Evaluating regional cloud-permitting simulations of the WRF model for the Tropical Warm Pool International Cloud Experiment (TWP-ICE), Darwin, 2006

Yi Wang,1,2 C. N. Long,1 L. R. Leung,1 J. Dudhia,3 S. A. McFarlane,1 J. H. Mather,1 S. J. Ghan,1 and X. Liu2

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Data from the Tropical Warm Pool International Cloud Experiment (TWP-ICE) were used to evaluate Weather Research and Forecasting (WRF) model simulations with foci on the performance of three six-class bulk microphysical parameterizations (BMPs). Before the comparison with data from TWP-ICE, a suite of WRF simulations were carried out under an idealized condition, in which the other physical parameterizations were turned off. The idealized simulations were intended to examine the interaction of BMP at a “cloud-resolving” scale (250 m) with the nonhydrostatic dynamic core of the WRF model. The other suite of nested WRF simulations was targeted on the objective analysis of TWP-ICE at a “cloud-permitting” scale (quasi-convective resolving, 4 km). Wide ranges of discrepancies exist among the three BMPs when compared with ground-based and satellite remote sensing retrievals for TWP-ICE. Although many processes and associated parameters may influence clouds, it is strongly believed that atmospheric processes fundamentally govern the cloud feedbacks through the interactions between the atmospheric circulations, cloudiness, and the radiative and latent heating of the atmosphere. Based on the idealized experiments, we suggest that the discrepancy is a result of the different treatment of ice-phase microphysical processes (e.g., cloud ice, snow, and graupel). Because of the turn-off of the radiation and other physical parameterizations, the cloud radiation feedback is not studied in idealized experiments. On the other hand, the “cloud-permitting” experiments engage all physical parameterizations in the WRF model so that the radiative heating processes are considered together with other physical processes. Common features between these two experiment suites indicate that the major discrepancies among the three BMPs are similar. This strongly suggests the importance of ice-phase microphysics. To isolate the influence of cloud radiation feedback, we further carried out an additional suite of simulations, which turns off the interactions between cloud and radiation schemes. It is found that the cloud radiation feedback plays a secondary, but nonnegligible role in contributing to the wide range of discrepancies among the three BMPs.


1. Introduction

It is well established that understanding cloud climate feedbacks are crucial to future climate prediction [Stephens, 2005; Randall et al., 2007]. It is also well known that the water vapor (one of most effective greenhouse gases) content of large parts of the atmosphere is controlled effectively by cloud and precipitation processes through condensation, transportation, and evaporation. To resolve cloud and precipitation processes at subgrid scales, global and/or regional climate models employ parameterizations. One of the most widely used parameterization is the bulk microphysical parameterization (hereafter, BMP). Original development of BMPs is based on the works of Lin et al. [1983] and Rutledge and Hobbs [1984]. Over the last two decades, more sophisticated/advanced BMPs have been developed [Hong et al., 2004; Thompson et al., 2004; Morrison et al., 2005; Hong and Lin, 2006; Tao et al., 2003; Tao, 2007; Thompson et al., 2008]. Compared to explicit size-resolved (bin spectrum) microphysics, BMPs

1Pacific Northwest National Laboratory, Richland, Washington, USA.
2SKLLOQ, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an, China.
3Mesoscale and Microscale Meteorology Division, ESSL, National Center for Atmospheric Research, Boulder, Colorado, USA.

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have the advantage due to their economic treatments and more practical applications. Recent development of BMPs [Thompson et al., 2008; Morrison et al., 2009] has adapted techniques generally found only in spectral bin microphysical schemes through the use of lookup tables.

Because of the scarcity of detailed (in situ) observations, the constrained modeling studies are more limited in the tropics [Xu and Randall, 1996c; Grabowski et al., 1998] than in middle (high) latitudes [Ghan et al., 2000; Khairoutdinov and Randall, 2003; Xie et al., 2005, 2006, 2008]. In particular, large uncertainties [Zhang et al., 2006; Zhang and Mu, 2005; Xie et al., 2006] occurred in simulated cloud systems regarding their microphysical properties (e.g., cloud liquid water content, ice water content, shortwave, longwave radiative, and latent heating rates). This is particularly true when detailed cloud microphysical processes cannot be resolved realistically in large-scale model grid boxes. The subgrid-scale nature of cloud formation and interactions with the atmosphere can be addressed partially when a global climate model is run at quasi cloud resolving scales [Miura et al., 2007], but this is computationally expensive.

Recently, one of the most complete data sets of tropical deep convection and cloud formation was collected during the Tropical Warm Pool International Cloud Experiment (hereafter, TWP-ICE) in Darwin, Australia, in 2006 [May et al., 2008]. This field campaign was intended to examine convective cloud systems from their initial to decaying stages and the resulting thin high-level cirrus with particular emphasis on their microphysics (MP) [Frederick and Schumacher, 2008]. The TWP-ICE design includes an unprecedented array of soundings and other in situ and remotely sensed observation platforms (see Figure 1 and Section 2 for details). Although the duration of TWP-ICE is not long enough to help us extract the statistics of tropical deep convection and cloud formation, the unprecedented observations are useful to evaluate the performance of BMPs in global and/or regional climate models, and hence may improve the understanding of the causes of model biases and critical feedbacks between cloud and climate in greater details.

The comparison between observations and models has proven to be extremely challenging [Ghan et al., 2000; Jakob et al., 2004]. Because of the different temporal and spatial scales, time- and domain-averaging have been routinely used in such a task [Xu and Randall, 1996c; Ghan et al., 2000; Xie et al., 2002, 2005, 2008]. This is primarily due to the short-term intensive observation period, which would not grant a statistical characterization or probabilistic extraction of observations that could be used as the basis for a statistical model-observation intercomparison. Alternatively, objective (variational) analysis techniques have been developed for intercomparison between observations and

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Figure 1. The detailed domain of TWP-ICE and instrumentation. Five radiosondes (blue pentagons) sites surrounding the ACRF Darwin site (131°E, 12°S, northern Australia) constitute the objective analysis domain.
models [Zhang et al., 2001] and to reconcile the sampling and measurement errors [Ghan et al., 2000]. This article will utilize the objective analysis data set from TWP-ICE to provide information to evaluate quasi convective resolving (cloud permitting) studies of three advanced BMPs (Purdue Lin [Chen and Sun, 2002], WSM6 [Hong and Lim, 2006], and Thompson scheme [Thompson et al., 2004, 2008]) in a consistent WRF modeling framework. The systematic development of the WRF modeling framework ensures an unbiased intercomparison in the same physical parameterization packages and dynamical core, except for BMPs, while previous modeling intercomparison studies [Xu and Randall, 1996c; Ghan et al., 2000; Xu et al., 2002; Xie et al., 2008] were given using different physical parameterization packages and/or dynamical cores. Our approach reduces the uncertainties associated with modeling discrepancy that might be caused by using different physical parameterizations other than BMPs. Detailed bin microphysical schemes that explicitly predict evolution of the size distribution and mass concentration are computationally challenging and therefore not feasible for applications developed in this study.

The primary focus of this paper is to evaluate the performance of WRF simulations for an idealized two-dimensional thunderstorm case and for the TWP-ICE case using the developed objective analysis data set [Zhang et al., 2001]. To illustrate the sensitivity of cloud simulations among different BMPs, we first conduct a suite of idealized thunderstorm simulations. By the comparison in an idealized condition, we can identify the strength and weakness of the three BMPs in the WRF, which will guide our real-time case study for TWP-ICE. Our focus for the TWP-ICE case is assessing the performance of three sophisticated BMPs during the “active” and “dry” monsoon periods (see Section 2 for more details). With the same modeling platform, we can assume that the resulting discrepancies among different simulations are caused primarily by the different BMPs, and their interactions with other physical schemes. In order to attribute the effect of cloud-radiation interactions to the wide discrepancy of WRF TWP-ICE simulations, we further carry out a suite of experiments, in which the cloud radiation feedback is disabled. Our paper is organized as follows. Section 2 details the instrumentation, and major synoptic features during TWP-ICE. Section 3

![Figure 2. Three two-way nested domains with horizontal resolution of 36, 12, and 4 km over the TWP-ICE domain.](image)

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<th>WRF Options</th>
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<td>CAM SW radiation</td>
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<td>Cloud MP8 scheme</td>
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*Only larger domains 1 (36 km) and 2 (12 km) applied for cumulus schemes.
describes the WRF model and the experimental designs. Section 4 briefly summarizes the major difference among the three BMPs. Model evaluations are presented in Section 5, with a focus on the performance of the model in simulating cloud ice-phase microphysical properties and the cloud-radiation interactions. Finally, conclusions and future perspectives are given in Section 6.

2. Tropical Warm Pool International Cloud Experiment

[TWP-ICE was a large multiagency field campaign, including substantial contributions from the U.S. Department of Energy’s Atmospheric Radiation Measurement (ARM) Program, U.S. National Aeronautics and Space Administration, the Australian Bureau of Meteorology, and Commonwealth Scientific and Industrial Research Organization. Beginning January 19 and ending February 14, 2006, the experiment was located near Darwin, Australia (Figure 1) and included: 1) the ARM Climate Research Facility (ACRF) site, which is fully equipped with sophisticated instruments for measuring cloud and other atmospheric properties; 2) a fleet of five research aircraft; 3) a research ship located in the Timor Sea west of Darwin; 4) six radiosonde sites launching at 3 hour intervals; 5) a broad coverage of four surface energy flux sites, including broadband radiometer measurements; and 6) radar wind and cloud profilers, including a 35 GHz millimeter wavelength cloud radar (MMCR), a cloud lidar (micropulse lidar), a microwave radiometer (MWR), and two scanning C band Doppler radars (C-POL) [Frederick and Schumacher, 2008; May et al., 2008].

The timing of TWP-ICE was synchronized with the onset of the Australian summer monsoon season. From January 13 to February 2, 2006, the summer monsoon came across north Australia [May et al., 2008]. In particular, from January 13 to 25, “active” monsoon dominated the experiment domain with numerous deep convective storms. From January 26 to February 2, suppressed “dry” monsoon controlled the experiment domain with relatively shallow storms, which was followed by three completely clear days ending on February 5, 2006. At the end of TWP-ICE, a “break” period occurred from February 6 to 13, 2006. The maximum daily precipitation (about 100 mm) was recorded at Darwin on January 24 and was closely associated with an overnight mesoscale convection system that developed on January 23. The break period was generated due to an inland heat trough across north Australia [May et al., 2008]. The succession of these events was associated with a large amplitude Madden-Julian Oscillation (MJO) [Madden and Julian, 1972, 1994; Zhang, 2005; Y. Wang et al., Convective signals from surface measurements at ARM Tropical Western Pacific site: Manus, submitted to Climate Dynamics, 2009].

The raw observational data set, including MMCR retrievals, radiosondes, and surface fluxes, has been combined with large-scale background information from the European Centre for Medium-Range Forecasts (ECMWF) operational analysis and satellite measurements using the
constrained variational objective analysis [Zhang et al., 2001] (hereafter referred to as objective analysis). The objective analysis data cover the period from January 17 to February 12, 2006, and are available at both 25 hpa and 10 hpa vertical resolution. The objective analysis domain can be found in Figure 1 and details of the data set used can be found at http://acrf-campaign.arm.gov/twpice/. The objective analysis grid points overlap the five boundary sounding stations (Figure 1, blue pentagons) that are available during the field campaign. During TWP-ICE, sounding balloons were launched to measure the vertical profiles of temperature, relative humidity, and winds every 3 hours at the five boundary sounding stations from January 22 to February 13, 2006. Soundings also are available every 6 hours from the ACRF Darwin site (the center of the domain). The measured upper air data are first analyzed using the analysis scheme of [Cressman, 1959] with the background field from the ECMWF operational analysis and forecasting system (see http://www.arm.gov/xds/static/ecmwf.stm for details). The domain-averaged surface and top-of-the-atmosphere fluxes required by the objective analysis are obtained from the TWP-ICE surface and satellite measurements (i.e., Japan’s Multifunctional Transport Satellite). Surface precipitation is from the C-POL precipitation radar data [May et al., 2008].

The radiative heating profiles are derived following the methodology of Mather et al. [2007]. Radiosondes, surface temperature, and MWR precipitable water vapor are combined to produce a continuous atmospheric profile [McFarlane et al., 2007; Mather et al., 2007]. The measured radar reflectivity from the MMCR, the liquid water path from the MWR, and the temperature profiles are used to retrieve cloud ice water content (IWC) [Liu and Illingworth, 2000]. A four-stream correlated k distribution radiative transfer model is used to calculate the radiative heating given the retrieved cloud properties and atmospheric profile. Mather et al. [2007] described the method and discussed the uncertainty associated with the radiative heating calculations.

The retrieval of ice cloud by the MMCR is affected by both sensitivity and attenuation of the radar. Under normal operating conditions, the minimum detectable cloud IWC by the radar is approximately $10^{-4}$ g m$^{-3}$ [Mather et al., 2007], and the MMCR misses a large percentage of thin cirrus with optical depths less than 0.1 [Comstock et al., 2007] and clouds above 15 km in the tropics [Comstock et al., 2002]. Prior to TWP-ICE, the MMCR was damaged by a lightning strike, resulting in a loss of sensitivity of 10 to 15 dB, which was not detected until after the experiment; thus the minimum detectable IWC was reduced probably to about $10^{-3}$ g m$^{-3}$ and the MMCR likely missed the top parts of cirrus clouds and thin isolated cirrus, which are often dominated by smaller ice crystals. The MMCR reflectivity is attenuated also by underlying hydrometeors, especially during heavy precipitation, so the retrieval of cloud IWC likely is underestimated during precipitation. To overcome the uncertainty related to MMCR retrievals, a combined remote

![Figure 4.](left) One hour snapshot and (right) two hour snapshot of mixing ratios (units g/kg) for graupel (shading) and cloud ice (contours) from idealized thunderstorm experiments. Contour levels for MP2, MP6, and MP8 (0.01, 0.05, 0.1, 0.2, and 0.4). The melting line is marked as a thicker, red line.
sensor retrieval is under development (J. M. Comstock and S. A. McFarlane, personal communication, 2009).

Because of the larger uncertainty of the MMCR retrievals during TWP-ICE, three-dimensional cloud IWC also is examined [Seo and Liu, 2005, 2006] over the 10 degree by 10 degree area centered near the ACRF Darwin site retrieved by combining ground cloud radar and satellite high-frequency microwave measurements. For TWP-ICE, measurements from four satellites (NOAA 15, 16, 17, and 18) were used. We averaged the satellite retrieved IWC over an 80 km by 80 km area centered at the ACRF Darwin site for a comparison with the MMCR retrieval and model simulations.

3. Model Description and Experimental Design

The modeling framework used in the paper is based on the Weather Research Forecasting (WRF, version 3) model, developed at the National Center for Atmospheric Research (NCAR) [Michalakes et al., 2001, 2005; Skamarock et al., 2005; Skamarock and Klemp, 2008], with support from multiple partners (the National Centers for Environmental Prediction (NCEP) and the Forecast Systems Laboratory of the National Oceanic and Atmospheric Administration (NOAA), Air Force Weather Agency, and Naval Research Laboratory). The WRF is a community model suitable for both research and forecasting. The dynamical core of WRF is based on the fully compressible, nonhydrostatic Euler equations, with terrain following Eta coordinate [Skamarock et al., 2005]. The model has been used in weather forecasting [Hong et al., 2004; Hong and Lim, 2006; Xiao et al., 2008], ice cloud microphysical studies [Thompson et al., 2004, 2008; Morrison et al., 2009], and regional climate research [Leung et al., 2006; Lo et al., 2008]. The WRF nonhydrostatic dynamical core is intended for studies of high-resolution (250–1000 meters) simulations with the capability to explicitly resolve convections and cloudiness. The WRF model can be nested so that the high-resolution domain can be forced both by the model output from coarse-resolution domain and observational reanalyses. Associated with the development of WRF nonhydrostatic dynamical core is the testing and implementing of eight advanced BMPs as of December 2008 [Kessler, 1969; Lin et al., 1983; Chen and Sun, 2002; Hong et al., 2004; Hong and Lim, 2006; Thompson et al., 2004, 2008; Morrison et al., 2009; Tao et al., 2003]. These BMPs include the Kessler [Kessler, 1969], Purdue Lin [Chen and Sun, 2002], Ferrier (new ETA), WSM3, WSM5, WSM6 [Hong et al., 2004; Hong

Figure 5. (left) The hydrometeor paths (kg m⁻²) and (right) precipitable water (PW, red, centimeters) and rain rate (RR, blue, mm/10min) from idealized thunderstorm experiments. The thicker dashed lines in the hydrometeor path plots represent the sum of hydrometeor paths of cloud water (QC, black), rain (QR, orange), graupel (QG, green), snow (QS, blue), and cloud ice (QI, red).
and Lim, 2006], Thompson [Thompson et al., 2004, 2008], Morrison Schemems [Morrison et al., 2009], and improved Goddard microphysics (MP) [Tao et al., 2003]. For the following experiments, we will focus on three single-moment (only predicting mixing ratios of six-class hydrometeors) BMPs, namely, Purdue Lin [Chen and Sun, 2002], WSM6 [Hong and Lim, 2006], and Thompson scheme [Thompson et al., 2004, 2008], which are referred as MP2, MP6, and MP8, respectively, herein.

3.1. Idealized Simulations

The WRF model is well adapted for idealized simulations to study baroclinic waves, thunderstorm dynamics, or topographically induced flows. The idealized 2D thunderstorm experiment is set up to simulate a high-instability (high-CAPE) continental-type structure storm, and is designed to systematically distinguish the essential differences among the three BMPs by fixed initial conditions and the absence of other nonmicrophysical processes, which in turn will help understand the impact of changes in the microphysics in the 3D framework. We choose a 2D domain in the X direction (east-west). The grid in this direction is comprised of 201 points with a 250 m grid spacing. The number of vertical layers is 80 stretching up to 20 hpa. The model is integrated for 2 hours with a timestep of 3 seconds. The initial condition includes a warm bubble with a 4 km radius and a maximum perturbation of 3 K at the center of the domain. A wind with a velocity of 12 ms$^{-1}$ is applied in the positive x direction at the surface; the surface wind decreases to zero at 2.5 km above ground, with no wind above. Open boundary conditions are applied, and there is no Coriolis force or friction. The only physical parameterization is the microphysical scheme, and other physical processes including radiation, vertical diffusion, land surface, and deep convection due to the cumulus parameterization scheme are turned off. This experiment serves to

Figure 6. (left) First-hour and (right) second-hour mean profiles of mixing ratios for cloud water (QC, orange marks), rain (QR, green marks), graupel (QG, blue marks), snow (QS, red marks), and cloud ice (QI, black marks) from idealized thunderstorm experiments. Units are 10 g/kg for cloud water (QC) and cloud ice (QI) and g/kg for rain (QR), graupel (QG), and snow (QS).
demonstrate the microphysics in a quasi steady state (large-scale) that simplifies the interpretation of the results. Although we realize that the idealized simulations may be different in some respects from tropical environment, this part of the experimental design is intended to evaluate primarily ice-phase microphysical differences from a different and simpler perspective.

3.2. TWP-ICE Simulations

[15] The two-way nested experiment is designed to simulate the real-time case of TWP-ICE. We have chosen three domains with horizontal resolutions of 36, 12, and 4 km (Figure 2). The 4 km domain covers an area of 1152 km (east-west) by 636 km (north-south) larger than the TWP-ICE domain of objective analysis (Figure 1). Based on previous experiences, continuous integration with a single initialization and updated lateral and lower boundary conditions (LLBC) has caused the unrealistic drifting of large-scale environment. Therefore, we set up to run WRF for every three days and only save the last two day model output. This consecutive integration with frequent reinitializations for every three days with continuously updated LLBC ensures a realistic large-scale environment and hence a favorable comparison between model and observation. The large-scale LLBC is given by the 1 degree NCEP Global Final Analysis and sea surface temperature (SST) from real-time, global SST analysis (RTG-SST, http://polar.ncep.noaa.gov/sst/oper/Welcome.html). A recent study [Lo et al., 2008] indicates that the reinitialized experiment increases the utilization of the large-scale coarse-resolution

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**Figure 7.** Cloud fraction comparison from the objective analysis and WRF TWP-ICE simulations. On top of cloud fraction (no unit, shading), we also plot the water vapor mixing ratio (g/kg) in contour levels of 1, 2, 4, 8, and 16.
data during the model integration, and hence, could generate realistic regional structures not resolved by the coarse-resolution forcing data. Table 1 lists detailed model MP, shortwave (SW) and longwave (LW) radiation, surface layer, planetary boundary layer (PBL) schemes, and other integration options.

[16] Regarding the selection of horizontal and vertical resolutions of our TWP-ICE simulations, we have considered results from a recent study by Kain et al. [2008]. It has been shown that during the 2005 NOAA Hazardous Weather Testbed Spring Experiment two different high-resolution configurations of WRF model were used to produce 30 hour forecasts 5 days a week for a total of 7 weeks. Except for the different horizontal (i.e., 4 km and 2 km) and vertical (i.e., 35 level and 51 level) resolutions, other physical parameterization packages and the input data set for the LLBC are the same. In general, the 2 km forecasts provide more detailed presentations of convective activity, but there appears to be little improvement of forecast skill on the scales where the added details emerge. Their results further

Figure 8. Cloud IWC comparison from the MMCR and satellite retrievals and WRF TWP-ICE simulations. On top of cloud IWC (10^{-3} g m^{-3}, shading), we also plot the air temperature (degrees Celsius) in contour levels of 0, −20, −40, and −60.
suggest that the added values provided by decreasing the grid space from 4 to 2 km (with commensurate adjustments to the vertical resolution) may not be worth the considerable increases in computational expenses. To study the effect of the feedbacks that occur due to the interactions between the radiation schemes and cloud MP, we further carry out a suite of experiments, in which the interactions between the BMPs and radiation schemes are turned off. This suite of experiments is called “TWP-ICE RAD” simulations.

The model has been integrated from January 16 to February 17, 2006, to overlap with the period of TWP-ICE, and compared with the TWP-ICE objective analysis from January 17 to February 13, 2006, for the high-resolution (4 km) domain. The 4 km domain outputs were sampled every hour, and averaged over the ACRF Darwin site for an area of 80 km by 80 km (20 by 20 grid boxes). We also have linearly interpolated the model outputs to the pressure and/or height levels of the objective analysis and/or retrievals. For the MMCR retrieved IWC, and SW, and LW radiative heating profiles, we compared model output directly with retrievals every hour and calculated the root-mean-square error (RMSE) and biases. For other variables, we averaged the hourly model output to 3 hour intervals to be compared with the objective analysis at the same timescale and calculated the RMSE and biases.

The cloud fraction as used in the radiation calculation is parameterized in the WRF model, as well as in other climate models (see Xu and Krueger [1991] and Xu and Randall [1996a] for a review on this topic). The formulation of this parameterization is based on the work of Xu and Randall [1996b]. In brief, equation 1 of Xu and Randall [1996b] is adapted to estimate the cloud fraction used in the WRF radiation calculation. The subdomain-averaged cloud water, water vapor, cloud ice and snow mixing ratios are used to derive the primary predictor ($Q_l$ in their equation 1) for cloud fraction. The critical (saturation) vapor pressures derived from the work of Murray [1967] are used to estimate the relative humidity with respect to water and ice. Because the Murray formulation introduces large biases when temperature drops below around $-20^\circ C$, we suggest that this may cause problems in estimating high-level (low temperature) thin cirrus clouds as in the TWP-ICE case. A future paper on this direction is in preparation.

4. Brief Comparison of Purdue Lin, WSM6, and Thompson BMPs

Purdue Lin BMP is based on the original Lin microphysical scheme [Lin et al., 1983] with some modifications [Chen and Sun, 2002]. The WSM6 BMP was developed by adding processes related to the graupel

Figure 9. Snow contents ($10^{-3}$ gm$^{-3}$, shading) from WRF TWP-ICE simulations for (a) Purdue Lin BMP, (b) WSM6 BMP, and (c) Thompson BMP.
species into the WSM5 BMP [Hong and Lim, 2006]. The WSM6 scheme improves rainfall simulations at high resolutions [Hong and Lim, 2006]. A detailed description of WSM6 BMP is given by Hong and Lim [2006]. Thompson BMP has been developed continuously and tested at NCAR [Thompson et al., 2004, 2008]. The Thompson scheme incorporates many improvements to the physical processes, it employs many techniques found in more sophisticated spectral/bin microphysical schemes (e.g., using lookup tables). Unlike any other BMPs, the assumed snow size distribution in the Thompson scheme depends on both ice water content and temperature, and is represented as a sum of exponential and gamma functions. Furthermore, snow assumes a nonspherical shape with a bulk density that varies inversely with diameter as derived from observations. This is in contrast to nearly all other BMPs that assume spherical snow with constant density [Thompson et al., 2008]. Based on four idealized sensitivity experiments [Thompson et al., 2008], it was found that the sphericity and constant density assumptions play a major role in producing supercooled liquid water while the prescribed distribution shape plays a lesser, but nonnegligible role.

[20] The uniqueness of the Thompson scheme is that it also predicts the number concentration of cloud ice. As a double-moment species, cloud ice has differential sedimentation by the mixing ratios and number concentration using their respective mass-weighted and number-weighted terminal velocities [Thompson et al., 2008]. Due to the potential imbalance between mass and number concentration, cloud ice number is constrained such that its mass-weighted mean size is bound between 30 and 300 microns. Because other BMPs in the study do not include this quantity, we have chosen not to analyze the number concentration of cloud ice from the Thompson scheme. Nevertheless, in all three BMPs, the six-class prognostic water substance includes the mixing ratios of water vapor (QV), cloud water (QC), cloud ice (QI), snow (QS), rain (QR), and graupel (QG). The most important difference in these three BMPs is the treatment of ice-phase microphysical processes. The WSM6 scheme treats the ice crystal number concentration (NI) as a function of QI amount, and the ice nuclei number concentration (NI0) is separated from the NI [Hong and Lim, 2006]. The Purdue Lin scheme uses the formula of Fletcher [1962] for both NI and NI0. The snow intercept parameter in the WSM6 scheme is a function of temperature [Houze et al., 1979]. A detailed comparison of the WSM6 and Purdue Lin schemes is given by Hong et al. [2009]. A generalized gamma distribution shape is employed for each water substances (hydrometeor species, except for snow). The Y intercept of QG depends on the graupel mixing ratio [Thompson et al., 2008]. The terminal velocity constants for graupel are taken directly from Heymsfield and Kajikawa

Figure 10. Graupel contents (10^{-3} \text{ gm}^{-3}, shading) from WRF TWP-ICE simulations for (a) Purdue Lin BMP, (b) WSM6 BMP, and (c) Thompson BMP.
These constants cause low mixing ratios of graupel to fall roughly twice as fast as snow (see Thompson et al. [2008, Figure A1] for terminal velocities of QI, QS, QG, and QR). Since the number concentration of QI is predicted, its shape parameter is the only free parameter that needs to be preset.

5. WRF Model Evaluations

5.1. Idealized Thunderstorm Simulations

We show here the one hour and two hour snapshots from the idealized thunderstorm for snow and rain mixing ratios (Figure 3), and for graupel and cloud ice mixing ratios (Figure 4). It is very clear that the Purdue Lin BMP produces much less snow and graupel (shadings) than the WSM6 and Thompson BMPs. Among other differences, the WSM6 scheme produces much larger graupel than the Thompson scheme, while the Thompson scheme produces much larger snow than the WSM6 scheme. For cloud ice (contours), Purdue Lin and WSM6 schemes have approximately the same magnitudes, which are slightly larger than that produced by the Thompson scheme. However, for rain (contours), the Purdue Lin scheme has a much smaller amount compared to the other two BMPs at the one hour and two hour snapshots.

Figure 11. RMSEs (solid curves) and biases (dashed curves) of (a and b) temperature (K), (c and d) water vapor (g/kg), and (e and f) cloud fraction (percentage) for two periods of WRF TWP-ICE simulations, for (left) “active” monsoon and (right) “dry” monsoon, with respect to three BMPs.
To further study the time evolution of the 6-class water substances, we derived the domain-averaged hydrometeor paths for QC, QR, QG, QS, and QI by integrating the corresponding values in the vertical direction and averaging over the entire domain (Figure 5). The total hydrometeor path (TOT, unit kg m$^{-2}$) is derived by adding the hydrometeor paths for QC, QR, QG, QS, and QI. We also derive the domain-averaged precipitable water (PW, unit cm) and rain rate (RR, unit mm per 10 minute) for these three BMPs. The hydrometeor path plot (Figure 5, left) clearly indicated the wide discrepancy, in particular, for ice-phase species (i.e., QG, green curves, QS, blue curves, and QI, red curves). Consistent with the findings in Figures 3 and 4, we notice that the WSM6 scheme has the largest graupel peak values, while the Thompson scheme has the least graupel peak values during the two hour integration. The Thompson scheme produces the largest snow values among the three BMPs over the development of thunderstorms. At the end of the two hour experiment, the Purdue Lin scheme has minimum values for the total hydrometeor path (TOT, thicker, dashed black curves). This also is reflected in the precipitable water and rain plot (Figure 5, right). Overall the largest rain rate is found in the Thompson scheme, while the Purdue Lin and WSM6 schemes produce similar peak rain rate values during the two hour integration.

To study the vertical distributions of QC (unit 10 g/kg), QR (unit g/kg), QG (unit g/kg), QS (unit g/kg), and QI (unit 10 g/kg), we also plot the domain-averaged mixing ratios for these values (Figure 6) for first-hour mean (Figure 6, left) and second-hour mean (Figure 6, right). To focus on the ice-phase species, we notice that snow (red marks) stays at the highest values (at about 9 km above ground level, AGL) in the Thompson scheme. On the other hand, graupel (blue marks) stays at the highest values (at about 8 km AGL) in the WSM6 scheme. (Graupel in the Purdue Lin scheme also has a relative high value at about 7 km AGL.) With respect to QI (black marks), the Purdue Lin and WSM schemes have similar profiles, while the Thompson scheme produces two to four times smaller values. In the Thompson scheme, snow forms by vapor deposition growth onto cloud ice particles until those ice crystals grow beyond a threshold size (currently 200 microns). The threshold itself is relatively arbitrary and certainly artificial but allows for slowly falling tiny ice crystals to coexist with more rapidly falling snow. We believe that this threshold value may cause a relatively small QI category compared to those of the other two BMPs.

5.2. TWP-ICE Simulations

The continuous time series of domain-averaged cloud fraction profiles over the entire TWP-ICE period illustrates some weaknesses in the model simulations (Figure 7). The three BMPs almost totally miss the first convective system during the first couple days of TWP-ICE. According to observations, this first convective system is
associated with a strong MJO event passing northern Australia. Large-scale forcing data might miss this critical MJO signal, hence could not provide a favorable condition to initiate the first convection. Around January 23–25, three BMPs reproduce the major feature of deep convection. Furthermore, the Thompson scheme seems to overestimate the high cirrus cloudiness. This might be due to the overestimation of snow mixing ratio (QS) as found in previous idealized simulations. Overall, the largest bias can be found in two areas: 1) precipitating clouds and 2) high-level cirrus clouds (above 14 km). As we discussed earlier, the MMCR retrievals of cloud suffer two major problems during the TWP-ICE. First, precipitating clouds are underestimated because of large radar signal returns by the large raindrops. High-level, thin cirrus clouds (low cloud optical depth) are underestimated due to the undetected lightening strike damage that occurred briefly before the TWP-ICE [Mather et al., 2007; McFarlane et al., 2007].

[25] The accurate retrieval of cloud IWC is an active area of research. The retrieval of cloud IWC might be affected by the above mentioned issues (e.g., reduced sensitivity of MMCR, precipitating clouds). To constrain the uncertainty associated with the MMCR retrievals of cloud IWC (Figure 8), we also derive the domain-averaged (80 by 80 km

Figure 13. RMSEs (solid curves) and biases (dashed curves) of cloud (a and b) SW, (c and d) LW, and (e and f) net radiative heating (K/day) for two periods of WRF TWP-ICE simulations, for (left) “active” monsoon and (right) “dry” monsoon, with respect to three BMPs.
surrounding the ACRF Darwin site) satellite retrieved cloud IWC from a combination of satellite and surface observations [Seo and Liu, 2005, 2006]. As noticed above, the first convective system is missing in all three BMPs. Except for the Thompson scheme, the other two BMPs capture the main feature of cloud IWC. Previous idealized simulations have identified that the Thompson scheme underestimates the cloud ice (QI). This may help to understand why the IWC in the Thompson scheme is so low. Furthermore, large biases exist among MMCR (model simulations) and satellite retrievals. We suggest these large biases might be caused by different vertical and horizontal resolutions among models and two observations. Overall, model simulations are closer to MMCR retrieved cloud IWC than satellite derived values.

[26] To compare the ice-phase properties with idealized thunderstorm simulations, we also plot the snow (Figure 9) and graupel (Figure 10) contents for the “active” and “dry” monsoon periods from the WRF TWP-ICE simulation. It is very clear that the Thompson scheme produces the maximum snow content, while the Purdue Lin scheme produces the minimum snow content among the three BMPs (Figure 9). This corresponds quite well with the results from idealized thunderstorm simulations (see Figures 4, 5, and 6), where the graupel hydrometeor path contributes more than 50% of the total hydrometeor path at the end of the two hour simulation (see Figure 5 for MP8). On the other hand, the WSM6 scheme produces the maximum graupel content, while the minimum graupel is produced by the Thompson scheme (Figure 10). Again, this corresponds quite well with results from idealized thunderstorm simulations (see Figures 4, 5, and 6), where the graupel hydrometeor path contributes over 60% of the total hydrometeor path at the end of the two hour simulation (see Figure 5 for MP6). The above similarities among two suites of simulations (i.e., idealized simulations and TWP-ICE simulations) indicates strongly that the importance of ice-phase cloud MP in contributing to the wide discrepancy of simulated differences among ice species (e.g., cloud ice, snow, graupel), while the interactions between the ice-phase cloud MP and other schemes play less important roles.

[27] To generate a consolidated view of model observation intercomparison, we plot the RMSE and biases for temperature, water vapor, and cloud fraction (Figure 11) between WRF simulations and TWP-ICE objective analysis for “active” and “dry” monsoon periods during the TWP-ICE. During the “active” monsoon period, the model generally overestimates the temperature within the boundary layer (i.e., below 1.5 km) and above the tropopause (i.e., above 13.5 km). In between, the temperature biases are within the range of ±0.5K (Figure 11a). This is reflected also in the RMSE profiles of temperature. For water vapor
(Figure 11c), the model generally underestimates the water vapor below 9 km. The largest biases and RMSE are found at about 1.0 km. The cloud fraction also is underestimated by the model (Figure 11e) under about 6 km. From 6 km and above, the largest discrepancy could be found among the three BMPs. We believe that this is contributed primarily by the ice-phase cloud microphysics. In particular, the Thompson scheme greatly overestimates cloud fraction up to 40% above 9 km, while the other two BMPs only slightly overestimate cloud fraction up to 15%. As mentioned before, the Thompson scheme could overestimate the snow content, and hence produce a large bias in cloud fraction used in radiation calculations. This is because the adapted parameterization of cloud fraction [Xu and Randall, 1996b] only takes into account cloud water, cloud ice, and snow (i.e., graupel is not considered). During the “dry” monsoon period, temperature and cloud fraction biases are much smaller than the “active” monsoon period (Figure 11b) except that at about 13 km, a strong underestimated temperature is found in line with the cooling caused by the overestimated cirrus clouds in the model (Figure 11f). For water vapor (Figure 11d), the model systematically underestimates it within boundary layers (i.e., below 2 km), and overestimates it between 2 and 6 km with a maximum bias at about 4 km.

[28] During the “active” monsoon period, the model underestimates cloud IWC between 4 and 10 km compared to MMCR retrievals (Figure 12a). Compared with satellite retrieved cloud IWC, the model underestimates cloud IWC between 5 and 14 km (Figure 12c). Overall, the difference between model and satellite is 5 times larger than that between the model and MMCR during the “active” monsoon period. During the “dry” monsoon period, this difference is much smaller among model simulations, MMCR, and satellite retrievals (Figures 12b and 12d). Overall, the cloud IWC error is 10–50 times smaller during the “dry” monsoon period than during the “active” monsoon period. We suggest this might be caused by three critical points. First, the MMCR retrieval is attenuated by precipitating clouds during the “active” monsoon period, while this is not true for the “dry” monsoon period. Second, the cloud overlapping may contribute to the overall larger bias in satellite retrievals, while during the “dry” monsoon period, this overlap is reduced substantially. Finally, the interactions between cloud microphysical and other physical schemes may contribute to the overall larger discrepancy during the “active” monsoon periods, while these interactions are decreased substantially during the “dry” monsoon period due to less interacting processes in the model and reality.
The radiative heating profile reflects the interaction between cloud microphysics and radiation schemes. Overall LW heating biases (Figures 13c and 13d) dominate the net heating biases profiles during both the “active” and “dry” monsoon periods because the magnitudes of LW heating errors are 2–4 times larger than those of SW heating errors (Figures 13e and 13f). In particular, the SW heating is underestimated between 4 and 10 km during the “active” monsoon period, while it is overestimated slightly between 2 and 10 km during the “dry” monsoon period. For LW heating, overall it is overestimated during the “active” monsoon period while underestimated during the “dry” monsoon period. Large discrepancies can be found for both cloud macrophysical (cloud fraction, cloud base and top heights) and microphysical (cloud liquid and ice water contents) states among model simulations. These discrepancies may be caused by the cloud BMP itself, or may also be caused by the interactions between cloud BMP and other physical schemes (e.g., radiation scheme). To further isolate one of the most important feedbacks between cloud microphysics and radiation scheme, we have carried out another suite of WRF simulations, in which we have turned off the interaction between the cloud BMP and radiation schemes.

5.3. TWP-ICE RAD Simulations

Figure 14 shows the cloud fraction difference between TWP-ICE RAD and TWP-ICE simulations (former minus latter). It is clear that overall the cloud fraction is not changed too much when we turn off the cloud radiation feedback (Figure 14). However, during the strongest “active” monsoon period, the Purdue Lin BMP cloud fraction (Figure 14a) is perturbed strongly without the cloud radiation feedback. While for the other two BMPs, the change in cloud fraction is much smaller during the same period (Figures 14b and 14c). In particular, the cirrus cloud fraction in the Thompson scheme has changed quite a bit before and after the strongest convective event (January 23–25). However, compared to the wide discrepancies of cloud fraction among the three BMPs (see Figure 7), the difference in cloud fraction is pretty small. The Purdue Lin scheme seems to be a bit more sensitive to cloud radiation feedback compared to the other two BMPs.

Figure 15 shows the cloud IWC difference (units $10^{-3}$ gm$^{-3}$) between TWP-ICE RAD and TWP-ICE simulations (former minus later). Consistent with Figure 14, the cloud IWC has not changed much between the TWP-ICE RAD and TWP-ICE simulations. This is particularly true for the Thompson scheme, which has produced the minimum cloud IWC among three BMPs (see Figure 8 for WRF MP8). While during the strongest “active” monsoon period, both the Purdue Lin (MP2) and WSM6 (MP6) schemes show some changes in cloud IWC. In particular, consistent with the higher sensitivity in cloud fraction, the Purdue Lin
scheme has the largest overall changes in cloud IWC. This indicates that the cloud radiation feedback also depends critically on the cloud BMP, although this feedback has been shown to play a secondary role in contributing to the wide discrepancy among the three BMPs.

[32] Figure 16 shows the snow difference (units 10^{-3} gm^{-3}) between TWP-ICE RAD and TWP-ICE simulations (former minus later). Compared to the cloud IWC, the snow content changes are relatively larger and consistent with the cloud fraction changes (Figure 14). This consistency is caused primarily by the parameterization of cloud fraction in the WRF model. As we mentioned earlier, snow (not graupel) is considered as one of the critical moisture parameters in the calculation of cloud fraction [Xu and Randall, 1996b]. Figure 17 shows the graupel difference (units 10^{-3} gm^{-3}) between TWP-ICE RAD and TWP-ICE simulations (former minus later). Compared with the snow content changes, the graupel difference is relatively small, and confined with more limited days during the strongest “active” monsoon period in the three BMPs. The common features among the changes for snow and graupel indicate that the cloud radiation feedback is most important during the convective clouds and/or precipitation periods, while during the other periods in TWP-ICE, it plays a negligible role in contributing to the wide discrepancy among the three BMPs.

6. Conclusions and Future Perspectives

[33] Based on in situ observations from TWP-ICE, idealized high-resolution thunderstorm simulations, and two suites of nested, “cloud-permitting” WRF simulations with three sophisticated cloud BMPs, we find that wide discrepancies exist among simulations and observations (Figures 7 and 8 and Figures 11–13). These discrepancies are consistent between idealized thunderstorm (Figures 3–6) and TWP-ICE (Figures 7 and 8) simulations for each BMP scheme. For example, the Thompson scheme substantially overestimates the snow content (Figure 9) and hence produces biases in cirrus clouds (Figure 7) during the “dry” monsoon period, while it produces more realistic mixed-phase clouds during the “active” monsoon period. On the other hand, the WSM6 and Purdue Lin schemes have a better representation of cirrus clouds (Figure 7) than the Thompson scheme, which could be related to a more realistic simulation of cloud ice (Figure 8). All three of the BMPs miss the initial convective system on January 18 (Figure 7) that might be associated with a strong MJO event. By turning off the cloud radiation feedback, we
notice that the ice-phase cloud microphysics play the most important role in contributing to the wide discrepancies, while the interaction between cloud and radiation takes the secondary, but nonnegligible role (Figures 14–17). The cloud-radiation interaction is most important during the convective precipitating periods of TWP-ICE for all three BMPs (Figure 14). It is shown that the cloud radiation feedback is quite sensitive to the ice-phase cloud microphysical scheme as well (Figure 15).

[34] We suggest the early systematic errors in model simulations might be related to the forcing data based on large-scale (1 degree) NCEP real-time analysis. It is well known that in tropical regions, due to the lack of observational data, the largest bias is expected in our forcing data. In particular we believe that the critical MJO signal may be missing or delayed in the forcing data from NCEP so that the initial convective period is not well simulated by all three of the BMPs. In the future, we will develop a multiyear combined real-time analysis data set so that the model biases introduced by the large-scale forcing may be eliminated (J. Dudhia and L. R. Leung, personal communication, 2008).

[35] On the other hand, the cloud macrophysical and microphysical retrievals from ground-based remote sensing and satellite suffer from a few caveats. First, the satellite data have coarse temporal and spatial resolutions compared to model and ground-based remote sensing. Second, the satellite data have the largest bias under cloud overlapping conditions because the sensor onboard cannot penetrate thicker clouds. Third, the ground-based remote sensing suffers from the precipitating clouds due to the attenuation of radar signals. Finally, the higher, thinner cirrus clouds have the weakest radar signals and may not be detectable. This is particularly true because the MMCR used during the TWP-ICE was damaged by a lightening strike before the experiment. This damage caused a 10 times less sensitivity and was found only after the TWP-ICE.

[36] In addition, it is also well known that the crucial techniques to retrieve the cloud liquid and ice microphysical properties are still active areas of research and have a wide range of uncertainties [Comstock et al., 2007]. For a fair comparison with sophisticated cloud microphysical schemes as used in the paper, we need to test and develop advanced approaches to characterize the detailed cloud liquid and ice properties under conditions such as precipitating and thin cirrus clouds. Furthermore, the overestimation of cirrus clouds in model simulations may be related to biases in estimated saturation vapor pressure and relative humidity due to the cold temperature. When the temperature drops below minus 40°C, the calculation of saturation vapor pressure can have a bias of more than 20% [Murray, 1967].

[37] Clouds are an integral part of the climate system. Through their influence on radiation, atmospheric heating/moistening effects, and precipitation, clouds regulate the water and energy cycles of the climate system. Improving the representation of tropical clouds has been identified as the primary uncertainty in accurately predicting the radiation budget in climate models [Wielicki et al., 2002]. Tropical convective systems and their associated clouds can persist for days and spread over thousands of kilometers, and hence have a large radiative impact in the region. Therefore, an improved understanding of the multi-scale structure of tropical clouds and their interactions with the environment is critical to observational and modeling communities. The TWP-ICE provided, for the first time, a suite of observational data sets that can be used in model evaluations and parameterization development.

[38] Overall, TWP-ICE was focused on clouds, in particular, deep convective clouds, their life cycle and interactions with radiation and large-scale dynamics. In particular, we find that deep convective clouds generally are formed later in the model (at 4 km resolution) and last longer after their formation than observations show (Figure 7). These issues may be related to the threshold behavior of the explicit cloud BMP. In particular, most cloud BMPs [Chen and Sun, 2002; Hong and Lim, 2006; Thompson et al., 2004, 2008] are designed to study midlatitude, continental cloud systems (more observations available), and may not have been applied in the tropical environment before. To realistically simulate convective clouds and their life cycle in the tropical environment is an active and challenging field of research.

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J. Dudhia, Mesoscale and Microscale Meteorology Division, ESSL, National Center for Atmospheric Research, 3450 Mitchell Lane, P.O. Box 3000, Boulder, CO 80301, USA. (dudhia@ucar.edu)

S. J. Ghan, L. R. Leung, C. N. Long, J. H. Mather, S. A. McFarlane, and Y. Wang, Pacific Northwest National Laboratory, 902 Battelle Boulevard, P.O. Box 999, MSIN: K9-24, Richland, WA 99354, USA. (steve.ghan@pnl.gov; ruby.leung@pnl.gov; chuck.long@pnl.gov; jim.mather@pnl.gov; sally.mcfarlane@pnl.gov; ywang699@gmail.com)

X. Liu, SKLLQG, Institute of Earth Environment, Chinese Academy of Sciences, Xi’an 710075, China. (liuxd@loess.llqg.ac.cn)