Evaluation of a multi-scale WRF-CAM5 simulation during the 2010 East Asian Summer Monsoon

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HIGHLIGHTS

- WRF-CAM5 adequately predicts meteorology and chemistry down to 4 km resolution.
- Overall good model performance for rain, but issues with convective vs. grid-scale rain.
- Model performance for rain improves with increasing horizontal resolution to 4 km.
- Widespread underpredictions in surface and column aerosol concentrations.
- WRF-CAM5 is limited for regional-scale applications of aerosol-cloud interactions.

ABSTRACT

The Weather Research and Forecasting model with Chemistry (WRF-Chem) with the physics package of the Community Atmosphere Model Version 5 (CAM5) has been applied at multiple scales over Eastern China (EC) and the Yangtze River Delta (YRD) to evaluate how increased horizontal resolution with physics designed for a coarser resolution climate model impacts aerosols and clouds, and the resulting precipitation characteristics and performance during the 2010 East Asian Summer Monsoon (EASM). Despite large underpredictions in surface aerosol concentrations and aerosol optical depth, there is good spatial agreement with surface observations of chemical predictions, and increasing spatial resolution tends to improve performance. Model bias and normalized root mean square values for precipitation predictions are relatively small, but there are significant differences when comparing modeled and observed probability density functions for precipitation in EC and YRD. Increasing model horizontal resolution tends to reduce model bias and error for precipitation predictions. The surface and column aerosol loading is maximized between about 32°N and 42°N in early to mid-May during the 2010 EASM, and then shifts north while decreasing in magnitude during July and August. Changing model resolution moderately changes the spatiotemporal relationships between aerosols, cloud properties, and precipitation during the EASM, thus demonstrating the importance of model grid resolution in simulating EASM circulation and rainfall patterns over EC and the YRD. Results from this work demonstrate the capability and limitations in the aerosol, cloud, and precipitation representation of WRF-CAM5 for regional-scale applications down to relatively fine horizontal resolutions. Further WRF-CAM5 model development and application in this area is needed.

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radiative (direct) and microphysical (indirect) effects of aerosols (Huang et al., 2007; Wu et al., 2013; Lim et al., 2014). The EASM is a sub-system of the larger Asian summer monsoon that brings warm moist air from the Indian and Pacific Oceans over East Asia, resulting in a seasonal and northward progression of heavy precipitation that affects about one third of the world’s population (Yihui and Chan, 2005). The EASM precipitation exerts a strong influence on the societal and economic activity of eastern China (EC), in particular over the rapidly developing city of Shanghai. The EASM precipitation exhibits significant variability on intraseasonal, interannual, and multidecadal time scales. For example, a westward shift in the West Pacific Subtropical High and an intense La Niña phase in the Pacific Ocean led to a warmer sea surface in the western Pacific, positive precipitation anomalies, and devastating floods in China during the 2010 EASM (Mujumdar et al., 2012). With the exception of intense dust storms, the composition and radiative effects of aerosols over the developing regions of EC and the Yangtze River Delta (YRD) are dominated by sources of anthropogenic origin, and are mainly composed of sulfate (SO$_4^{2-}$) and organic compounds (Xu et al., 2002). Rapid economic development in China has led to further increases in both primary and secondary anthropogenic aerosol emissions (Ohara et al., 2007; Lei et al., 2011), and consequently observations show high aerosol number concentrations over EC and the YRD city-cluster (Cheng et al., 2013; Ding et al., 2013). Ding et al. (2013) showed that over a 1-year period, about 40% of the 24-hr average fine particulate matter (PM$_{2.5}$) concentrations measured at the Xianlin site in YRD exceeded the National Ambient Air Quality Standards in China (75 µg m$^{-3}$). The YRD city-cluster includes China’s largest city of Shanghai, as well as other developing economic centers such as Nanjing, Suzhou, Hangzhou, and Ningbo.

With periods of such high aerosol loading over Asia, aerosol effects (direct + indirect) may have a significant influence on the Asian monsoon circulation and precipitation. Lau and Kim (2006) showed that the direct radiative forcing of absorbing aerosols can produce an elevated heat pump effect, which altered the monsoon strength in South Asia. A combination of remote sensing and radiative transfer modeling confirmed that aerosols can effectively reduce shortwave radiation during the Asian pre-monsoon season by about 20–30 W m$^{-2}$ on a seasonal average, although this shortwave reduction was shown to have a minimal impact on the large-scale monsoonal flow patterns (Kuhlmann and Quaas, 2010). Long-term data analysis combined with cloud-resolving modeling showed that the high aerosol concentrations in EC leads to a spatially coherent increase in cloud droplet number concentrations (CDNCs), which reduces the light rain in EC over the past 50 years (Qian et al., 2009).

There is continued interest in studying the connections between aerosols and the EASM using coupled meteorological-chemical simulations. Table 1 shows a list of coupled models’ system, period, type (online vs. offline), domain(s), vertical and horizontal resolutions, major chemistry and aerosol treatments, cloud microphysics, cumulus parameterizations, aerosol activation treatment (i.e., aerosol-cloud interactions), and what (if any) aerosol direct, semidirect, indirect, or total (direct + indirect) effects were investigated for previous studies of aerosol and East Asian climate interactions compared to our work (last column).

From studies listed in Table 1, there is evidence that aerosols impact the EASM’s precipitation intensity and distribution over China through both direct and indirect effects, but results from studies using different modeling systems (e.g., online vs. offline chemistry, prognostic vs. prescribed aerosols), model representations of physical processes, and domain configuration/spatial resolution notably vary. Online-coupled general circulation models over larger global domains at 2.8° × 2.8° horizontal resolution show that aerosol scattering and absorption impacts the atmospheric circulation and weakens the EASM during both winter and summer (Liu et al., 2009). Early regional modeling studies at 60 × 60 km showed that the aerosol microphysical effect dominated the direct radiative effect in decreasing precipitation in East Asia (Giorgi et al., 2003; Huang et al., 2007), while Zhang et al. (2012) later showed that the direct radiative forcing has an impact on surface cooling and weakening of the land/sea temperature contrast, which leads to less (more) precipitation in southern (northern) EC. Other offline-coupled chemical transport simulations demonstrated that the interactions between aerosols and the EASM are not only one-way, but rather that a decadal-scale weakening of the EASM circulation may in turn enhance aerosol concentrations through changes in convergence patterns (Zhu et al., 2012). Application of online-coupled regional climate models at a resolution of 36 × 36 km showed that during the first phase of EASM (early May – mid June), the aerosol radiative effect promotes an anticyclonic circulation in northern EC that serves to decrease precipitation in southern EC, while aerosol microphysical effects during the second EASM phase (mid-June – August) may shift the precipitation band farther north in EC (Wu et al., 2013). Implementation of a cumulus parameterization that incorporates a two-moment cloud microphysics parameterization in a coupled regional climate simulation indicates that aerosols reduce the simulated surface precipitation during the EASM by about 10% (Lim et al., 2014). This precipitation reduction was less significant when microphysical processes are excluded from the cumulus parameterization, suggesting the importance of aerosol impacts on microphysical processes of convective clouds. Use of finer spatial resolutions along with more accurate representations of the aerosol-cloud microphysical processes and their feedbacks, can provide a more accurate representation of the aerosol impacts on precipitation (e.g., Li et al., 2011). Recent regional climate simulations of the EASM, however, have only been applied to a single domain, usually at a relatively coarse 36 × 36 km horizontal resolution, while other studies do not show improvement in model performance with increased model resolution over the highly polluted regions of China (e.g., Tan et al., 2015). Hence, there is a need to perform additional investigations in the EC region using nested simulations at multiple resolutions, while evaluating the scalability of coupled models in their prediction of chemistry, aerosol, and precipitation characteristics and relationships.

The present paper uses a multiple nested (36, 12, and 4 km) and online-coupled regional climate model, and evaluates the meteorological, chemical and aerosol, cloud, and precipitation model performance during the anomalous 2010 EASM conditions over EC and the YRD region. Our main objectives are to 1) evaluate the model’s performance in reproducing meteorological and chemical variables and their characteristics, 2) investigate the impacts of increased spatial resolution on the model performance that uses physics designed for a coarser resolution climate model, and 3) provide insight into the model prediction of spatiotemporal relationships between aerosol, clouds, and precipitation predictions at multiple scales during the 2010 EASM. The following sections provide the full details of our nested model, setup, and simulation design (Section 2), evaluation, observations, and model analysis methods (Section 3), results of the analysis (Section 4), and conclusions (Section 5).

2. Model setup and simulation design

2.1. Model configuration and inputs

As shown in the last column of Table 1, our work uses a variant of the Weather Research and Forecasting Model with Chemistry
**Table 1**

Summary of model configurations used in previous studies on aerosols and the East Asian climate, as compared to our work (last column). The references for short-names and acronyms in the table are provided in the footnote.

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<td>KQ7</td>
<td>MATCH4-Pathfinder II9</td>
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<td>45 layers</td>
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<td>WRF-Chem 3.5/3.5.1$^a$</td>
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<td>East Asia, East Asia, and YRD (two-way)</td>
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<td>30 layers</td>
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<td>WRF-Chem 3.4.1/CAM 5.1$^c$</td>
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<td>East Asia, East Asia, and YRD (two-way)</td>
<td>36, 12, and 4 km</td>
<td>30, 10, and 3.3 km</td>
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(WRF-Chem) version 3.4.1 (Grell et al., 2005), which includes the Community Atmosphere Model (CAM) version 5.1 physical parameterizations (Neale et al., 2010) that were implemented by Ma et al. (2013), hereafter referred to as WRF-CAM5. The CAM5 physical package in this work includes an updated two-moment deep convection scheme (Zhang and McFarlane, 1995; Song and Zhang, 2011; Lim et al., 2014), the University of Washington shallow convection scheme (Park and Bretherton, 2009), a two-moment microphysics scheme (Morrison and Gettelman, 2008), a simple macrophysics scheme from CAM5 (Neale et al., 2010), and the three-mode (Aitken, Accumulation, and Coarse) modal aerosol module (MAM3) (Liu et al., 2012) coupled to the gas phase chemistry of Carbon Bond Mechanism version Z (CBMZ) (Zaveri and Peters, 1999).

Previous studies have used both offline and online-coupled modeling systems to probe the aerosol effects on climate and precipitation (Table 1); however, our work uses an online-coupled and two-way triple-nested modeling approach at high resolution that includes the Zhang and McFarlane (ZM) convective parameterization with a two-moment microphysics scheme for sub-grid cumulus clouds (Song and Zhang, 2011), as well as a two-moment scheme for grid-scale stratiform clouds (Morrison and Gettelman, 2008). As detailed in Lim et al. (2014), implementation of the new ZM scheme with two-moment cloud microphysics allows for the interactions of aerosols with microphysical processes in both resolved stratiform and parameterized cumulus clouds. Different from Lim et al. (2014), the WRF-CAM5 configuration in this work uses a more detailed aerosol activation parameterization, which is based on Fountoukis and Nenes (2005) (FN05), and includes updates from Barahona and Nenes (2007), Kumar et al. (2009), and Barahona et al. (2010). Compared to another widely used parameterization based on Abdul-Razzak and Ghan (2000) (AR-G00) that was used in Lim et al. (2014), FN05 shows better agreement of activated aerosol with a high-confidence numerical solution (Ghan et al., 2011), and with observations of shortwave radiation, cloud droplet number concentration, and precipitation (Bennartz, 2007; Zhang, 2013). Recent WRF-Chem simulations over the U.S., however, suggested that using the FN05 scheme may result in lower normalized mean bias but larger normalized mean error relative to AR-G00 for simulated CDNC against MODIS (Yahya et al., 2017).

The meteorological initial and boundary conditions (ICONS/BCONs) come from the National Centers for Environmental Prediction’s Final Global Data Assimilation System (NCEP-FNL) for 2010, and the chemical ICONs/BCONs are based on chemical profiles calculated from the linked Harvard/National Aeronautics and Space Administration (NASA) Goddard Earth Observing System-Chemistry (GEOS-Chem) and U.S. EPA Community Multi-Scale Air Quality (CMAQ) model simulations from 2005 (GEOS-Chem/ CMAQ). Anthropogenic emissions are based on the 2006 emission inventory for Asia in support of the Intercontinental Chemical Transport Experiment-Phase B (INTEX-B) funded by NASA (Zhang et al., 2009), and the 2010 Multi-resolution Emission Inventory for China (MEIC; http://www.meicmodel.org/). Biogenic emissions are based on MEGAN version 2 (MEGAN2; Guenther et al., 2006), dust emissions on Zender et al. (2003), and sea salt emissions on Gorg et al. (2002).

2.2. Simulation design

As shown in Fig. 1, the outermost domain is centered over the continent of Asia (d01: 36 × 36 km), and the two-way nested domains are over EC (d02: 12 × 12 km) and YRD (d03: 4 × 4 km). Domain d01 is comparable to many previous studies of the EASM at a grid resolution of 36 km (Table 1), and may be considered large enough to adequately cover the major parts of EC that are significantly impacted by the EASM’s circulation and precipitation patterns. Simulations of aerosol impacts on clouds and precipitation are sensitive to both model resolution and choice of cumulus parameterization, and studies at cloud-resolving scales have shown that the microphysical effects are a fundamental reason for observed changes in macrophysical properties (e.g., the increases of cloud
cover, cloud top height, and cloud thickness) for deep convective clouds (Fan et al., 2013). In this work we use the triple-nested model domains in Fig. 1, d01, d02, and d03 to evaluate the aerosols and EASM characteristics over YRD.

While the ZM cumulus parameterization was not originally designed to run at 4 km, we chose to implement the ZM scheme for all domains, including the d03 domain at 4 km resolution, as it is well known that there is a range in cloud permitting horizontal scales, or a “gray zone”, where cloud microphysics schemes have limitations in representing moist convection as the model grid spacing decreases from about 12 to 4 km (Hong and Dudhia, 2012). This gray zone is also dependent on the individual cumulus parameterization chosen, and recent efforts have been applied to develop new cumulus parameterizations that can be applied across such scales (e.g., Zheng et al., 2016). Our application of the ZM cumulus parameterization at 4 km may also be of interest to the community, as to our knowledge there has been no previous studies that apply the ZM scheme at the high resolution end (<4 km) of the gray zone. To check if the results at 4 km would be different when performing simulations with the ZM scheme and without by resolving convection, we performed a three-day test using the triple-nested configuration over d01, d02, and d03, which is the same configuration and design in this work, but with a test of turning off the ZM scheme (i.e., resolved convection) only for d03. We found that the differences in the daily total precipitation between the runs with ZM on and off are very small, thus indicating that using the ZM parameterization at 4 km is acceptable in this case. The results in Section 4 will provide insight into the model performance when applying ZM at increasingly higher resolutions.

The model time steps for dynamics and physics are 90, 30, and 10 s for d01, d02, and d03 respectively, and the chemistry time step was set at 300 s. The simulation time period analyzed is from May–August of 2010 (with one-month spin-up in April), which includes the onset of the EASM in the central Indochina Peninsula (April–May), through the EASM’s peak advance into Northern China (July–August) (Ding, 2004).

3. Observations, evaluation protocol, and model analysis methods

3.1. Observations and model evaluation protocol

The observational data used to evaluate the model performance includes 2-m temperature (T2), 2-m water vapor mixing ratio (Q2), 10-m wind speed (WS10), and precipitation (PREcip) from the National Climatic Data Center (NCDC; http://www.ncdc.noaa.gov). Also, a more spatially extensive comparison of model precipitation to the Tropical Rainfall Measuring Mission (TRMM) Multi-satellite Precipitation Analysis (TPMA; Huffman et al., 2007) is performed. For near-surface gas and aerosol model evaluations, a comparison against numerous air quality measurement networks include the following: 1) China’s Air Pollution Index (CH-API; http://datacenter.mep.gov.cn), 2) Hong Kong (HK; http://epic.epd.gov.hk/EPICDI/air/station/?lang=en), 3) Taiwan (TW; http://taqm.epa.gov.tw), 4) Japan (JP; http://www.mies.go.jp/), 5) South Korea (SK; http://www.airkorea.or.kr), 6) 500 nm aerosol optical depth (AOD) measurements from NASA’s Aerosol Robotic Network (AERONET; http://aeronet.gsfc.nasa.gov/), and 7) 550 nm AOD measurements from the Moderate Resolution Imaging Spectroradiometer (MODIS; Remer et al., 2005). Additional near-surface data has been retrieved from the Taihu Observatory and Xianghe sites in China, which are part of the East Asian Study of Tropospheric Aerosols: and International Regional Experiment (EAST-AIRE) data set (http://www.metoc.md.edu/~zli/EAST-AIRE/station.htm). A detailed summary describing the data frequency, uncertainty, number of sites, and their detailed sources may be found in Table A1 in Wang et al. (2017). Supplementary Section 1 provides a description of additional satellite data that are used to provide qualitative comparisons of the modeled spatial distributions for different aerosol, cloud, and precipitation characteristics.

The evaluation protocol includes statistical measures including the Mean Bias (MB), Normalized MB (NMB), Normalized Mean Error (NME), Root Mean Square Error (RMSE), Normalized RMSE (NRMSE), and Pearson’s Correlation Coefficient (R). Statistical summary tables of meteorology, chemistry, cloud, and precipitation variables are included in the supplementary material. Spatial comparisons and absolute/relative difference plots are also included. The WRF-CAM5 model performance may be compared against numerous criteria that are regularly cited in the literature (e.g., Seigneur et al., 2000; U.S. EPA, 2001, 2005; Zhang et al., 2006a, 2006b; Emery et al., 2016).

3.2. Model analysis methods

The model analyses are performed over slightly modified EASM stages that are based on climatological dates of the EASM evolution across East Asia (Ding, 2004). Specifically, we compare the following: 1) The EASM Onset Stages (EOS; May–June) in continental Asia, which are characterized by the earliest onset in continental Asia that is often observed in central Indochina Peninsula in late April and early May, with areal extension and advancement eastward to the South China Sea in mid to late May, and then first arrival of the EASM into the YRD region in early June. 2) The EASM Advance Stages (EAS; June–August) in continental Asia, which are characterized by further areal advance of the EASM across the YRD region in late June, and then followed by the EASM advancing farther northward to areas of Northern China in July through August. The EOS and EAS are compared to investigate the spatial and temporal patterns of meteorological, chemical, clouds, radiation, and precipitation variables across EC and the YRD.

4. Results

4.1. Chemistry and aerosol evaluation

Fig. 2 shows a bar chart comparison of the percent NMB for simulated AOD, PM10, PM2.5, carbon monoxide (CO), nitrogen oxides (NOx = NO + NO2), ozone (O3), and sulfur dioxide (SO2) against surface networks across all three domains and their domain inter-comparisons. The different observational networks were described in Section 3.1. Additional spatial MB plots against PM10 China API sites (PM10-CH-API) over d01, d02, and d03 are included in Supplementary Fig. S9.

Overall, there are predominant 1) underpredictions for AOD, surface PM10, and surface PM2.5, 2) underpredictions for surface CO, NOx, and SO2 concentrations, and 3) overpredictions for surface O3 concentration. The underpredictions in AOD/PM variables are consistent with the spatial comparisons in Fig. S4a – S4f, and are likely impacted by uncertainties in primary PM emissions and secondary precursor gases, a simplified MAM3 aerosol module that does not treat PM nitrate formation, and other model treatments of processes such as wet deposition that impact aerosol concentrations. The WRF-CAM5 underpredictions in AERONET AOD, as well as qualitatively compared to MODIS observations in Figs. S4a – S4f over China, are similar to previous studies (e.g., Chen et al., 2015). The underpredictions in PM10 are more prominent in the northern parts of EC, while there are some overpredictions that occur in southern EC, especially near the southeast coast (Figs. S9a and S9b).
There is evidence that the surface PM underpredictions have a strong impact on the column AOD underpredictions. The NMBs against MODIS and AERONET AOD are within 10% of one another (Table S1), and the NMB magnitude increases as spatial resolution is increased. There are however decreases in NMB when increasing model resolution from 36 (d01-in-d02 and d01-in-d03) to 12 km (d02 and d02-in-d03) for surface PM10 and PM2.5 at the China-API (PM10-CH-API and PM2.5-CH-API) and Taiwan (PM2.5-TW) sites. The disparity in sensitivity of model performance to increasing model resolution for the column and surface PM indicates that increasing resolution can lead to an improvement in the representation of local emissions and vertical distribution impacts on surface PM concentrations, while at the same time degrading the model performance of column PM due to impacts from other dynamic and meteorological processes (e.g., precipitation and wet deposition) that are also changed by increasing model resolution.

For the gas concentrations of CO and NOx there are consistent underpredictions; however, there are approximate overpredictions against domain-wide average column observations of CO and NOx at all resolutions. There are both under and overpredictions for surface SO2 depending on the specific observational network. Fig. S10 shows approximate spatial comparisons of observed and simulated column CO, NOx, and SO2 over d01, d02, and d03. Overall there is a good agreement in the spatial distribution of column CO, NO2, and SO2, and the statistics are generally better for the column abundances compared to the near-surface observations, with notably higher R correlation coefficients (Table S1).

**4.2. Precipitation evaluation**

Fig. 4 shows the May–August 2010 cumulative probability distribution functions (CDF) of model convective, grid-resolved, and total rain compared against the TMPA observed total rain for all rain periods (>0 mm day⁻¹), heavy rain periods (>25 mm day⁻¹), and
light rain periods (<10 mm day$^{-1}$).

There is relatively low average NMB for rain across EC (d02) and YRD (d03) for different model resolutions (Supplementary Figs. S1–S2 and Table S1); however, the CDF comparisons show some notable differences. When considering all rain periods in EC and YRD, the model grid-resolved and total rain have a similar CDF, and they are both quite different compared to the observed total rain CDF, which is more similar to the model convective rain CDF (Fig. 4a and b). This suggests that the predominant contribution to the model total rain distribution is from the grid-resolved rain, but that their distributions do not as accurately represent the observed total rain distribution, which is more closely resembled by the convective rain distribution across EC and YRD. There is a similar result when considering only the heavy rain periods (Fig. 4c and d), where the observed total rain distribution falls in the middle of the model grid-resolved, convective, and total rain in EC, but the model convective CDF is very similar to the observed total rain CDF in YRD. For the light rain periods only (Fig. 4e and f), the model convective CDF is very close to the observed total rain CDF, especially over EC where they are nearly identical. The model total and grid-resolved rain CDFs are progressively farther from the observed rain distribution, again demonstrating the limitation of the WRF-CAM5 model physics to accurately depict the partitioning between grid-resolved and convective rain that each contribute to the total rain during light rain periods, while also suggesting the importance of the convective-type rain distributions during these periods and for these scales. A direct comparison of the model and observed total rain CDFs during all periods in Fig. 4, shows that the predicted distribution is too steep, especially at the lower rain rates, which further suggests an overall larger frequency of underpredicted rain compared to the observations across the EC and YRD domains.

4.3. Aerosol, cloud, and precipitation comparisons

Fig. 5 shows a time series-meridional structure (i.e., zonal average) analysis of model column AOD, CCN, CDNC, COT, and surface PRECIP compared to observed TMPA precipitation for the d01-in-d02, d02, d02-in-d03, and d03 domains. Supplementary Fig. S11 also provides a similar analysis for near-surface dust, PM$_{10}$, PM$_{2.5}$, SO$_{4}^{2-}$, BC, OA, and SOA concentrations. For d01-in-d02 and d02 over EC, the AOD is the highest at the beginning of the EOS in early to mid-May, it decreases to lower values by the start of the EAS in early July, and higher values resume towards the end of the EAS (Fig. 5a and b). The spatiotemporal
Fig. 4. Cumulative probability distribution function (CDF) plots of model convective (red), model grid-scale (green), model total (solid black), and TMPA observed total (dashed black) daily rain (mm day$^{-1}$) in EC (d02; left) and YRD (d03; right) for a) – b) all rain periods, c) – d) heavy rain periods only, and e) – f) light rain periods only. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
pattern of the enhanced AOD band qualitatively agrees with enhanced bands of surface dust, PM\(_{10}\), and PM\(_{2.5}\), indicating a strong impact of surface PM on the column abundance in d01-in-d02 and d02 (Figs. S11a, S11b, S11e, S11f, S11i, and S11j). The clear northward shift in the enhanced aerosol band from the EOS to EAS is largely influenced by the northward shift of the enhanced SO\(_4^{2-}\) concentrations (Fig. S11m and S11n), and the AOD and PM concentrations are less in the EAS compared to the EOS. In EC, cloud and precipitation (Fig. 5q and r) are generally influenced by the northward propagation of the Meiyu front during the summer monsoon season. Since wet deposition is an important mechanism for aerosol removal, the spatiotemporal distributions of AOD and
PRECIP are also distinctly complementary. Generally, AOD in d02 is displaced further north compared to d01-in-d02, consistent with the more northward rain band in d02 compared to d01-in-d02.

The AODs in d02-in-d03 and d03 over the YRD region are largely comparable; both showing higher values during the early EOS across all latitudes, and then decreases through the EAS (Fig. 5c and d). Over YRD, dust concentrations are very low during both EOS and EAS (Figs. S8c and S8d), but the spatial patterns of surface PM10 and PM2.5 are comparable to that of the column AOD, which suggests that anthropogenic PM sources dominate over the natural sources in the YRD during EASM. In fact, SO4\(^2-\) and OA have relatively larger fractional contributions to the PM2.5 load over EC in d02, while SO4\(^2-\), OA, and SOA have high contributions to PM2.5 over YRD in d03 (Figures not shown).

Although high CCN values also display a general northward shift over time, the peak CCN values are farther south compared to the peak AOD values in d01-in-d02 and d02 (Fig. 5e-f). This suggests that the model may not account for the larger size dust particles (Fig. S11a-S11b) because the aerosol size distribution and hygroscopicity assumptions in the model may limit the maximum size of the dust particles to act as giant CCN at 0.5% supersaturation. The smaller SO4\(^2-\) particles (Fig. S11m-S11n) have better spatiotemporal agreement with the CCN patterns over EC in d02. This is partly related to the lower moisture in the north during the EOS. Over YRD in d03, there is good agreement between the enhanced column CCN and AOD during the EOS, along with similar patterns in surface PM2.5, SO4\(^2-\), BC, OA, and SOA (Fig. S11).

In regards to the spatiotemporal patterns of cloud variables, the CDNC is the highest during the EOS, with relatively large values extending across all latitudes over EC in d01-in-d02 and d02 (Fig. 5i and j). The CDNC decreases and moves northward during EAS, with the most elevated CDNC values north of about 33°N. This spatiotemporal pattern of enhanced CDNC qualitatively agrees well with the AOD, while CDNC shows less agreement with CCN at 0.5% supersaturation, as this CCN supersaturation estimation is likely smaller than many of the in-cloud supersaturation points. Similar relationships of AOD, CCN, and CDNC exist over YRD in d02-in-d03 and d03 (Fig. 5k and l), and the CDNC decreases during the EOS to EAS transition likely due to less clouds forming. The COT over EC is also most enhanced during EOS, and then decreases and shifts slightly north during EAS, where the most enhanced COT values are mainly found south of 33°N (Fig. 5m and n), which coincides with the higher water vapor concentrations and higher PRECIP (Figs. S2c and S2g). Similar spatiotemporal distributions of CDNC, COT, and PRECIP as well as their relationships are also found in YRD. The PRECIP in d02 has a better agreement with the observed TMPA PRECIP (Fig. 5u) than d01-in-d02. Similarly, the simulated precipitation over d03 is in better agreement with the TMPA observed precipitation (Fig. 5v) than d02-in-d03. These comparisons further establish that WRF-CAM5 can exhibit improved skill in simulating precipitation with increasing model resolution in EC and YRD, and the basic applicability of using the ZM cumulus parameterization down to at least 4 km horizontal resolution.

To further investigate the interconnections between the simulated aerosol, cloud, convection, and precipitation predictions during the 2010 EASM, we identify 5-day periods when the model largely overpredicts an observed light precipitation period (O-LPP), and also largely underpredicts an observed heavy precipitation period (U_HPP) across the YRD domain d03. Fig. 6 shows an average d03 time series of NCDC and TMPA observed precipitation compared against the modeled precipitation (Fig. 6a), and the contributions of modeled convective and grid-resolved precipitation to the total (Fig. 6b).

Overall the model qualitatively does a good job in the timing of the NCDC and TMPA daily precipitation patterns; however, in many instances the simulated magnitude is either underpredicted or overpredicted (Fig. 6a). On May 20–24 during EOS, the model largely overpredicts the precipitation observed by both NCDC and TMPA (i.e., O_LPP), and just after the start of EAS on July 09–13, the model largely underpredicts a relatively heavy precipitation period that was observed (i.e., U_HPP). In both of these cases, the modeled O_LPP and U_HPP total precipitation is dominated by grid-scale precipitation predictions; however, there is a larger contribution from the convective precipitation for the U_HPP compared to the O_LPP (Fig. 6b).

Fig. 7 shows spatial comparisons of observed TMPA and modeled total precipitation averaged over the O-LPP and U-HPP periods in YRD, as well as each period’s near-surface aerosol number concentration, total PM10 mass concentration, and CCN number at a supersaturation of 0.5%.
Fig. 7. Average 5-day O_LPP and U_HPP spatial plots of a) – b) observed TMPA precipitation and c) – d) simulated precipitation, e) – f) simulated total aerosol number, g) – h) simulated mass concentration of PM$_{10}$, and i) – j) simulated CCN number for domain d03.
The O_LPP and U_HPP are both maximized north of about 32’N (Fig. 7a–d), where the O_LPP has relatively lower total aerosol number concentrations (Fig. 7e–f), but larger total PM$_{10}$ mass concentrations (Fig. 7g–h) compared to the U_HPP. There is limited observational aerosol and cloud data over YRD for comparison during these periods; however, these results suggest that the U_HPP has a larger number of aerosol available for CCN compared to O_LPP (Fig. 7i–j), which in conjunction with a similar water vapor available for condensation may lead to a larger abundance of small CDNC that generate less precipitation for U_HPP compared to O_LPP. Such a large underestimation of the heavy precipitation, however, may also be because the model did not accurately simulate the overall convective system, which is largely controlled by the convective available potential energy (CAPE). While it was only analyzed for the average May–August 2010 period, Fig. S7 shows large areas of underpredicted T2 over YRD, which would corroborate an underprediction in the overall convective system during U_HPP. Thus the aerosol impacts on convective intensity shown here can only be assumed to be a secondary effect to an underprediction in CAPE. Nonetheless, there is some evidence that the WRF-CAM5 aerosol predictability impacts the predictability of light and heavy precipitation events over YRD during the 2010 EASM. These results help place into context previous investigations that used WRF-CAM5 and MAM3 aerosol simulations for similar regions and time periods, and suggests the need for continuous implementation of more developed aerosol and cloud model components/interactions for application to regional scale studies.

5. Summary and conclusions

An online-coupled WRF-CAM5 simulation for the months of May–August 2010 was implemented to evaluate its meteorological and chemical performance, assess the model predictions of spatial and temporal aerosol characteristics, and ultimately how such model physics designed for a coarser resolution climate model (i.e., CAM5) impacts precipitation performance during the East Asian Summer Monsoon (EASM) at the continental (d01 = 36 km; over Asia), regional (d02 = 12 km; over Eastern China; EC), and near-cloud resolving scales (d03 = 4 km; over Yangtze River Delta; YRD). The WRF-CAM5 model performs well for meteorological variables T2, Q2, and W510 against NCDC with NMBs within ±5% and NRMSE values < 0.5 across all domains. The model does not perform well for many cloud and radiation variables, and there are apparent underpredictions for cloud condensation nuclei (CCN), cloud optical thickness (COT), and liquid (LWP) and ice water path (IWP) determined by qualitative comparisons against satellite estimations. The model performs better for precipitation, and thus suggests that cloud and radiation predictions and evaluation methods need to be improved here, especially for cloud microphysical and macrophysical variables that are very important to the development of rain. Cumulative probability distribution functions of precipitation show that there is a larger frequency of underpredicted total rain compared to the observations across the EC and YRD domains, while suggesting the importance of the contribution of a convective rain distribution to the total rain, and a model deficiency in accurately predicting convective rain in this WRF-CAM5 configuration. The model performance also demonstrates a dependence on model grid resolution in some cases.

The AOD is most enhanced over northwestern and northern China, as well as over the YRD region. Although there is good spatial agreement, WRF-CAM5 underpredicts the magnitude of AOD and has an average NMB of about −5%, −62%, and −81% against MODIS AOD, and about −5%, −65%, and −75% against AERONET AOD for d01, d02, and d03 respectively. There is a clear relationship between enhanced AOD values and surface PM$_{10}$ and PM$_{2.5}$, with significant contributions from anthropogenic SO$_2^-$, BC, and organic PM to the localized PM$_{2.5}$ maxima over EC and YRD. There are model underpredictions for PM$_{10}$ and PM$_{2.5}$, in part due to underpredictions in emissions of primary PM and precursor gases such as SO$_2$. The model NMB increases for AOD with increasing spatial resolution, while there is reduced NMB against surface PM$_{10}$ and PM$_{2.5}$ when increasing model resolution. Increasing model resolution may lead to a better representation of local emissions and vertical distribution on surface concentration, while at the same time worsening the accuracy of the parameterization of other dynamic and meteorological processes at finer resolution that impact column AOD. The model generally captures the trend in decreasing AOD values during the May–June (EOS) period compared to the July–August (EAS) period, but consistently underpredicts AOD for d01, d02, and d03 at sites with relatively higher AOD.

The surface PM and column AOD are most enhanced between about 32’N and 42’N in early to mid-May during the EOS, and then shifts north during the EAS in July and August. The northward shift is evident in the SO$_2^-$ concentrations as well. Over both EC and YRD, the AOD and PM are higher during the EOS compared to the EAS, and there are relatively larger anthropogenic sources of PM compared to natural sources during both periods. The spatiotemporal trends of AOD and CDNC agree during the EOS to EAS transition over EC. There is also lower CDNC and higher COT near regions of lower AOD during EOS and EAS, especially south of 33’N due to relatively higher water vapor abundance and lower aerosol concentrations in this region. Increasing spatial resolution from 36 km to 12 km over the EC region shows somewhat different patterns for the spatiotemporal evolution of aerosols and their composition, related cloud variables, and precipitation, and the simulation over d02 had better agreement with the observed TMPA PRECIP compared to d01-in-d02. Over the YRD region, there is relatively enhanced AOD and CDNC and lower COT during the EOS compared to EAS. The simulated precipitation over d03 has better agreement with TMPA observations compared to d02-in-d03.

These results demonstrate the overall adequacy of WRF-CAM5 in predicting the characteristics and evolution of aerosols and precipitation during relatively large-scale dynamic changes (e.g., EASM) at regional scales from 36 to 4 km. At the same time, however, the results present significant underpredictions in aerosols, as well as large over (O_LPP) and underpredictions (U_HPP) in precipitation events, which highlight existing weaknesses when applying WRF-CAM5 physics to regional and local-scale investigations. There are inherently some limitations in modeling the aerosol, cloud, and precipitation interactions accurately with a relatively older WRF-Chem version 3.4.1 in WRF-CAM5, especially when compared to the most recent version of WRF-Chem that has undergone substantial improvement by the time of writing this paper (i.e., version 3.9.1). In a recent comprehensive evaluation of WRF-CAM5 (also with WRF-Chem version 3.4.1) by He et al. (2017), they also demonstrate that this model can generally reproduce meteorology, chemistry, and climate well, but that there are uncertainties in aerosol and cloud treatments contribute the most to the model biases. Thus the results of He et al. (2017) further corroborate the overall conclusions in the present paper, while further emphasizing the need to reduce such biases for future investigations of aerosol-cloud interactions.

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