Impacts of A Priori Databases Using Six WRF Microphysics Schemes on Passive Microwave Rainfall Retrievals

JU-HYE KIM AND DONG-BIN SHIN
Department of Atmospheric Sciences, Yonsei University, Seoul, South Korea

CHRISTIAN KUMMEROW
Department of Atmospheric Sciences, Colorado State University, Fort Collins, Colorado

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ABSTRACT

Physically based rainfall retrievals from passive microwave sensors often make use of cloud-resolving models (CRMs) to build a priori databases of potential rain structures. Each CRM, however, has its own cloud microphysics assumptions. Hence, approximated microphysics may cause uncertainties in the a priori information resulting in inaccurate rainfall estimates. This study first builds a priori databases by combining the Tropical Rainfall Measuring Mission (TRMM) precipitation radar (PR) observations and simulations from the Weather Research and Forecasting (WRF) model with six different cloud microphysics schemes. The microphysics schemes include the Purdue–Lin (LIN), WRF Single-Moment 6 (WSM6), Goddard Cumulus Ensemble (GCE), Thompson (THOM), WRF Double-Moment 6 (WDM6), and Morrison (MORR) schemes. As expected, the characteristics of the a priori databases are inherited from the individual cloud microphysics schemes. There are several distinct differences in the databases. Particularly, excessive graupel and snow exist with the LIN and THOM schemes, while more rainwater is incorporated into the a priori information with WDM6 than with any of the other schemes. Major results show that convective rainfall regions are not well captured by the LIN and THOM schemes-based retrievals. Rainfall distributions and their quantities retrieved from the WSM6 and WDM6 schemes-based estimations, however, show relatively better agreement with the PR observations. Based on the comparisons of the various microphysics schemes in the retrievals, it appears that differences in the a priori databases considerably affect the properties of rainfall estimations.

1. Introduction

Rainfall measurements from passive microwave sensors are based on a general relationship between the observed brightness temperature and the integrated water and ice content in a cloud. The surface rainfall, however, depends upon details of the vertical structure of various hydrometeors and their vertical velocity near the surface. Physically based retrieval algorithms must therefore employ some cloud model that converts integrated hydrometeor amounts to surface fluxes. Early retrievals based only on emission signatures from raindrops at low-frequency channels exploited a simple onedimensional (1D) conceptual cloud model. Wilheit et al. (1991) provide an example of an emission-based rainfall algorithm. The algorithm has been successfully used in global rainfall estimations at climate scales from the Special Sensor Microwave Imager (SSM/I), the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI), and Special Sensor Microwave Imager/Sounder (SSMIS). More recent algorithms attempt to simultaneously exploit emission and scattering signatures available from the above sensors. In these schemes, 3D cloud-resolving models (CRMs) have been used to simulate more realistic radiometric signatures from multichannel microwave radiometers (Kummerow et al. 1996; Olson et al. 1996). However, cloud-resolving models with assumed microphysics are known not to reproduce the observed brightness temperatures (TBs) exactly. These differences can affect the retrieval quality, but it can also be used to diagnose the applicability of specific cloud-resolving model microphysics packages to observed scenes.
The uncertainties in cloud microphysics parameterizations based on investigations of model-simulated and observed radiometric signatures have been investigated. For example, Lang et al. (2007) compared the brightness temperatures and reflectivities obtained from cloud radiative simulations of the TRMM Large-Scale Biosphere–Atmosphere Experiment in Amazonia (TRMM LBA) with the direct observations of TMI and TRMM precipitation radar (PR), respectively. In the study, depressions of observed and simulated TBs at 37- and 85.5-GHz frequencies for two convective systems from the Goddard Cumulus Ensemble (GCE) model were evaluated. It was found that eliminating dry growth of graupel and lowering the snow collection efficiency removed the unrealistic presence of high-density ice throughout the anvil and reduced excessive snow contents. It was also reported that CRM simulations employing a single-moment scheme had difficulty in implementing realistic size distributions; thus, a double-moment approach for both ice and liquid phases may be required. Han et al. (2010) also evaluated five cloud microphysical schemes in the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) using observations of TMI and PR. Radiative properties including TBs, radar reflectivity, attenuation, and scattering in precipitation liquid and ice layers from five schemes were compared with those values obtained for different distributions of hydrometeors. It was suggested that major differences between the radiative properties originated from the characteristics of precipitation ice particles.

As a different approach, Zhou et al. (2007) used the GCE model to simulate the China Sea monsoon and compared their simulated cloud products with TRMM-retrieved (level 2) products from the South China Sea Monsoon Experiment (SCSMEX) field campaign. It was reported that relatively good agreement in convective precipitation is found, while the amount of simulated rainfall from the stratiform precipitation region is much lower than that from the level-2 product. Large differences between CRM simulations and observations also exist in the rain spectrum together with the vertical distribution of hydrometeors. However, it should be noted that there may exist an ambiguity in direct comparisons of CRM simulations with low earth-orbiting satellite observations owing to difficulties in matching temporal and spatial scales and the intervention of uncertainties in the retrieved products.

Other studies have discussed the shortcomings in cloud microphysics parameterizations of CRMs from the perspective of passive microwave rainfall estimations. Shin and Kummerow (2003) highlighted that when the liquid portion of the profile is matched for the model and observation combined a priori databases, the CRMs consistently specify ice particles of an incorrect size and density, which in turn leads to a lower than observed TB. This divergence between CRMs and observations is consistent with the study by Viltard et al. (2000) that also showed significant disagreement between PR and TMI at the scattering frequencies. Based on an observation-based a priori database from TMI and PR, Grecu and Olson (2006) delineated that the larger amounts of ice-phase precipitation above the freezing level that were estimated from the Goddard profiling (GPROF) algorithm (version 6) may be attributed to the assumptions in its forward model, the GCE model. The study also emphasized that more realistic and diverse CRM simulations are required to better estimate the precipitation field together with variables that are not directly observed, such as latent heating.

As discussed, many previous studies noted that the ambiguity associated with cloud microphysics in CRM simulations may affect estimations of hydrometeors from passive microwave sensors. However, discussions from most of the previous works were limited to a single set of hydrometeor microphysics schemes facilitated in a specific model. In this study, the impacts of cloud microphysics on the quality of an a priori database in a microwave rainfall retrieval will be comprehensively evaluated using various advanced microphysics parameterizations. We will then compare the retrieved precipitation fields representing mesoscale structures of intense tropical cyclones (TC), when various simulations from different microphysics schemes are used in generating the a priori database. This study utilizes the Weather Research and Forecasting (WRF) model that includes recently developed cloud and precipitation microphysics schemes. Within the framework of the parametric rainfall retrieval algorithm introduced by Shin and Kummerow (2003), the WRF model simulations are used as previously prepared databases that provide complete geophysical parameters to PR-observed rainfall fields. The WRF model, which is available as a community model in the public domain, can be operated at multiple scales, from cloud to global scale, and for both operational and research purposes. Because of its flexible structure and growing use by development groups, the WRF model furnishes the latest microphysics schemes, such as various single- and double-moment cloud physics, as well as the GCE microphysics scheme. It is known that model simulations of precipitation are highly sensitive to the characteristics of cloud microphysics schemes. Thus, microphysics schemes can be a large source of uncertainty in numerical simulations of precipitation fields that can be used as a priori information for satellite precipitation retrieval algorithms.
2. Data for a priori databases and retrievals

This study focuses on the TMI and PR observations for Typhoon Sudal, which is a strong tropical cyclone that formed on 4 April and dissipated on 15 April 2004. The TRMM overpass data over the typhoon captured several features of the typhoon including intensifying and asymmetric rainfall structures. The PR 2A25 product—observed rainfall exceeding 124.5 mm h$^{-1}$ in the typhoon. Three orbits captured the typhoon (orbit numbers 36522, 36532, and 36537). The first two orbits are used for database construction and the third orbit is used for retrievals. The histograms of TBs at each TMI channel for the first two orbits and the third orbit are compared in Fig. 1, which shows that the distribution of TBs for the databases sufficiently cover the ranges of TBs for the retrieval target (the third orbit). That is, the observational components of the a priori database include sufficient information on the retrieval target scenes.

Another event, Typhoon Choiwan in 2009, is used as a different retrieval target case (TRMM orbit number 67461) in section 5. The observed TBs are mostly included within the TB range of Typhoon Sudal. Greater than 90% of the total pixels are included in the range of three databases. Moreover, the bimodal distributions of TBs at 19, 21, and 37 GHz from Typhoon Choiwan are similar to the characteristics of the a priori database with the shifted modes (Fig. 1).

3. Construction of databases with various microphysics

This study does not intend to construct a comprehensive a priori database to provide global precipitation but rather to investigate the impact of various CRM cloud microphysics on microwave rainfall retrievals based on simple databases associated with distinct rainfall events. For this purpose, the case of Typhoon Sudal in 2004 was selected to build the a priori databases. WRF model simulations of Typhoon Jangmi in 2008 are conducted with six different microphysics schemes in order to provide hydrometeor profiles for the a priori databases. Characteristics of the selected schemes are described below.

a. Cloud microphysics schemes in the WRF model

The six schemes include the Purdue–Lin (LIN; Chen and Sun 2002), WRF Single-Moment 6 (WSM6; Hong and Lin 2006), Goddard Cumulus Ensemble (Tao et al. 1989; Lang et al. 2007), Thompson (THOM; Thompson et al. 2004), WRF Double-Moment 6 (WDM6; Lim and
condensation nuclei (CCN). Thus, the microphysical processes of the WDM6 scheme that are related to the ice phase are identical to those of the WSM6 scheme. Lim and Hong (2010) showed that WDM6 produces stronger reflectivity near the freezing level when accompanied by an increasing amount of rainwater. Hong et al. (2010) compares the WSM6 and WDM6 schemes for representing precipitating moist convection in 3D platforms. The WDM6 scheme improves rainfall prediction by suppressing spurious precipitation and by enhancing heavy precipitation. These changes can be explained by the fact that the WDM6 scheme has a wider range in cloud and rain number concentrations than the WSM6 scheme. The MORR scheme (Morrison et al. 2005; Morrison and Pinto 2005) includes more complicated microphysics, including predicted number concentrations and mixing ratios of four hydrometeor species (cloud, cloud ice, rain, and snow), predicted rain size distribution, and reduced (increased) rates of rain evaporation in stratiform (convective) regions. This scheme contains options to optimize simulations for Arctic weather by accommodating the selection of the ice nucleation method and the CCN spectra (Morrison et al. 2005).

b. CRM simulations

CRM simulations were conducted for Typhoon Jangmi, which began as a tropical wave at 0000 UTC 24 September 2008. The typhoon rapidly intensified as it moved in the northwestern direction from 1200 UTC 25 September to 1200 UTC 27 September. It attained 59 m s⁻¹ at its peak intensity and reached a minimum pressure of 905 hPa. After 0900 UTC 28 September, the typhoon made landfall in Taiwan and curved to the east before it dissipated on 1 October.

For its rapid intensification period from 1200 UTC 25 September to 1200 UTC 27 September, three-dimensional simulations of the typhoon were performed using the triply nested domains of the Advanced Research WRF model (ARW-WRF), version 3.1. The outer domain has a grid spacing of 30 km, and the most inner one has a 3.3-km horizontal resolution. Based on the typical ratio of 3 used in the WRF model, it is implied that the second nest has 10-km grid spacing. The coarse mesh, with a 30-km horizontal resolution, allows global analysis using the National Centers for Environmental Prediction (NCEP) final analysis (FNL; 1° × 1° global grid) for both the model initial state and lateral boundary conditions during the simulation period. Simulations are made at 28 vertical layers with the model top at 0.5 hPa.

Every 6 h, the fine mesh grid with 3.3-km resolution was saved and used for CRM databases for the period from 0000 UTC 26 September to 1200 UTC 27 September.
Physical parameterization packages other than the microphysics include the Rapid Radiative Transfer Model (RRTM) longwave radiation (Mlawer et al. 1997) and the simple shortwave radiation for radiation processes (Dudhia 1989) and the Yonsei University (YSU) scheme for the planetary boundary layer (Hong et al. 2006). The Kain–Fritsch cumulus parameterization scheme for convective processes (Kain and Fritsch 1993) is adopted for domains 1 and 2.

Figure 2 shows the domain- and time-averaged hydrometeors from WRF model simulations of Typhoon Jangmi (2008) with (a) LIN, (b) WSM6, (c) GCE, (d) THOM, (e) WDM6, and (f) MORR microphysics schemes, respectively. The averaged hydrometeor profiles are obtained from every 6-hourly snapshots with the fine mesh grid at 3.3-km resolution. It appears that the three WRF model runs employing single-moment microphysical schemes (LIN, WSM6, and GCE) produce similar profiles of liquid phases of cloud and rainwater (Figs. 2a,b,c) because of their warm rain processes. The profiles of the LIN and WSM6 schemes are particularly similar. Contrary to the similarity in liquid phases, the LIN experiment produces a much smaller amount of ice-related particles than those yielded by the WSM6 and GCE experiments. Moreover, from 6 to 8 km in altitude, only graupel exists in the LIN simulation. The reduction of frozen hydrometeors near and above the melting layer in the LIN simulation differs distinctly from the results of the other microphysics schemes. It is also found that the GCE scheme tends to produce more ice particles than the LIN and WSM6 schemes. One can also note that slightly more rainwater is present from about 3 to 5 km in altitude in the WRF model run as compared with that present in the GCE schemes.

Comparing results from three double-moment microphysical schemes (Figs. 2d,e,f), the characteristics of the vertical profiles of the five hydrometeors seem to
differ considerably between schemes. For liquid-phase hydrometeors, the WDM6 experiment produces a significantly larger amount of rainwater but a smaller cloud droplet mixing ratio than the other schemes. The THOM scheme experiment produces the smallest amount of rainwater. By contrast, the snow mixing ratio from the THOM scheme experiment is much larger than the ratios produced by the other experiments. Also, the MORR scheme tends to produce similar amounts of graupel but larger amounts of snow than the WDM6 scheme.

We may also capture the difference between the WSM6 and WDM6 schemes (Figs. 2b,e). Both experiments show similar vertical distributions of ice-phase particles resulting from their identical ice-related microphysics. However, modified warm rain processes in the WDM6 scheme, and larger rain number concentration near the melting layer and convective regions, yield an increased rainwater mixing ratio but a smaller amount of cloud water (Lim and Hong 2010).

c. Parametric rainfall retrieval algorithm

The a priori databases of precipitation profiles and associated TBs are constructed by the parametric rainfall retrieval algorithm as described in Shin and Kummerow (2003). The key goal of this methodology is to generate three-dimensional precipitation fields by matching the PR reflectivity profiles with those calculated from CRM-derived hydrometeor profiles. The generated raining systems over PR observation fields can be applied to any radiometers that are unaccompanied with a radar for microwave radiative calculation with consideration of each sensor’s channel and field of view. Masunaga and Kummerow (2005) also described the technical aspect of the parametric rainfall retrieval method and reduced the inconsistency in microwave TBs by iterating the retrieval procedure with updated assumptions of DSD and ice-density models. Elsaesser and Kummerow (2008) developed a nonraining framework that retrieves surface wind (wind), total precipitable water (TPW), and cloud liquid water path (LWP) from TMI observations. It facilitates merging parametric background retrievals with rainfall retrievals using an optimal estimation method. Building on those researches, Kummerow et al. (2011) developed a new a priori database, an observationally constrained database for use in passive microwave rainfall retrieval algorithms over oceans. Previous works by Shin and Kummerow (2003), Masunaga and Kummerow (2005), Elsaesser and Kummerow (2008), and Kummerow et al. (2011) may be referred to for more detailed technical instructions and procedure adjustment methods.

The observational component of the database contains just 1608 profiles distributed over two different orbits because only a few PR pixels from the center of the swath were used to generate the three-dimensional structures to avoid poorly corrected surface echoes and the bias resulting from the shadow zone at the edges of the swath. For rainfall inversion, the Bayesian retrieval methodology developed by Shin and Kummerow (2003) is used in conjunction with previously generated databases to derive the most likely surface rainfall as well as its vertical structure.

4. Comparisons of the constructed databases

a. Radiative indices

Based on the parametric rainfall retrieval approach discussed in the previous section, six different a priori databases are constructed using the TRMM observations of Typhoon Sudal and the WRF model simulations of Typhoon Jangmi with six different microphysics schemes. In addition, we also prepared a database consisting of TBs observed from TMI and rainfall rates from the PR level-2 product (2A25) at the same pixels used in the PR- and CRM-based a priori database. This database is termed the observation database. The observation database is not applicable to other channels or viewing geometries except for TMI sensor specification. However, the observation database can be used to validate the databases constructed by the parametric approach as well as investigate the errors introduced by CRMs.

To examine the agreement between the database TBs simulated with six microphysical schemes and observed TBs, the attenuation $P$ and scattering index $S$ introduced by Petty (1994) are used. Normalized polarization difference $P$ is represented as

$$P = \frac{T_V - T_H}{T_{V,0} - T_{H,0}},$$

where $T_V$ and $T_H$ are the vertically and horizontally polarized TBs, and $T_{V,0}$ and $T_{H,0}$ are TBs for the clear sky at the scene. The $P$ ranges from 0 to 1. The minimum of $P$ indicates that the pixel consists of a heavy liquid cloud droplet and the maximum indicates that the pixel represents a cloud-free region.

The $S$ is represented as

$$S = PT_{V,0} + P(1 - P)T_C - T_V,$$

where $T_C = 273$ K. The large value of $S$ implies a strong scattering due to precipitation particles.

Figure 3 shows scatter diagrams of the five indices from the six simulated databases and the observation database. The three attenuation indices ($P_{10}, P_{19}, and
Fig. 3. Comparisons of four modified attenuation indices $P$ and one scattering index $S$ from simulated TBs with (a) LIN, (b) WSM6, (c) GCE, (d) THOM, (e) WDM6, and (f) MORR microphysics schemes with observed counterparts.
$P_{37}$ from simulations and observations, presented in the first three columns, agree well with strong correlations ranging from 0.98 to 0.99. The biases are typically smaller in the attenuation index at 10- and 19-GHz for the six databases, especially in the WSM6 and WDM6 scheme-based databases. Moreover, it is apparent that the comparison statistics of $P_{37}$ for the six databases are quite similar to each other, which indicates good agreement between the simulations and observations. Relatively good correlations between the simulated and observation databases are also found for the attenuation index at 85 GHz ($P_{85}$), but the differences are found to be somewhat larger for the scattering index at 85 GHz ($S_{85}$), as indicated by correlations around 0.7 and root-mean-square (RMS) errors greater than 18. It is notable that the correlations of $S_{85}$ are slightly larger between the observation database and the simulated databases with the WDM6 and WSM6 schemes than with the other schemes.

b. EOF analysis

To evaluate how well the simulated databases represent observational variability, the empirical orthogonal function (EOF) analysis is conducted using the attenuation and scattering index vectors defined in the previous section. Five indices are declared by the notation $I$, a column vector:

$$I = \begin{bmatrix} P_{10} \\ P_{19} \\ P_{37} \\ P_{85} \\ S_{85} \end{bmatrix}.$$  

The spatial area averages of indices for the five categories are given by

$$\overline{I} = \frac{1}{M} \sum_{i=1}^{M} I_i,$$

where $M$ denotes the number of raining pixels. The anomaly at each pixel ($I'_i$) is given by

$$I'_i = I_i - \overline{I}.$$  

These anomalies are then expressed with respect to EOFs of each observation or simulation dataset such that

$$I'_i = \sum_{j=1}^{N} \alpha_{ij} e_j,$$

where $\alpha_{ij}$ is the amplitude associated with the $j$th mode EOF $e_j$ for the $i$th radiance index vector, and $N$ is the number of EOFs (in this study $N = 5$).

We compared the EOF patterns of the observation database and the databases simulated with the six microphysical schemes. The first and second EOFs of each database are shown in Tables 1 and 2, respectively. The variances explained by the first EOFs are about 99.9%. The observed pattern is characterized by the zero crossing between $P_{85}$ and $S_{85}$, indicating the opposition of variability associated with excess and depressed TBs from emission and scattering-based channels. The first EOFs from the databases simulated with the six different microphysical schemes show similar patterns. The patterns tend to mimic the observational variability relatively well, which suggests that each database seems to contain the variability present in the observation database.

5. Retrieval differences

a. Description on the retrieval scene

As discussed in section 2, the retrieval scene is selected from TRMM orbit number 36 537 over Typhoon Sudal. The PR and TMI provide rain rates at resolutions of 4 and 12 km, respectively. The maximum rainfall intensity of the typhoon estimated from the PR reaches 124.5 mm h$^{-1}$. To compare rain rates from the two instruments, PR rain rates (2A25) are averaged at the resolution of the TMI 37-GHz channel ($\approx 12 \times 12$ km$^2$), which is comparable to the resolution of the TMI rain rates (2A12 product). Rain rates from PR and TMI at the resolution of the TMI 2A12 product are presented in Figs. 4a and 4b.

Figure 4a illustrates that the regions with heavy precipitation colored in red are located near the northern hemisphere of the typhoon eyewall. Relatively strong precipitation areas colored in orange and red are found over the northeastern quadrant of the typhoon eyewall. Figure 4c also shows the distributions of convective and stratiform precipitation classified by the PR 2A23 product. The convective region is exhibited at the area surrounded by the typhoon eye and some intermittent pixels near the spiral band. The location of the convective area generally agrees with the region where strong precipitation above 20 mm h$^{-1}$ occurs in the PR rainfall estimation.

Figure 4b shows the rainfall distribution from TMI estimated by the GPROF, version 7 (2A12; Kummerow et al. 2011). The highest rainfall areas are located at the northern hemisphere of the typhoon eyewall, although the rainfall intensity estimated from the TMI is much
weaker than that from the PR. Only a few pixels show rain rates exceeding 30 mm h\(^{-1}\). This may be because the reflectivity \(Z\) to rain rate \(R\) used in the PR rainfall algorithm has no upper limit; thus, high rain rates correspond with high \(Z\) values. It is also, at least in part, due to the Bayesian scheme used in the GPROF scheme. Bayesian schemes, by virtue of their statistical nature, will always underestimate extreme rainfall events and overestimate extremely light events. Disagreements in rainfall intensity and rainfall distribution were one of the motivations to select this case as a retrieval target.

**b. Retrieved precipitation**

The precipitation fields of Typhoon Sudal, retrieved using the six different a priori databases, are presented in Fig. 5. The retrieved precipitation fields can be compared with the PR estimates (Fig. 4a) over the PR swath. It seems that the general patterns of the typhoon, such as its center, eyewall, and boundary, may be described by the retrievals based on the six different databases.

**TABLE 1. The first EOF and its variances for five indices from the simulated a priori databases and corresponding observation databases.**

<table>
<thead>
<tr>
<th></th>
<th>(P_{10})</th>
<th>(P_{19})</th>
<th>(P_{37})</th>
<th>(P_{85})</th>
<th>(S_{85})</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs</td>
<td>0.0102</td>
<td>0.0154</td>
<td>0.0160</td>
<td>0.0060</td>
<td>-0.9997</td>
<td>99.90</td>
</tr>
<tr>
<td>LIN</td>
<td>0.0052</td>
<td>0.0074</td>
<td>0.0076</td>
<td>0.0067</td>
<td>-0.9999</td>
<td>99.96</td>
</tr>
<tr>
<td>WSM6</td>
<td>0.0059</td>
<td>0.0088</td>
<td>0.0092</td>
<td>0.0081</td>
<td>-0.9999</td>
<td>99.95</td>
</tr>
<tr>
<td>GCE</td>
<td>0.0062</td>
<td>0.0089</td>
<td>0.0093</td>
<td>0.0081</td>
<td>-0.9999</td>
<td>99.93</td>
</tr>
<tr>
<td>THOM</td>
<td>0.0070</td>
<td>0.0101</td>
<td>0.0110</td>
<td>0.0103</td>
<td>-0.9998</td>
<td>99.93</td>
</tr>
<tr>
<td>WDM6</td>
<td>0.0063</td>
<td>0.0095</td>
<td>0.0104</td>
<td>0.0098</td>
<td>-0.9998</td>
<td>99.95</td>
</tr>
<tr>
<td>MORR</td>
<td>0.0061</td>
<td>0.0090</td>
<td>0.0093</td>
<td>0.0081</td>
<td>-0.9999</td>
<td>99.93</td>
</tr>
</tbody>
</table>

**TABLE 2. As in Table 1, but for the second EOF.**

<table>
<thead>
<tr>
<th></th>
<th>(P_{10})</th>
<th>(P_{19})</th>
<th>(P_{37})</th>
<th>(P_{85})</th>
<th>(S_{85})</th>
<th>Variance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Obs</td>
<td>0.2236</td>
<td>0.4025</td>
<td>0.5144</td>
<td>0.7232</td>
<td>0.0210</td>
<td>0.09</td>
</tr>
<tr>
<td>LIN</td>
<td>0.2358</td>
<td>0.4066</td>
<td>0.5156</td>
<td>0.7163</td>
<td>0.0130</td>
<td>0.04</td>
</tr>
<tr>
<td>WSM6</td>
<td>0.2309</td>
<td>0.4002</td>
<td>0.5082</td>
<td>0.7267</td>
<td>0.0154</td>
<td>0.05</td>
</tr>
<tr>
<td>GCE</td>
<td>0.2447</td>
<td>0.4135</td>
<td>0.5158</td>
<td>0.7091</td>
<td>0.0157</td>
<td>0.07</td>
</tr>
<tr>
<td>THOM</td>
<td>0.2391</td>
<td>0.4087</td>
<td>0.5093</td>
<td>0.7184</td>
<td>0.0188</td>
<td>0.07</td>
</tr>
<tr>
<td>WDM6</td>
<td>0.2258</td>
<td>0.3958</td>
<td>0.5004</td>
<td>0.7360</td>
<td>0.0176</td>
<td>0.05</td>
</tr>
<tr>
<td>MORR</td>
<td>0.2418</td>
<td>0.4120</td>
<td>0.5149</td>
<td>0.7116</td>
<td>0.0158</td>
<td>0.07</td>
</tr>
</tbody>
</table>

**FIG. 4.** TRMM observations of Typhoon Sudal: (a) TRMM PR rain rates at TMI 37-GHz resolution, (b) TRMM GPROF rain rates, and (c) discrimination of convective (yellow) and stratiform (blue) regions from PR observation at the 37-GHz resolution.
However, the heavy rainfall regions associated with strong convection are displayed in different ways. That is, the results from the WSM6 and WDM6 databases properly capture the strong precipitation band around the eyewall where the rain rate exceeds 30 mm h\(^{-1}\), colored in orange and red in Fig. 4. The retrieval based on the database with the LIN scheme, however, does not simulate the heavy precipitation region around the northeastern part of eyewall but locates it in the southwestern part. For the cases with the GCE and MORR schemes, the regions with rain rates between 20 and 30 mm h\(^{-1}\) correspond relatively well to the estimation from the PR, but the heavy rainfalls associated with the strong convection are weaker and more sparsely distributed compared to the estimations from the PR. The experiment with the THOM scheme shows features similar to the cases with the GCE and MORR schemes, but the area with rain rates from 20 to 30 mm h\(^{-1}\) seem to be distributed more widely. Results clearly show that the different retrieved rainfall patterns are related with the microphysics differences in the amounts and vertical distributions of liquid and frozen hydrometeors.

Retrieval statistics including correlation, bias, and RMS error are computed for the retrieval experiments with each database. The PR estimate at the resolution of 37 GHz is considered as a reference rainfall in this study. Figure 6 compares the retrieval performances based on the six different databases. The rainfall estimated from the GPROF, version 7 (2A12), is also compared in the figure. The highest correlation (0.81) and the lowest RMS error (8.64) are found in the retrieval with the WDM6 scheme. Relatively good correlations from 0.78 to 0.79 and RMS error ranging from 8.87 to 9.43 are found in the retrievals with the WSM6, GCE, and MORR schemes. Meanwhile, results from the LIN scheme–based database shows low correlation with relatively high RMS
error and bias statistics. Furthermore, the retrieved rainfall intensity from 2A12 tends to be below 30 mm h\(^{-1}\), which may be due to the database focusing on the mapping of global precipitation and its related lack of heavy rainfall information.

Tables 3 and 4 compare rainfall retrieval statistics for convective and stratiform pixels, respectively. In general, correlations between the convective pixels are relatively higher than those between the stratiform pixels for the experiments, particularly with the WSM6, GCE, THOM, WDM6, and MORR schemes. However, their rainfall intensities tend to be underestimated and RMS and bias scores are considerably higher for the convective pixels than for the stratiform pixels. It is worth noting that the correlation and RMS error statistics may be important in terms of instantaneous rainfall retrievals, but the bias statistics may be meaningful from a climatological perspective. From the climatological perspective,
focusing on the correlation and RMS statistics, the retrieval with the WDM6 scheme–based database presents the highest correlation (0.89) and the lowest RMS error (27.10) for convective precipitation, and the WSM6 scheme–based database yields the stratiform precipitation with the highest correlation (0.77) and the lowest RMS error (9.43).

This retrieval experiment is also applied to another case of Typhoon Choiwan in 2009. A major feature of the typhoon observed by PR is that strong precipitation regions with rain rates greater than about 30 mm h\(^{-1}\) are located in the northeastern part of the typhoon eye. Measured precipitation from the TMI (2A12) is presented in Fig. 7b, and retrieval statistics are also compared to the PR-measured values (2A25). The TMI pixels with strong rain rates exceeding 40 mm h\(^{-1}\) are not well matched to those from the PR. Retrievals with the a priori database based on the WDM6 scheme capture strong precipitation regions with rain rates less than 30 mm h\(^{-1}\) relatively well but fail to produce the heavy rain rates greater than 30 mm h\(^{-1}\). It is also found that measured rainfalls from the WSM6 and WDM6 scheme-based databases show better retrieval scores than the databases based on other schemes (Figs. 7c–h). However, overall retrieval performance in terms of correlation and RMS are degraded for Typhoon Choiwan compared to the case of Typhoon Sudal. It is noteworthy that the TMI-observed TBs for the typhoon are mostly included within the ranges of distributions of the a priori databases. The modes of the histograms from the a priori database and the typhoon, however, are significantly different, as previously shown in Fig. 1, indicating differences in rainfall characteristics between the two typhoons (Sudal and Choiwan). For these reasons, we may expect that retrievals for Typhoon Choiwan with the a priori databases based on Typhoon Sudal can be degraded.

6. Conclusions

In this study, we constructed various a priori databases based on the WRF model simulations with six different microphysics schemes (LIN, WSM6, GCE, THOM, WDM6, and MORR) in conjunction with the observations from TRMM PR. Two well-developed typhoons, Jangmi and Sudal, are selected for WRF model simulation and to collect the observational information of PR, respectively. Construction of the databases includes the matching of simulated reflectivity profiles from the WRF model outputs to the PR-observed reflectivity profiles. The matched WRF model profile is then used to compute TBs as observed by TMI. The modified attenuation (emission) and scattering indices are calculated to examine agreement between the simulated databases and corresponding observations. The indices related to emission signals agree well with the observations, but the indices associated with scattering show some discrepancies relative to their observed counterparts. This

<table>
<thead>
<tr>
<th>Mean</th>
<th>Std dev</th>
<th>Correlation</th>
<th>RMS</th>
<th>Bias</th>
</tr>
</thead>
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<tr>
<td>True</td>
<td>Retrieved</td>
<td>True</td>
<td>Retrieved</td>
<td>Correlation</td>
</tr>
<tr>
<td>27.82</td>
<td>15.90</td>
<td>36.46</td>
<td>25.03</td>
<td>0.42</td>
</tr>
<tr>
<td>WSM6</td>
<td>12.48</td>
<td>16.58</td>
<td>0.84</td>
<td>28.61 (102.8)</td>
</tr>
<tr>
<td>GCE</td>
<td>13.46</td>
<td>15.43</td>
<td>0.85</td>
<td>29.04 (104.4)</td>
</tr>
<tr>
<td>THOM</td>
<td>14.30</td>
<td>16.40</td>
<td>0.78</td>
<td>27.10 (97.4)</td>
</tr>
<tr>
<td>WDM6</td>
<td>13.34</td>
<td>16.47</td>
<td>0.89</td>
<td>29.85 (107.3)</td>
</tr>
<tr>
<td>MORR</td>
<td>12.69</td>
<td>14.10</td>
<td>0.84</td>
<td>32.59 (117.1)</td>
</tr>
</tbody>
</table>

| 2A12 | 11.42 | 10.81 | 0.82 | 36.33 (130.6) | −11.92 (42.8) |

Table 3. Statistics corresponding to rainfall retrievals using six different a priori databases for convective region indicated in Fig. 4c. Numbers in parentheses indicate percent value of true mean.

Table 4. As in Table 3, but for stratiform region indicated in Fig. 4c.
FIG. 7. Retrieved rain rates for Typhoon Choiwan from (a),(b) the TRMM products and (c)–(h) the six different a priori databases and their retrieval statistics.
difference is consistent with the results from Shin and Kummerow (2003). It appears that matching the simulated and PR-observed reflectivity profiles seems to constrain the liquid portion of the profiles, but the ice properties remain dependent on the different characteristics of ice habit in the six microphysics schemes. The EOF analysis of the indices was also carried out to check the representativeness of the six databases. It is suggested that each database seems to contain the variability of scattering and emission signals that appeared in observations.

Impacts of the different characteristics of the six databases on rainfall estimations were then investigated by the parametric rainfall retrieval algorithm employing a Bayesian inversion approach. Retrievals for the case of Typhoon Sudal (TRMM orbit number 36.537) from the six databases tend to be different from each other. Compared with the PR observations, overall rainfall distributions including strong convective rainbands are reasonably represented from the WDM6 and WSM6 scheme–based databases. However, the convective rainbands are not well captured or dislocated from the LIN and THOM scheme–based retrievals, which suggests that excessive graupel allocated in the LIN scheme and the large amount of snow in the THOM scheme may not be appropriate, at least for strong convective rainfall systems, from the perspective of microwave rainfall measurements. Furthermore, comparing retrieval results from the WSM6 and WDM6 scheme–based databases, it was determined that the double-moment approach of the prognosed CCN number concentration in warm rain microphysics may help to achieve a more realistic simulation of convective rain and rainfall retrievals. However, it seems that the intensities of precipitation estimates over convective regions tend to be underestimated. Meanwhile, the differences over stratiform regions appear to be smaller than those over convective regions for rainfall estimates from all of the six microphysics schemes. Retrievals for another typhoon, Typhoon Choiwan, show similar results to those obtained in the case of Typhoon Sudal.

Our results demonstrate that differences in a priori databases owing to the uncertainties in assumed microphysics can substantially affect the properties of rainfall estimations. Further understanding and advances in microphysics scheme development, particularly regarding frozen hydrometeors, may be needed for more accurate rainfall measurements from passive microwave sensors. Current experimental frameworks aimed at understanding the impacts of different assumed microphysics on rainfall estimations can be applied to better estimate precipitation by including various types, characteristics, and variability of precipitation in a priori databases.

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REFERENCES


