Intercomparison of different physics schemes in the WRF model over the Asian summer monsoon region

QUE Lin-Jing, QUE Wei-Lun and FENG Jin-Ming

College of Global Change and Earth System Science (GCESS), Beijing Normal University, Beijing, China; Longjiang County Meteorological Bureau, Heilongjiang Meteorological Bureau, Longjiang, China; Key Laboratory of Regional Climate–Environment for Temperate East Asia (RCE-TEA), Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ABSTRACT
Enhancing the ability of the WRF model in simulating a large area covering the West Pacific Ocean, mainland China, and the East Indian Ocean is very important to improve prediction of the East Asian monsoon climate. The objective of this study is to identify a reasonable configuration of physical parameterization schemes to simulate the precipitation and temperature in this large area. The Mellor–Yamada–Janjic (MYJ) and Yonsei University (YSU) PBL schemes, the WSM3 and WSM5 microphysics schemes, and the Betts–Miller–Janjic (BMJ) and Tiedtke cumulus schemes are compared through simulation of the regional climate of summer 2008. All cases exhibit a similar spatial distribution of temperature as observed, and the spatial correlation coefficients are all higher than 0.95. The cases combining MYJ, WSM3/WSM5, and BMJ have the smallest biases of temperature. The choice of PBL scheme has a significant effect on precipitation in such a large area. The cases with MYJ reproduce a better distribution of rain belts, while YSU strongly overestimates the precipitation intensity. The precipitation simulated using WSM3 is similar to that using WSM5. The BMJ cumulus scheme combined with the MYJ PBL scheme has a smaller bias of precipitation. However, the Tiedtke scheme reproduces the precipitation pattern better, especially over the ITCZ.

KEYWORDS
WRF model; precipitation; temperature; PBL scheme; microphysics scheme; cumulus parameterization scheme

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CONTACT
FENG Jin-Ming fengjm@tea.ac.cn

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1. Introduction
The West Pacific Ocean and the East Indian Ocean have considerable effects on the East Asian monsoon climate, as the difference between the distribution of land and ocean generates the seasonal variation of heating to the atmosphere from land and ocean (Zhang and Li 2004). For East Asia in boreal summer, the substantial temperature difference between the large heat source over the East Asian continent and the strong cold source over the Pacific, east and south of the East Asian continent, is the main driving force for the formation of the East Asian summer monsoon. The Asian summer monsoon transports a large amount of water vapor from the tropical oceans to the monsoon area, which is fundamental to the formation of precipitation during the Asian summer monsoon period (Zhang and Li 2004). Therefore, tropical ocean thermal conditions can not only affect the intensity of the summer monsoon, but also the water vapor transport in the monsoon region—by influencing monsoon airflow. Subsequently, precipitation in the monsoon region is affected, leading to droughts and floods and other meteorological disasters (Zhang and Li 2004). During the East Asian summer monsoon, the monsoon circulation of the Indian summer monsoon can not only directly affect the airflow in East Asia, but also the large amount of water vapor transported from the Indian Ocean to the East Asian monsoon region, which is a major source there of summer precipitation. Therefore, it is important to simulate the climate over this large region.
encompassing the West Pacific Ocean and East Indian Ocean.

However, in regional climate simulation, different physical process schemes vary in their performance. Hu, John, and Zhang (2010) examined the simulation ability of the WRF model over Texas in July–September 2005 when configured with three different PBL schemes: the Mellor–Yamada–Janjic (MYJ) scheme, the Yonsei University (YSU) scheme, and version 2 of the Asymmetric Convective Model (ACM2). The results showed that the WRF model underestimated temperature and overestimated moisture transport near the surface. The MYJ PBL scheme resulted in the largest bias because it simulated lower temperature and higher moisture than YSU and ACM2 in the boundary layer during daytime. The YSU PBL scheme simulated higher temperature and lower moisture than MYJ and ACM2 at nighttime.

De Silva et al. (2010) reported that, when using the Betts–Miller–Janjic (BMJ) cumulus parameterization scheme in simulating precipitation over the tropical Kelani River basin in Sri Lanka, the results were not as good as when using the simplified Arakawa scheme; the BMJ scheme supplied insufficient moisture. Meanwhile, Ardie et al. (2012) indicated that the BMJ scheme was capable of simulating the spatial features of three heavy rainfall episodes over the southern peninsula of Malaysia during the winter monsoon of 2006/2007. Wang et al. (2011) reported that a simulation using the Tiedtke cumulus scheme yielded less precipitation for stratiform rainfall compared with TRMM observation.

Huang, Chen, and Zhu (2011) demonstrated the superior performance of the WSM3 microphysics scheme in predicting the moderate and heavy rain of a torrential rainfall event related to the large-scale weather system in Xinjiang region during 25–26 May 2009. The WSM5 scheme also performed very well. Indeed, more recently, Zhu, Lin, and Cao (2014) reported that WSM3 was the best scheme among eight (Lin, Kessler, WSM3, WSM5, and WSM6, Eta, WDM5, WDM6) for simulating the light to heavy rainfall and downpours of a heavy rainfall event that took place in southern China during 6–7 May 2010.

Other studies have also examined the performance of the WRF model configured with different parameterization schemes. Rafael et al. (2008) used the WRF model with a combination of the YSU PBL scheme, WSM6 microphysics scheme, the Noah land-surface model, the Eta GFDL longwave radiation scheme, and the MMS shortwave radiation scheme, to simulate two one-week-long periods in the Iberian Peninsula during winter and summer 2005. Based on a spatial resolution of 3 km, their results showed that the performance of this combination of schemes was better than others that they tested.

Despite these many experiments using different parameterization schemes to evaluate the performance of the WRF model, the simulation domains have generally been quite small. Little attention has been paid to evaluating the model’s performance over larger areas, such as that covering the West Pacific Ocean, mainland China, and the East Indian Ocean. In this context, the objective of the present study is to identify a reasonable configuration of parameterization schemes for simulating the precipitation and temperature in such a large area. The study focuses on the choice of PBL, microphysics and cumulus parameterization scheme through intercomparison of the MYJ and YSU, WSM3 and WSM5, and BMJ and Tiedtke schemes, respectively. Section 2 introduces the WRF model, the data and the design of the experiment in detail. Section 3 presents the results, and conclusions are drawn in Section 4.

### 2. Experiments and data

This study uses version 3.6 of the WRF model to simulate the summer temperature and precipitation in 2008. The domain includes mainland China, the West Pacific Ocean, and the East Indian Ocean. The resolution is 20 km × 20 km and the central position is (22°N, 115°E). The simulation is initiated at 0000 UTC (1800 CST) 1 May 2008. The initial and lateral boundary conditions are from the NCEP GFS FNL Operational Global Analyses data. The first month is used as the spin-up period, after which we only compare June, July, and August 2008. TRMM data at 0.5° × 0.5° resolution are used to compare with the modeled precipitation results. The CRU TS v. 3.21 of high-resolution gridded data of month-by-month variation in climate (January
1901–December 2012) and NCEP-2 data, both at 2.5° × 2.5° resolution, are used to compare with the modeled temperature results.

The Noah land-surface scheme (Chen and Dudhia 2001) and RRTM (Iacono et al. 2008) are used in all simulations. The MYJ (Janjic 2002) and YSU (Hong, Noh, and Dudhia 2006) PBL schemes, the WSM3 (Hong, Dudhia, and Chen 2004) and WSM5 (Hong, Dudhia, and Chen 2004) microphysics schemes, and the BMJ (Janjic 1994, 2000) and Tiedtke (Tiedtke 1989) cumulus parameterization schemes are compared.

MYJ is a PBL scheme of turbulent kinetic energy prediction, which is a local closure scheme, while YSU is a first-order non-local scheme. The YSU PBL scheme has stronger boundary layer top entrainment and boundary layer inner mixing than that of MYJ (Zhang et al. 2012). The WSM5 microphysics scheme allows supercooled water to exist, and a gradual melting of snow falling below the melting...
The different combinations of schemes tested are shown in Table 1, and the following temperature and precipitation figures are the results from eight cases. By comparing these results and analyzing their statistical characteristics, including model bias, correlation, and RMSE, we aim to identify a reasonable set of parameterization schemes for the simulation of this large region by the WRF model.

Figure 2. Bias of mean surface air temperature (°C) of the eight cases. (a) MYJ_WSM3_BM3; (b) MYJ_WSM3_Tiedtke; (c) MYJ_WSM5_BM3; (d) MYJ_WSM5_Tiedtke; (e) YSU_WSM3_BM3; (f) YSU_WSM3_Tiedtke; (g) YSU_WSM5_BM3; (h) YSU_WSM5_Tiedtke.

layer (William et al. 2008), whereas WSM3 does not. The Tiedtke cumulus scheme is a mass flux scheme. It includes three types of convection: penetrative convection, shallow convection, and midlevel convection (Wang et al. 2011). However, the BM3 cumulus scheme is a convective adjustment scheme. It describes the change in total moisture at each layer in the column but does not describe the vertical moisture flux or entrainment within the convective plume (Pérez et al. 2011).
Figure 2 shows the bias of mean surface air temperature of the eight cases. The eight cases all exhibit a considerable cold bias over the west of the Tibetan Plateau and a warm bias over northern China. However, the cases involving the MYJ PBL scheme present a colder than observed bias over southern China.

Figure 3 shows the mean 850-hPa air temperature of the eight cases and the observation. The eight cases and the observation present progressively decreasing temperature at 850 hPa from west to east.

3. Results

This study covers three main regions: the West Pacific Ocean, mainland China and the East Indian Ocean. Figure 1 shows the three-month (June–July–August, JJA) mean surface air temperature of the observation and eight cases. The eight cases almost simulate the same spatial distribution as the observation. The observation and eight cases all present low temperature over the Tibetan Plateau.

Figure 2 shows the bias of mean surface air temperature of the eight cases. The eight cases all exhibit a considerable cold bias over the west of the Tibetan Plateau and a warm bias over northern China. However, the cases involving the MYJ PBL scheme present a colder than observed bias over southern China.

Figure 3 shows the mean 850-hPa air temperature of the eight cases. The eight cases and the observation present progressively decreasing temperature at 850 hPa from west to east.
south to north. However, over ocean, the cases involving the YSU PBL scheme yield better simulation results than those involving the MYJ PBL scheme.

Figure 4 shows the three main sub-regions and the three-month (JJA) mean precipitation of the observation and eight cases. Sub-region 1 is China, sub-region 2 is the East Indian Ocean, and sub-region 3 is the West Pacific Ocean. The TRMM data (Figure 4(b)) shows that there are some main precipitation zones; namely, an equatorial Pacific precipitation zone, a South China mainland precipitation zone, and a Northeast Indian Ocean precipitation zone. It is clear that the precipitation simulated by the WRF model when configured with the YSU PBL scheme (Figure 4(g) and (h)) is strongly overestimated compared to that derived from TRMM. This is because the YSU PBL scheme has stronger vertical mixing processes. The spatial distribution of precipitation simulated by the cases involving the MYJ PBL scheme is closer to the observation. For the
cases with the two different microphysics schemes (WSM3 and WSM5), the results are almost the same. Meanwhile, the cases with the different cumulus schemes (BMJ and Tiedtke) simulate a different spatial distribution of precipitation. The MYJ_WSM3_BMJ (Figure 4(c)) and MYJ_WSM5_BMJ (Figure 4(e)) cases simulate the precipitation zone in the north of the East Indian Ocean and overestimate the precipitation in the West Pacific, and the situation is the reverse for MYJ_WSM3_Tiedtke (Figure 4(d)) and MYJ_WSM5_Tiedtke (Figure 4(f)). This may be attributable to the fact that the Tiedtke scheme underestimates stratiform rainfall, and the proportion of frontal precipitation reaches more than 50% in subtropical regions (Wang et al. 2011). The cases involving the MYJ PBL scheme reproduce the spatial distribution of the main rain belt in the region, but fail to reproduce the ITCZ rain belt.

Table 2 shows the bias, RMSE and spatial correlation coefficients of the temperature between the eight cases and observation. For surface air temperature, the statistics of the eight cases feature similar RMSE, and high correlation coefficients (<0.95). The bias of case MYJ_WSM3_BMJ is the smallest. For 850-hPa air temperature, the eight cases also feature high correlation coefficients (<0.95). The bias of case YSU_WSM5_Tiedtke is the smallest. The cases involving the YSU PBL scheme produce lower RMSE than those involving the MYJ PBL scheme.

Table 3 shows the bias, RMSE, and spatial correlation coefficients of the precipitation between the eight cases and observation. It is clear that, for the whole region, the bias and RMSE of cases involving the YSU PBL scheme are much larger than those involving the MYJ PBL scheme. Among the four cases involving the MYJ PBL scheme, the MYJ_WSM5_BMJ case yields the smallest RMSE and bias (>0.1). Although the correlation coefficient of case MYJ_WSM5_BMJ is not the largest, the four cases involving the MYJ PBL scheme are very close. For the three sub-regions, the cases involving the MYJ PBL scheme feature similar correlation coefficients in sub-region 1 and sub-region 2. For sub region-3, cases MYJ_WSM3_Tiedtke and MYJ_WSM5_Tiedtke feature higher correlation coefficients than the other cases involving the MYJ PBL scheme.

### 4. Conclusion

This study evaluates the ability of the WRF model in simulating temperature and precipitation over a large region when configured with eight different combinations of physical schemes, including the MYJ and YSU PBL schemes, the WSM3 and WSM5 microphysics schemes, and the BMJ and Tiedtke cumulus parameterization schemes. The large region includes the West Pacific Ocean, mainland China, and the East Indian Ocean.

The spatial distributions of surface air temperature simulated by all cases are almost the same. The statistics indicate that they all have high correlation coefficients and similar RMSEs. However, the MYJ_WSM3_BMJ case produces the smallest bias.

### Table 2. Statistical results of the eight cases.

| Notation               | CRU (temperature) | NCEP (temperature) |
|------------------------|-------------------|---------------------|
|                        | Bias (°C) | RMSE  | Correlation coefficient | Bias (°C) | RMSE  | Correlation coefficient |
| MYJ_WSM3_BMJ           | −0.01      | 2.40  | 0.95                  | −0.41      | 1.01  | 0.96                  |
| MYJ_WSM3_Tiedtke       | 0.45       | 2.32  | 0.95                  | −0.51      | 1.27  | 0.95                  |
| MYJ_WSM5_BMJ           | 0.11       | 2.48  | 0.95                  | −0.29      | 1.02  | 0.96                  |
| MYJ_WSM5_Tiedtke       | 0.18       | 2.56  | 0.95                  | −0.50      | 1.22  | 0.95                  |
| YSU_WSM3_BMJ           | 0.13       | 2.43  | 0.95                  | 0.07       | 0.85  | 0.97                  |
| YSU_WSM3_Tiedtke       | 0.71       | 2.46  | 0.95                  | 0.06       | 1.01  | 0.96                  |
| YSU_WSM5_BMJ           | 0.20       | 2.40  | 0.95                  | 0.10       | 0.86  | 0.97                  |
| YSU_WSM5_Tiedtke       | 0.24       | 2.36  | 0.96                  | −0.02      | 0.85  | 0.97                  |

### Table 3. Statistical results of the eight cases.

| Notation               | TRMM (precipitation) |
|------------------------|----------------------|
|                        | Bias (mm d⁻¹) | RMSE  | Correlation coefficient | Sub-region 1 (China) correlation coefficient | Sub-region 2 (East Indian Ocean) correlation coefficient | Sub-region 3 (West Pacific Ocean) correlation coefficient |
| MYJ_WSM3_BMJ           | −0.24      | 4.37  | 0.52                  | 0.66                  | 0.36                  | 0.22                  |
| MYJ_WSM3_Tiedtke       | −1.26      | 4.26  | 0.38                  | 0.73                  | 0.35                  | 0.51                  |
| MYJ_WSM5_BMJ           | −0.09      | 4.25  | 0.55                  | 0.65                  | 0.39                  | 0.29                  |
| MYJ_WSM5_Tiedtke       | −0.99      | 4.43  | 0.55                  | 0.63                  | 0.24                  | 0.48                  |
| YSU_WSM3_BMJ           | 3.04       | 6.38  | 0.66                  | 0.61                  | 0.45                  | 0.59                  |
| YSU_WSM3_Tiedtke       | 1.77       | 6.77  | 0.57                  | 0.74                  | 0.22                  | 0.55                  |
| YSU_WSM5_BMJ           | 3.28       | 6.58  | 0.68                  | 0.66                  | 0.52                  | 0.63                  |
| YSU_WSM5_Tiedtke       | 2.45       | 7.47  | 0.56                  | 0.71                  | 0.21                  | 0.56                  |
The cases involving the YSU PBL scheme are better at simulating the 850-hPa air temperature pattern. The YSU_WSM5_Tiedtke case produces the smallest bias. The choice of PBL and cumulus scheme has a significant effect on the precipitation simulation ability. The simulations involving the YSU PBL scheme simulate much more precipitation than observed. Meanwhile, the simulation abilities of the WRF model when configured with the two types of microphysics scheme (WSM3 and WSM5) are very close. The statistics indicate that the two cases of MYJ_WSM3_Tiedtke and MYJ_WSM5_Tiedtke produce higher correlation coefficients than other cases involving the MYJ PBL scheme.

In conclusion, from the statistical results, the surface and 850-hPa air temperature of the eight cases all feature considerably low biases, similar RMSEs, and high correlation coefficients. The cases of MYJ_WSM3_Tiedtke and MYJ_WSM5_Tiedtke are better than others in simulating the precipitation over this large area covering the East Indian Ocean, mainland China, and the West Pacific Ocean.

It is important to note that this work simulates the temperature and precipitation in summer 2008 only. It is necessary to simulate more years and more variables to further evaluate the performance of the WRF model with these parameterization schemes.

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Notes on contributors
Que Lin-Jing is a student of master’s degree at College of Global Change and Earth System Science (GCCESS), Beijing Normal University. Her main research interest is climate simulation. Her recent publication is in Atmospheric and Oceanic Science Letters.

Que Wei-Lun works at Longjiang County Meteorological Bureau, Heilongjiang Meteorological Bureau. His main research interests are climate simulation and data analysis. His recent publication is in Atmospheric and Oceanic Science Letters.

Feng Jin-Ming is a professor at Key Laboratory of Regional Climate-Environment for East Asia (RCE-TEA), Chinese Academy of Sciences. His main research interests are climate simulation, the development of climate models, the regional impacts of urbanization and anthropogenic heat release on climate across China, meteorological statistical methods, data computation and analysis, image processing, and some programming languages. More than 60 scientific articles are published in journals of SCI and CSCD.

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