simulations also capture the fact that the typhoon moved slowly and weakened after it made landfall over Taiwan.

Case 2 (new improved microphysics) simulated the strongest typhoon compared to other cases. Case 5 (new microphysics, Goddard radiation, Grell-Devenyi and MYJ scheme simulated the weakest typhoon. However, the difference between these two cases is about 10 hPa. For Cases 1, 3 and 6 simulated very similar intensity. The differences between Case 1 and 3 are microphysics and radiation. The difference between Case 3 and 6 is PBL scheme..



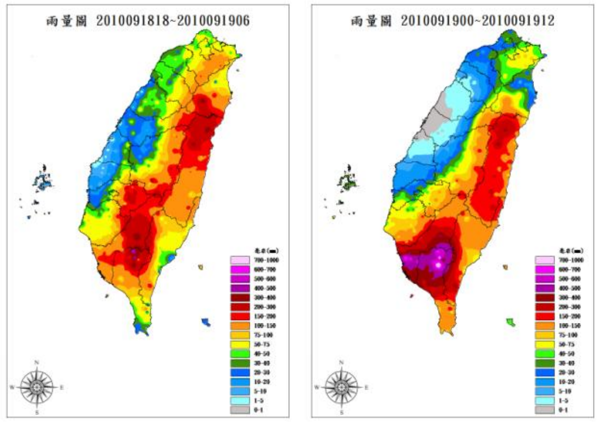


Fig. 14 *Observed and accumulated daily rainfall of Typhoon Fanapi 2010. The left panel shows 12 h accumulated rainfall from 12 Z September 18 to 00Z September 19. The middle panel is from 18 Z September 18 to 06 Z September 19. The right panel is from 00 Z September 19 to 12Z September 19.*

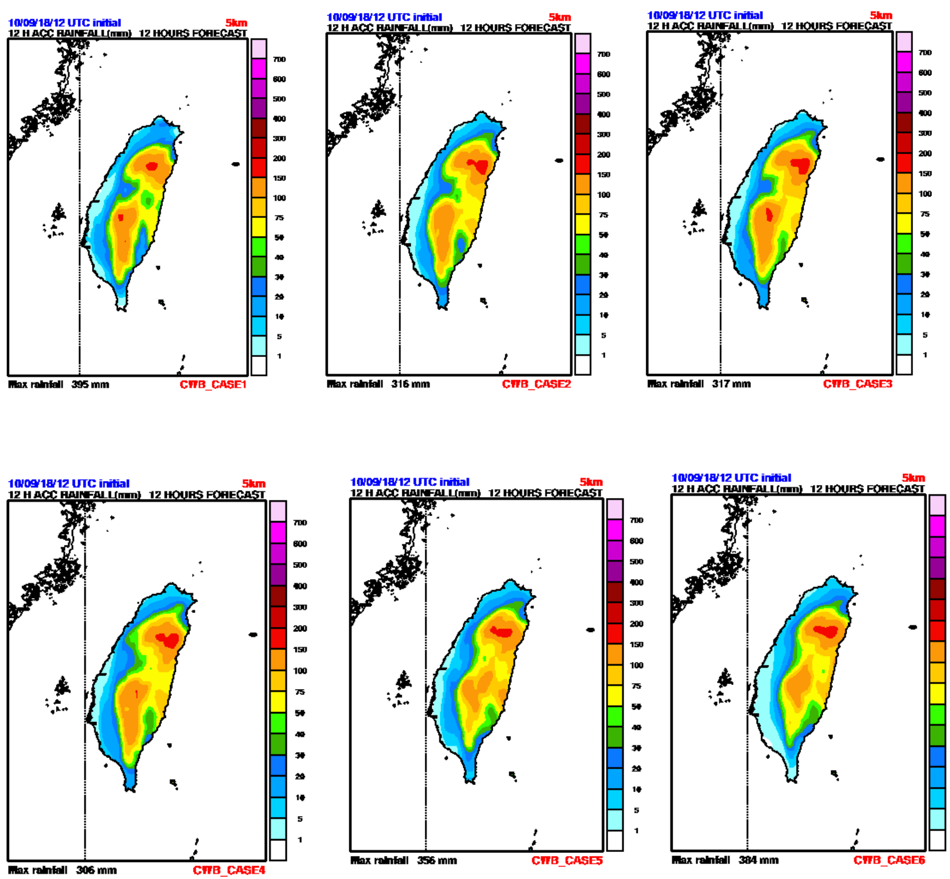


Fig. 15 *CWB's WRF simulated surface rainfall (mm) WRF simulated accumulated surface rainfall (mm) first 12 h for Cases 1 to 6.*

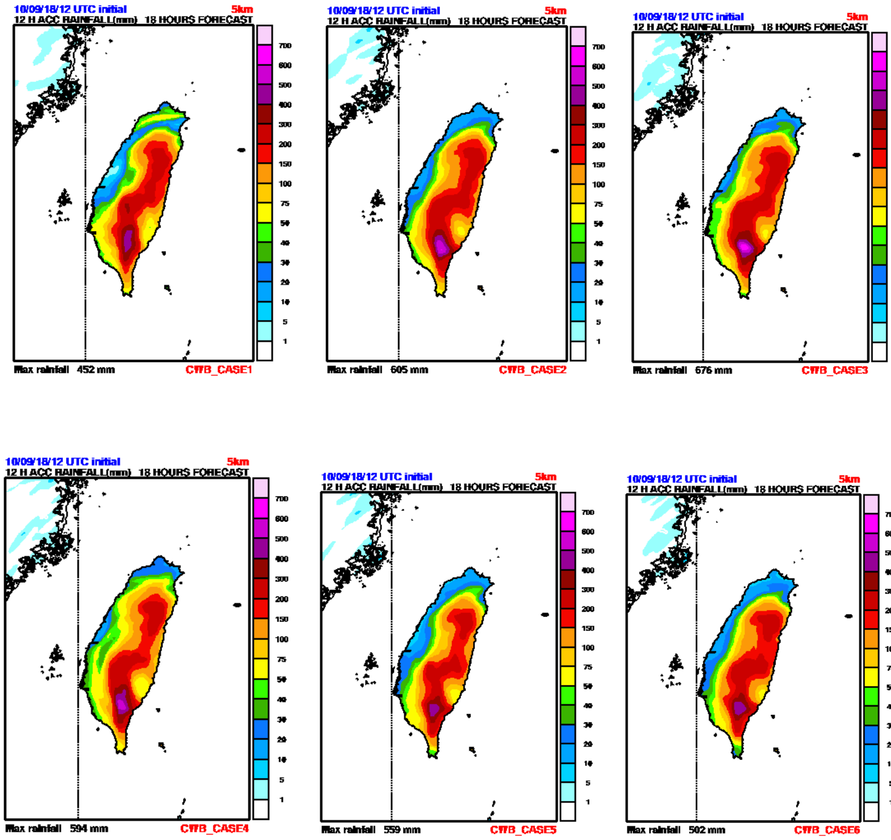
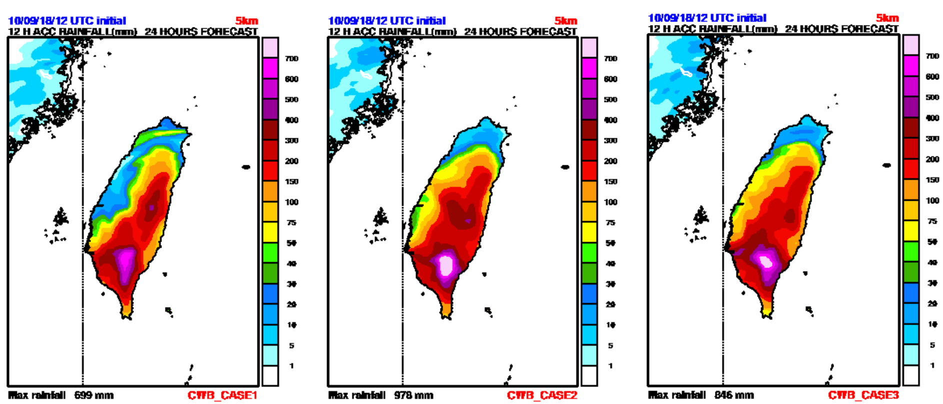


Fig. 16 CWB's WRF simulated surface rainfall (mm) WRF simulated accumulated surface rainfall (mm) second 12 h for Cases 1 to 6



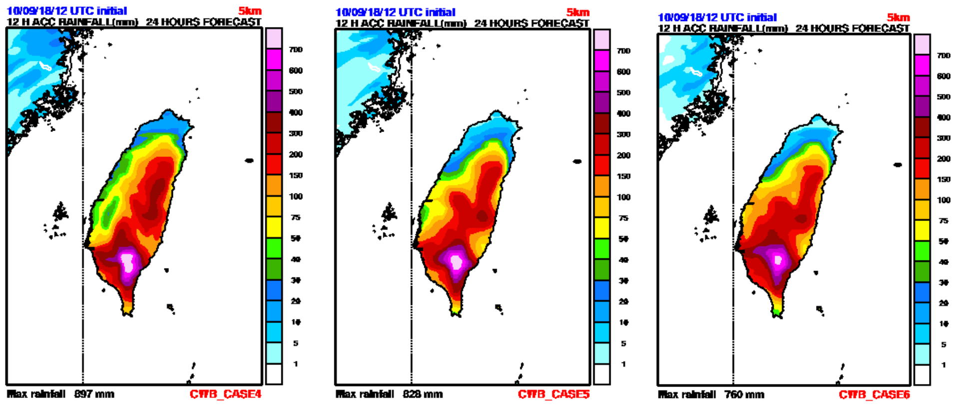


Fig. 17 CWB's WRF simulated surface rainfall (mm) WRF simulated accumulated surface rainfall (mm) third 12 h for Cases 1 to 6.

Figures 14, 15, 16 and 17 show the observed and model simulated rainfall amount and pattern. In all cases, simulated rainfall pattern is quite similar and generally agree with observations. For example, the simulated rainfall mainly occurred over the Central-Southern Taiwan and east coast of Taiwan as observed. However, the simulated rainfall amounts from all cases are different. During the early stages of the system, Case 3 simulated rainfalls are slightly bettered compared to other cases (Fig. 15). Case 1 did a better simulation for northern Taiwan (Figs. 16 and 17). For the PBL scheme, it seems that the YSU scheme (Cases 3 and 4) produced more rainfall over Taiwan compared to the MYJ scheme (Cases 5 and 6). This result is consistent with the Morakot case (discussed in section 3.1). The difference in simulated rainfall amount between the Grell and Devenyi cumulus scheme (Case 3 and 4) and the Kain and Fritsch cumulus scheme (Case 3 and 6) is not large compared to those cases with different PBL and microphysics schemes.

In summary, simulated rainfall pattern is very sensitive to microphysics, PBL and cumulus parameterization schemes for this typhoon case. The radiation schemes have much less effect on model simulations for this typhoon case as in those in the Mei-Yu case.

3.3 Recommended Future Research

I would suggest that CWB adapted new Goddard microphysics and new Goddard radiation scheme because the cloud optical properties are consistent with the size distribution of the microphysics scheme. Also all cases presented in the report do show the good simulations (over Taiwan).

For testing the PBL and cumulus parameterization schemes, rigorous comparisons between the simulated and observed cloud features, such as vertical profiles of radar reflectivity, temperature profiles and surface rainfall will be needed. Then, a systematic method to separate the convective and stratiform regions (PI has provided a convective-stratiform separation code to CWB) will be employed. The temperature/moisture /low-level convergence associated with various spatially averaged convective regions will be compared for different cumulus parameterization schemes. Ms. Chang[1] (CWB) and Professor Pay-Liam Lin (National Central University) plan to continue conducting detailed analyses and comparisons with observations (SoWMEX/TiMREX cases). They plan to evaluate model forecasts with ground-based

[1] Mei-Yu Chang at CWB will focus on the PBL and microphysics processes for her Ph. D. thesis.

observations (i.e., radar, rain gauge) and satellite data. Model estimates of radar reflectivity will be produced from the simulated precipitation using the characteristics of the explicit microphysics package (i.e., hydrometeor type, size distribution). Actual radar reflectivity can then be interpolated to wrf grid to facilitate comparisons similar to the QPF evaluations. It is proposed to use the contoured frequency with altitude diagrams (CFADs) (Yuter and Houze 1995) to examine the frequency distributions of various fields as a function of height. Model integrates cloud water and cloud ice can also compared to satellite data to evaluate cloud cover. Subjective evaluation of such aspects as storm initiation (location and timing), storm morphology (growth, decay, and persistence), storm intensity, storm propagation (time and space), and storm complex orientation will be considered, as these particular aspects are not easily evaluated objectively. Statistical verification scores do not always provide a fully "objective" assessment of a rainfall forecast. Development of better evaluation methods for high-resolution non-hydrostatic models is greatly needed in the near future. The validation of model microphysics needs to work with CWB operational group.

In addition, sensitivity tests will be conducted to examine the impact of the model resolution, microphysics, PBL and convective parameterization on rainfall and patterns associated with heavy rainfall events (i.e., one more case from SoWMEX/TiMREX 2008).

4. CWB Visit

The PI, W.-K. Tao, has visited the CWB and worked with Ms. Li-Hui Tai and Ms. Mei-Yu Chang the week of June 20. He also presented a talk to CWB and its title is "*WRF Improvement and Application: Real Time and Diurnal Variation*". Dr. Tao also discussed with Ms. Tai and Ms. Chang on June 22 about the proposed research in terms of selecting cases, and sensitivity tests needed to be conducted in Summer and Fall 2011. Dr. Tao also met Ms. Tai and Ms. Chang on August 9.

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