Evaluation of extreme precipitation in the Yangtze River Delta Region of China using a 1.5 km mesh convection-permitting regional climate model

Guangtao Dong[1], Zhiyu Jiang[2], Ya Wang[3], Zhan Tian[4], and Junguo Liu[5]

[1]Shanghai Climate Center
[2]School of Atmospheric Sciences, Nanjing University
[3]Shanghai meteorological disaster prevention technology center
[4]School of Environmental Science and Engineering, Southern University of Science and Technology
[5]Southern University of Science and Technology

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Abstract

Realistic representation of detailed rainfall characteristics on local scale by current state-of-the-art climate models remains a key challenge, especially on sub-daily timescales. In this research, the convection-permitting Weather Research and Forecasting (WRF) model configured with 1.5 km grid spacing is used to simulate precipitation on sub-daily timescales over the Yangtze River Delta Region of China for continuous 10 years (2005–2014). The simulations are compared to rain gauge observations, reanalysis data, and the simulations of a lower resolution WRF with 9 km grid spacing that has a parameterization of convection. The results show that precipitation over the region can be well captured by using the convection-permitting model (CPM). Furthermore, the intensity, duration and coverage of these precipitation events can be more accurately described by the CPM. On the convection timescales of 1–4 hours, especially for heavy rainfall events, the CPM is more accurate than the convection-parameterized model in capturing the short-duration events, which may be related to its better account of physical processes related with the convection on the convection-permitting scale. In addition, the extreme events which are more localized and with short-duration can be represented better by the CPM while the convection-parameterized model tends to produce widespread precipitation events covering more grid cells than observed. Biases of the simulation by the 9-km mesh convection-parameterized mode appear to be related to the deficiencies in the representation of convections.

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Guangtao Dong[1,2], Zhiyu Jiang[3], Ya Wang[4], Zhan Tian[5 *], Junguo Liu[5]

[1]Shanghai Climate Center, Shanghai, 200030, China

[2] Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai, China Meteorological Administration, Shanghai, 200030, China

[3]School of Atmospheric Sciences, Nanjing University, Nanjing, China, 201400, China

[4]Shanghai Meteorological Disaster Prevention Technology Center, Shanghai, 200030, China

[5]School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China

Correspondingauthor:Zhan Tian (tianz@sustech.edu.cn)

Key Points:

- We employ a 1.5 km mesh convection-permitting regional climate model (CPM) and a 9 km regional climate model (RCM) to run and evaluate decadal continuous regional climate simulations on sub-daily timescales.
- The 9-km RCM tends to under-estimate the intensity of heavy rainfall events, and over-estimate their persistence and spreading extent. By contrast, the 1.5-km CPM gives a much better representation of their intensity, duration and spatial extent.
- The extreme events which are more localized and with short-duration can be represented better by the 1.5 km CPM due to its better account of physical processes related with convection.

Abstract

Realistic representation of rainfall characteristics on local scales by state-of-the-art climate models remains a key challenge, especially on sub-daily timescales. In this study, the convection-permitting Weather Research and Forecasting (WRF) model configured with 1.5 km grid spacing is used to simulate precipitation on sub-daily timescales over the Yangtze River Delta Region of China for continuous 10 years (2005–2014). The simulations are compared withrain gauge observations, reanalysis data, and the simulations of a lower resolution WRF with 9 km grid spacing that has a parameterization of convection. The results show that precipitation over the region can be well captured by using the convection-permitting model (CPM). Furthermore, the intensity, duration and coverage of these precipitation events can be more accurately described by the CPM. On the convection timescales of 1–4 hours, especially for heavy rainfall events, the CPM is more accurate than the convection-parameterized model in capturing the short-duration events, which may be due to its better account of physical processes related tothe convection on the convection-permitting scale. In addition, the extreme events which are more localized and with short-duration can be represented better by the CPM while the convection-parameterized model tends to produce widespread precipitation events covering more grid cells than observations Biases of the simulation by the 9-km mesh convection-parameterized mode appear to be related to the deficiencies in the representation of convections.

1 Introduction

Changes in the intensity and temporal distribution of sub-daily precipitation are of great interest due to their potentially important hydrological impacts (Ban et al., 2015). They are often responsible for flash floods and can cause significant damages in small and steep catchments as well as urban areas (Kendon et al., 2018). Changes in extreme and intensive precipitation are of particular concern because of their great impacts on the society through the generation of floods, leading to infrastructural damages and even human casualties (Helsen et al., 2019). Therefore, better understanding of the extreme sub-daily precipitation changes is crucial for decision makers to make more sustainable and responsive management plans. Precipitation data at sub-daily scales and spatial scales of 1–10 km^2 are needed for the urban drainage design (Arnbjerg-Nielsen et al., 2013). Therefore, it is of great significance to understand the processes influencing daily-scale or hourly-scale precipitation.

Regional climate models (RCMs) are widely used in regional climate researches and future climate simulations all over the world (Feser et al.,2 011; Donner et al., 2011), and it is a powerful tool for studying regional precipitation characteristics. The RCMs allow a better representation of details of orography and coastal zones, characteristics of vegetation and soil, and descriptions of atmospheric processes at smaller scales (Fosser et al., 2015). These characteristics enable RCMs to produce more realistic simulation results than global circulation models (GCMs), and to better capture the temporal and spatial characteristics of the regional climate (Feser et al., 2011). Generally, RCMs are able to capture the average statistics of daily and monthly precipitation. They show a good agreement with observations for moderate precipitation, but their simulation biases increase for heavier precipitation events (Kendon et al., 2012). RCMs also usuallyunderestimate non-precipitation days (Fowler et al., 2007) and overestimate continuous light-rain days (Boberg et al., 2009; Kendon et al., 2019). When the horizontal resolution is coarser than 10 km, the convective parameterization is adopted to represent convections. The parameterization is known as a major source of the error and uncertainty in climate simulations (Prein et al., 2015; Brisson et al., 2016), usually leading to the misrepresentation of the diurnal cycle of convective precipitation (Kendon et al., 2012, 2014; Prein et al., 2015; Maraun et al., 2017) and the underestimation of hourly precipitation intensities (Prein et al., 2015).

Previous studies have shown that model resolution is an important factor affecting the simulation ability of RCMs (Lucas-Picher et al., 2017). Generally speaking, the higher the resolution is, the better the temporal and spatial characteristics of the regional climate can be captured. With the horizontal resolution increasing until reaching the convection-permitting (CP) scales (~4 km), the cumulus convective parameterizations could be switched off and it is possible to explicitly representthe convection when simulating the regional climate (Guo et al., 2019b). In these convection-permitting models (CPMs), the convection parameterization can be switched off, and the representation of surface and boundary layer processes can be greatly enhanced (Guo et al., 2019a). To date, there have been increasing number of studies on regional climate simulations using CPMs. Kendon et al. (2012) showed that rainfall simulated by the 1.5-km-resolution RCM is much more realistic than that simulated by the 12-km-resolution RCM, due to that much continueslight rain and pretty reduced errors in the diurnal cycle by the 1.5-km-resolution RCM. Stratton et al. (2018) also emphasized the CPMs' improvement over coarse

RCMs on extreme precipitation through a case study over pan Africa. Long-term (more than ten years) continuous simulations in Europe and the United States show that CPMs can significantly improve the representation of both hourly intensity distribution and diurnal cycle of precipitation (Prein et al., 2015; Kendon et al., 2015). Some studies have found that there are some large errors in the hourly precipitation simulated by the coarse-resolution model compared with the observation—the duration of precipitation is significantly longer than the observation (Berthou et al., 2019), the intensity of hourly precipitation is weaker than the observation (Knist et al., 2018), and the spatial coverage of strong hourly precipitation is larger than the observed one (Chang et al., 2018).By contrast, the CPMs have exhibited an obviously better performance on the sub-daily scale, and can well capture the precipitation with the short duration, high intensity and concentrated range (Chan et al., 2014; Ban et al., 2014; Fosser et al., 2015; Yang et al., 2019). The improvement in precipitation characteristics simulated by CPMs is attributed to the fact that the CPMs can generate realistic showers by better representating the organization of convections, and forecast local extreme events, which is hardly captured when the resolution is not fine enough(Kendon et al., 2012). The convection-permitting scale has added values in the representation of the precipitation field and the corresponding atmospheric fields (Fosser et al., 2015).

In China, Li et al. (2018) simulated precipitation during the warm season (April–September) in China, showing that CPMs can improve the simulated spatial distribution of precipitation in summer. Xiong et al. (2013) showed that the Regional Integrated Environmental Model System 2.0 (RCMs without the convection parameterization) with the resolution of 3 km had a good representation of the seasonal cycle of precipitation during January 1 to December 31, 2000 in the Heihe River Basin. In the eastern China, the effects of microphysics parameterization (MP) schemes on precipitation characteristics were investigated by Guo et al. (2019b) with a six-year warm-season climate simulation, and Guo et al. (2019a)with a 13-year continuous simulation. Their results indicated that CPMs can also capture the diurnal characteristics of the precipitation amount and frequency. Disastrous weather such as short-term heavy precipitation and mesoscale convective systems frequently occur in the eastern China (Yang et al., 2015), which can be explicitly represented in CPMs. Nevertheless, even in convection-committing scale, higher benefit can still be gained when resolution is enhanced from 4 km to 1.5 km due to insufficient representation of convective downdrafts in 4 km convection-permitting simulations

(Murata et al., 2017). So far, there have been no studies dealing with decadal long continuous convection-permitting simulations at 1.5 km resolution over eastern China. Thus there is an urgent need to conduct long-term continuous simulations by CPMs at 1.5 km resolution and to analyze the added values of such simulations over traditional RCMs in terms of hourly precipitation characteristics, such as the intensity, duration and coverage of extremely hourly precipitation as well as diurnal cyle.

By evaluating the performance of CPMs in reproducing the spatial-temporal distribution of precipitation in the Yangtze River Delta, this paper aims to explore what improvements CPMs can make in simulating the frequency, intensity, and duration of precipitation in the region, compared with the low-resolution model with convection being parameterized. The manuscript is organized as follows. Section 2 introduces the RCM model and experimental design, describes the observation and reanalysis datasets used in the analysis. The performance of CPM in reproducing extreme precipitation characteristics is assessed in Section 3, including the simulation effects of CPM on the precipitation duration, intensity and coverage. Finally, the discussion and conclusions from this study are given in section 4.

2 Methods and study area

2.1 Observation data

In this paper, three observation datasets are applied in evaluating the capacity of the model in simulating precipitation over the eastern China. Hourly precipitation during 2003–2012 and daily precipitation during 2005–2014and are used in the analysis. These data were obtained from 70 automatic weather stations in the Yangtze River Delta region, are provided by the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). The gauge–satellite merged dataset (AWSCMORPH; Shen et al., 2014), which is obtained by merging the observations at over 30,000 national and regional automatic weather stations with the precipitation product (Joyce et al. 2004), is from the NOAA Climate Precipitation Center Morphing Technique (CMORPH). This merged dataset has a temporal resolution of one hour and a spatial resolution of 0.1° × 0.1° for the observational period of 2008–2014. The CMORPH precipitation dataset has been applied widely to evaluate the features of rainfall over China, and it has been proven suitable for examining the detailed spatial patterns and temporal variations of precipitation over the eastern China (Qian et al., 2015; Chen et al., 2016). In this study, the simulated rainfall spatial coverage is evaluated by CMORPH hourly precipitation.

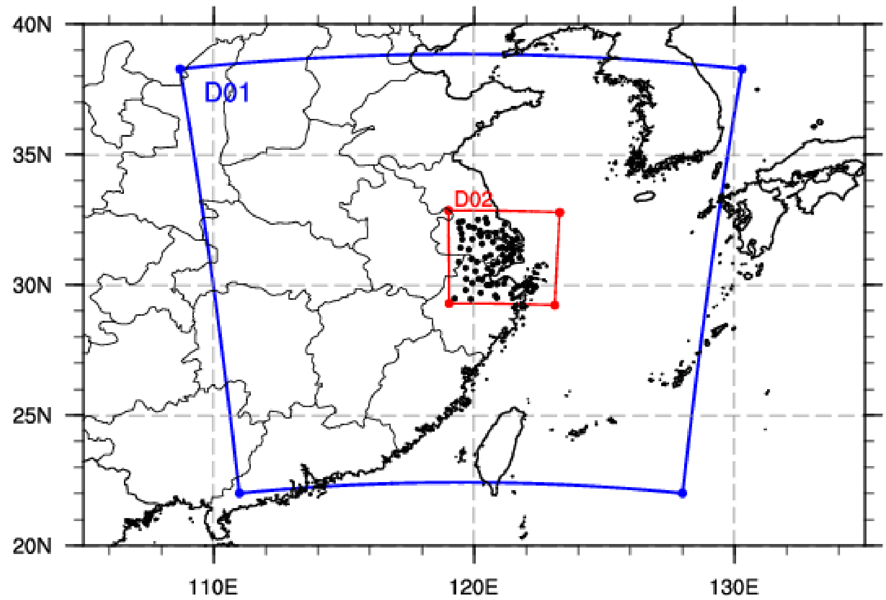

Figure 1. The domains of the WRF model domain configuration in this study: the boundary of the 9-km-resolution outer domain (D01, blue) and the 1.5-km-resolution inner domain (D02, red). Black dots are the locations of automatic weather stations used in the model evaluation.

2.2 Model configuration

The climate model used in this paper is the two-domain nested atmospheric model WRF (Weather Research and Forecasting model) version 3.7.1. The WRF driven by the ERA-Interim reanalysis data has been run with an outer resolution of 9 km (hereinafter referred to as 9-km models or W9k or LSM) in this study (Figure 1). In this configuration, deep convection is simulated by Kain-Fritsch convective parameterization scheme (Kain et al., 2004). The inner domain with a resolution of 1.5 km (hereinafter referred to as 1.5-km models or W1p5k or CPM) makes it possible to explicitly represent the deep convection without the convection parameterization scheme. The simulation was performed from December 1, 2004 to January 1, 2014. The data from the first month (i.e., December 2004) of the simulation was discarded as the spin-up. The simulated meteorological variable values at the grids closest to the weather stations are used for the comparison with the observation. The locations of the automatic weather stations are shown in Figure 1.

Table 1. Experiment design for the simulations.

Model property	W1p5k	W9k
Horizontal resolution	1.5 km	9 km
Vertical resolution	51 levels	51 levels
Time step	5 s	30 s
Convection scheme	None	Kain-fritsch(Kain et al., 2004)
Microphysics	WSM5	WSM5(Hong et al., 2004)
Radiation	Rrtmg	Rrtmg(Iacono etal., 2008)
Land surface	NOAH	NOAH(Chen and Dudhia, 2001)

2.3 Analysis methods

To evaluate the rainfall simulated by the W1p5k and W9k, the duration and intensity of rainfall events are examined in this paper. The analysis includes all the stations within the W1p5k inner domain (red rectangle in Figure 1). 10 years of hourly rainfall data from each dataset, corresponding to the period of 2005–2014 (hourly observation 2003-2012) are analyzed in this paper. For each station in the D02 domain, precipitation occurrences or ‘‘events’’ are defined as the precipitation amount/duration exceeds a given threshold at a given location. For each precipitation event, the duration of precipitation above the threshold and total precipitation are also recorded.

As our focus is on heavy precipitation, the intensity within a threshold range at the tail end of the precipitation distribution has been analyzed. Considering the uncertainty of observations and the possibility of underestimating heavy precipitation, percentile thresholds are used in this study. In particular, the p-th percentile of the hourly rainfall distribution for all ten years in each dataset is considered as the percentile threshold of p. Through the study on the temporal characteristics of rainfall over this percentile, we can see that the absolute values vary among different datasets. The advantage of using percentile values is that the effect of precipitation biases between simulations and observations could be eliminated, while the reliable information on precipitation patterns and behaviors could still be retained (Kendon et al., 2012).

In order to analyze the relationship between precipitation intensity and the precipitation duration, the joint probability distribution is analyzed in this paper. Let $\{a_1, a_2, \ldots, a_n\}$ denote the rainfall amount of all precipitation events, $\{d_1, d_2, \ldots, d_n\}$ the corresponding durations, then the rainfall and durations are further divided into predefined ranges, respectively, and are recorded as $\{A_1, A_2, \ldots, A_p\}$, $\{D_1, D_2, \ldots, D_q\}$. The joint probability is then defined as follows.

$$p_{ij} = P\{X = A_i, Y = D_j\} \quad (1),$$

where

$$p_{ij} \geq 0, \sum_i \sum_j p_{ij} = 1 \quad (2).$$

3 Results

In this section, the WRF simulation results are compared with the observations to assess the performance of the CPM. To facilitatethe direct comparison between W9k and W1p5k, the W9k provides lateral boundary conditions to the W1p5k.

3.1 The distribution of mean and extreme precipitation

To give a broad picture of precipitation in the study area, Figure 2 shows the monthly mean precipitation, wet days and wet hours. Table 2 further lists the statistical results including the correlation coefficients (CORs) and root mean square errors (RMSEs) between the observations (records at the automatic weather stations) and simulations. Figure 2a shows that precipitation in this region occurs mostly in the summer (June–August, JJA), with much lower level and relatively little variation in other months. The simulated rainfall exhibits significant peaks in June and July for W1p5k and W9k, respectively. In the summer, the W9k overestimates the precipitation amount, which is almost twice the observation in July. W1p5k has a much better performance than W9K, although it underestimates monthly rainfall in July and August. Both of themperform well in other months. In general, the simulation results of the CPM are close to those of the LSM in terms of monthly average precipitation in dry seasons. Major improvements of the CPM occur in the summer when precipitation is dominated by deep convections.

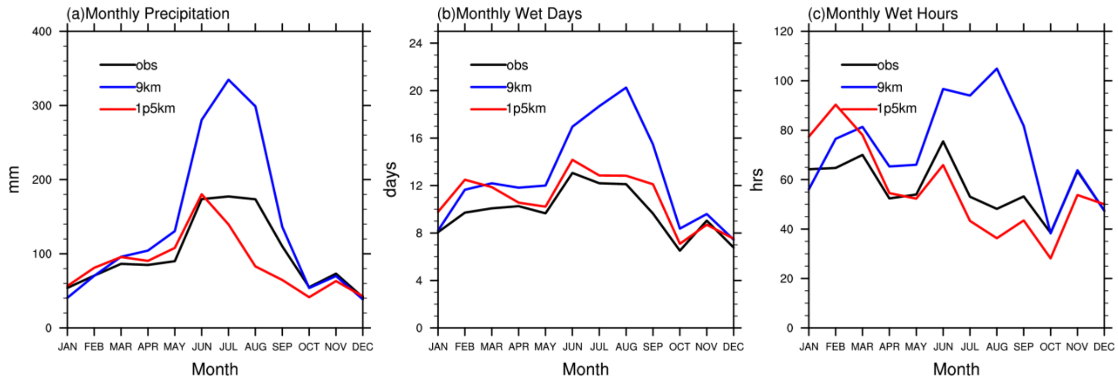

Figure 2. Seasonal cycles of monthly mean (a) precipitation, (b) wet days and (c) wet hours. Wet days/hours are define as precipitation ≥1 mmd^{-1} or 0.1mmh^{-1} respectively.

Table 2. Statistics between the simulations and observations for the seasonal cycle of precipitation.

Statistics	W9k		W1p5k	
	COR	RMSE	COR	RMSE
PRCPTOT	0.99	67.66 mm	0.77	32.36 mm
Wet days	0.80	3.85 day	0.91	1.40 day
Wet hours	0.40	23.82 h	0.80	11.29 h

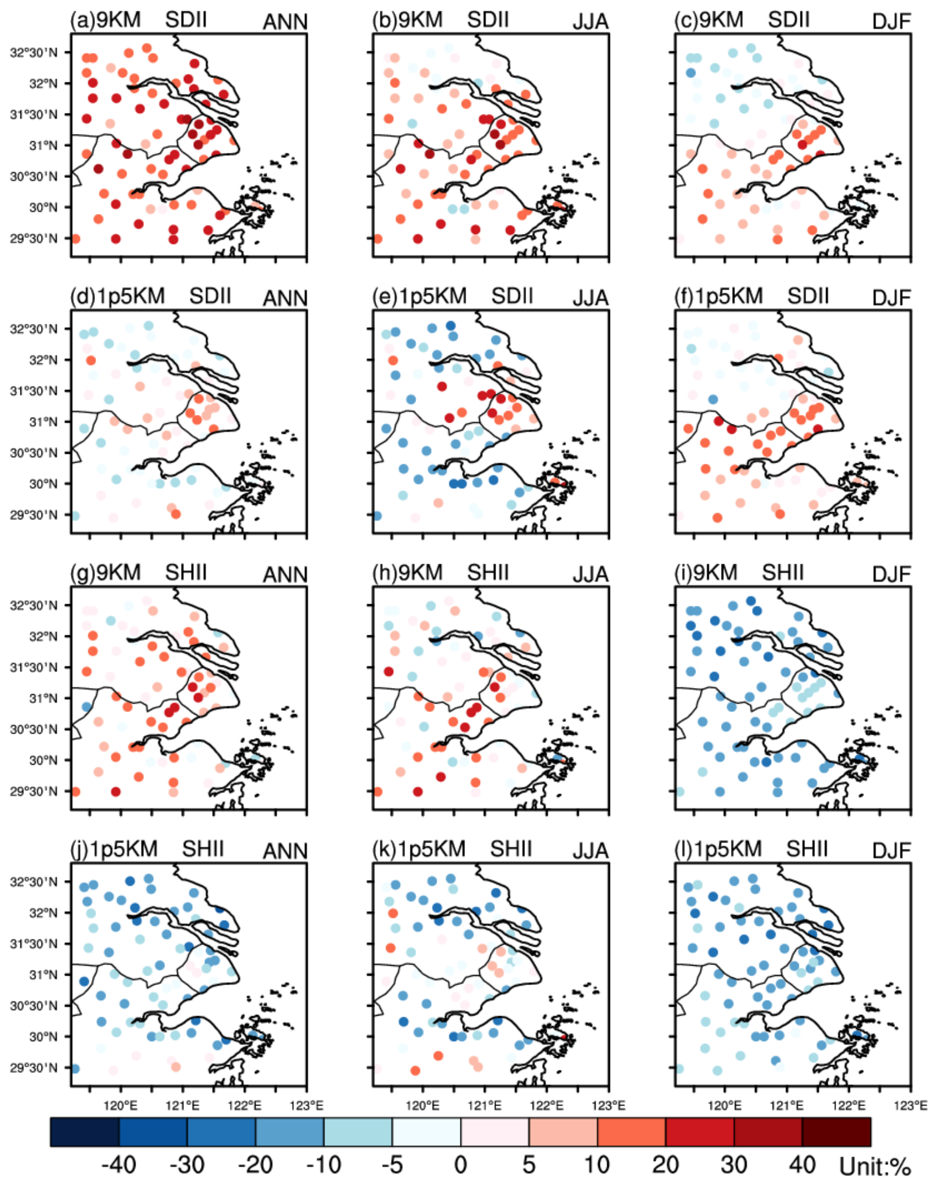

Figure 3. Biases of the RCM-simulated precipitation intensity compared with the observations on (a–f)daily and (g-l) hourly scales.

As shown in Figure 3, the precipitation intensity simulated by W1p5k is more consistent with that from the observation than W9k. The observed daily precipitation intensity is largely between 12.0 and 13.5 mmday^{-1}, and the simulated values at most stations by W1p5k are also within this range. The differences between the two are mostly below 10%. The simulated precipitation intensities at individual stations such as those located in Shanghai area, are up to 15 mmday^{-1}. In contrast, the daily precipitation intensity simulated by W9k is about 20% higher than the observations. Forhourly precipitation intensity, the simulations by both W9k and W1p5k are close to the observations, with the absolute difference below 30%. Although the annual-mean hourly precipitation intensity (defined as the annual total precipitation divided by the annual total rainy hours) simulated by W9k is close to the observations, the annual mean precipitation and rainy hours are over 20% higher than the observation. The results are much improved by W1p5k simulations which show good skills in simulating annual mean precipitation, rainy hours and hourly precipitation. Furthermore, the probability density distribution (PDF) of hourly precipitation is also better simulated by W1p5k. The occurrence frequency of precipitation within 0.1–15 mmh^{-1} simulated by W9k is significantly higher than the observed values, while W9k underestimates the occurrence frequency of above 15 mmh^{-1}. On the other hand, the PDF of the hourly precipitation simulated by W1p5k agrees well with that of the observations.

The precipitation amount simulated by W9k is much higher than the observations (Figure 4), especially for JJA (June, July and August), while that simulated by W1p5k is slightly lower than the observations in JJA. For the boreal winter (DJF), precipitation amount is well simulated by both W9k and W1p5k. Note that as precipitation amount in JJA is much more than that in DJF, the model errors in representing the annual (ANN) precipitation is largely caused bythe errors in JJA.

In order to investigate the reasons leading to the overestimation of JJA precipitation by 9-km RCM. The difference of the large-scale atmospheric circulationsbetween the 9-km RCM and ERA-interim Reanalysis are presentedin Supplementary Materials (SM). Figures and discussions in SM show that 9-km RCM lacks the skill for realistically simulating the position and intensity of the western Pacific subtropical high which leads to much of the moisture transport concentrates near Zhejiang province. The intensities of 850-hPa wind speed are also overestimated to some extent, which could be responsible for the overestimation of the summer precipitation over the eastern China.

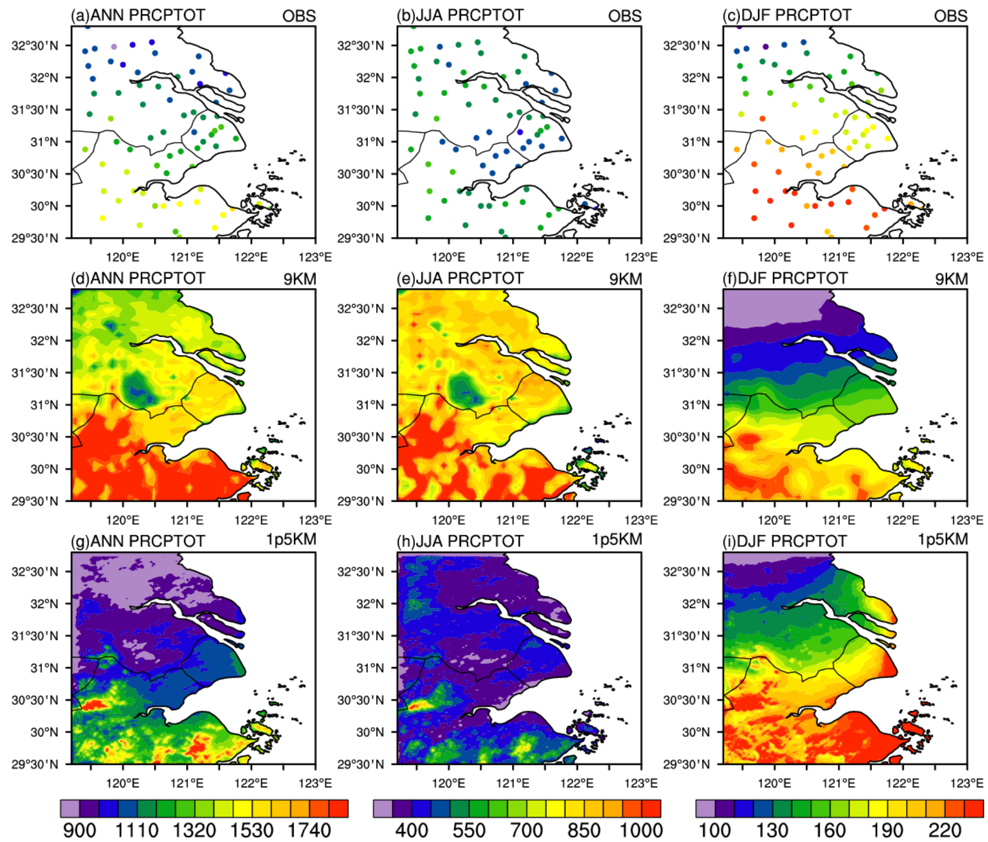

Figure 4. Spatial distribution patterns of annual mean (2005–2014) and seasonal mean precipitation in the observations (top) and the simulations by the RCMs (middle: W9k; bottom: W1p5k) (unit: mm).

Figure5a further shows the frequency distributions of daily precipitation intensity averaged over all the 70 stations from both the observations and simulations (W9k and W1p5k) during 2005–2014. Particular attention has been paid to the heavy or extreme precipitation with the intensity over 30 mm d^{-1}. For daily precipitation intensity within the range of 30–150 mm, the W1p5k simulation shows lower frequency than that by W9k, which agrees better with the observations. It can be clearly seen that W1p5k well simulates the rainfall frequency below the 99th percentile (Figure 6b). It is obvious that the high-resolution CPM makes better performance in simulating extreme precipitation, compared with coarser-resolution experiments using a convection parameterization which may overestimate the precipitation with a longer rainy season.

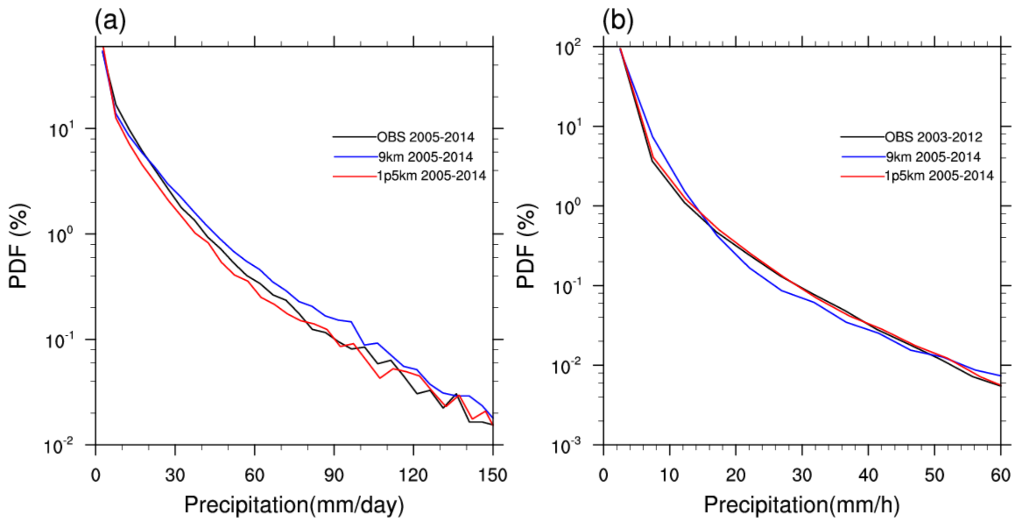

Figure5. Observed and two RCM simulated frequency distributions of the (a) daily and (b) hourly precipitation intensity .

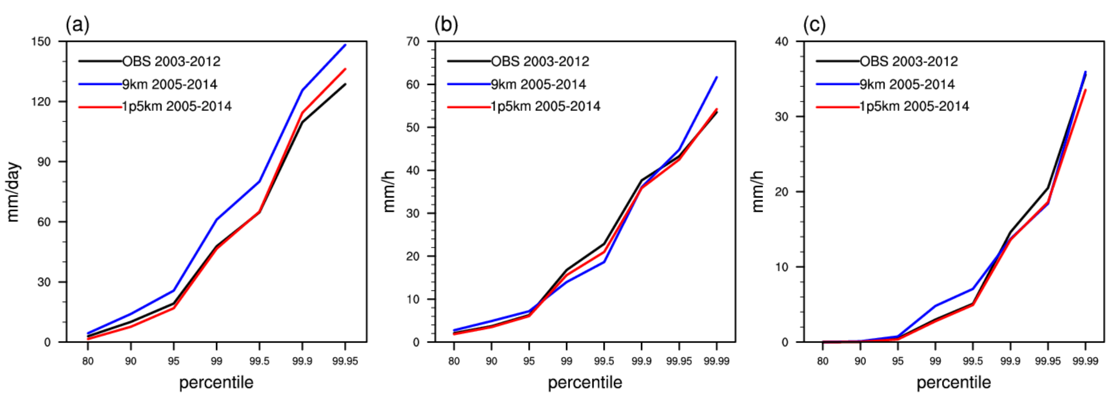

Figure6. (a) Daily precipitation intensity, (b) hourly intensity for cases with precipitation > 0.1 mmh^{-1} and (c) hourly intensity in all hours corresponding to a given percentile threshold in the observations and simulations by W1p5k and W9k during 2005–2014. The horizontal axis means the percentile threshold of hourly precipitation across the evaluation period (10 years).

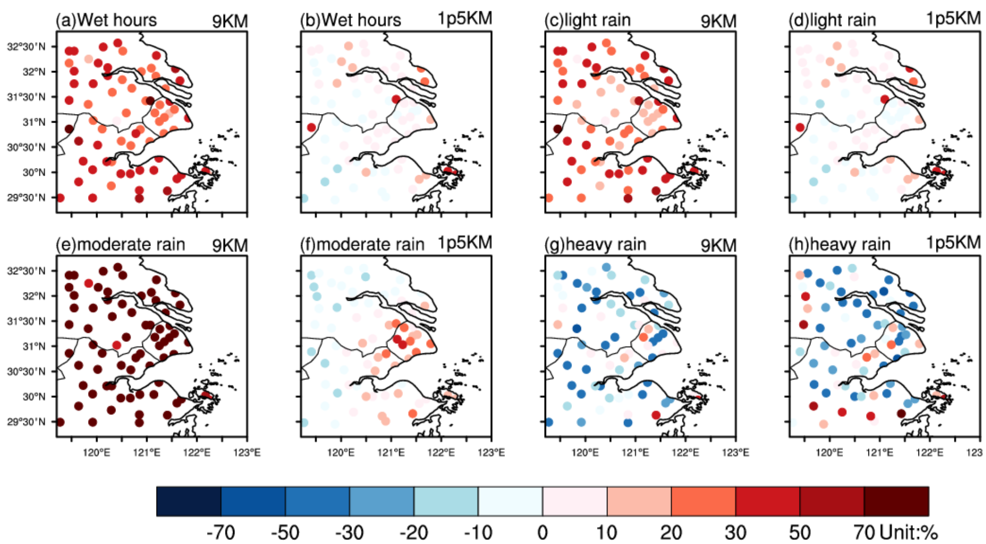

Figure7. Difference of the RCM-simulated frequencies with the observation at different precipitation grades, which are (a–b) wet (> 0.1 mm h^{-1}), (c–d) light rain (0.1–5.0 mm h^{-1}), (e–f) moderate rain (5.0–20.0 mm h^{-1}) and (g–h) heavy rain (>= 20.0 mm h^{-1}), respectively.

The performances of W9k and W1p5k for simulating precipitation with different intensity thresholds are assessed by analyzing their corresponding frequencies (Figure 7). W1p5k shows a good representation of the total precipitation hours and light rain hours (Figures 7a–7b) with the model biases at most stations within 10%. While the simulations by W9k are over 30% larger than the observations. The results for light rain are consistent with that of total rainy hours which lead to the large amount of light rain in the study area. Furthermore, the precipitation occurrence within the range of 5–20 mm h^{-1} (Figures 7e–7f) simulated by W9k is significantly overestimated by more than 70% above the observations, while that simulated by W1p5k at the stations nearby Shanghai is overestimated by around 30%. Nevertheless, there are little differences between the simulations of precipitation above 20 mm h^{-1} by W9k and W1p5k, with both of them exhibiting an underestimation in these extreme precipitation events.

3.2 Duration of heavy precipitation

It is found that precipitation in W9k peaks around 12:00pm (Figure8b), and the event with this peak lasts for 3–5 hours. This significantly differs from the observations which show that precipitation reaches its peak around 15:00-18:00pm and with duration of 1-3 hours. The precipitation diurnal cycle is improved in W1p5k which shows that more intensive precipitation occurs in the afternoon around 12:00-18:00pm, with duration of 1-3 hours. The observed precipitation generally lasts for no more than 8 hours, however the durations of events which start during 0:00–6:00 could last for about 10 hours in some cases. Comparing with W9k, more precipitation is produced by W1p5K during the period of 20:00–03:00, and the associated duration is longer than the observations. In addition, it is noted that the observed short-term precipitation during the period of 15:00–18:00 accounts for the largest ratio to the total precipitation. Generally, W1p5k performs better than W9k in both duration and distribution of heavy precipitation with short durations.

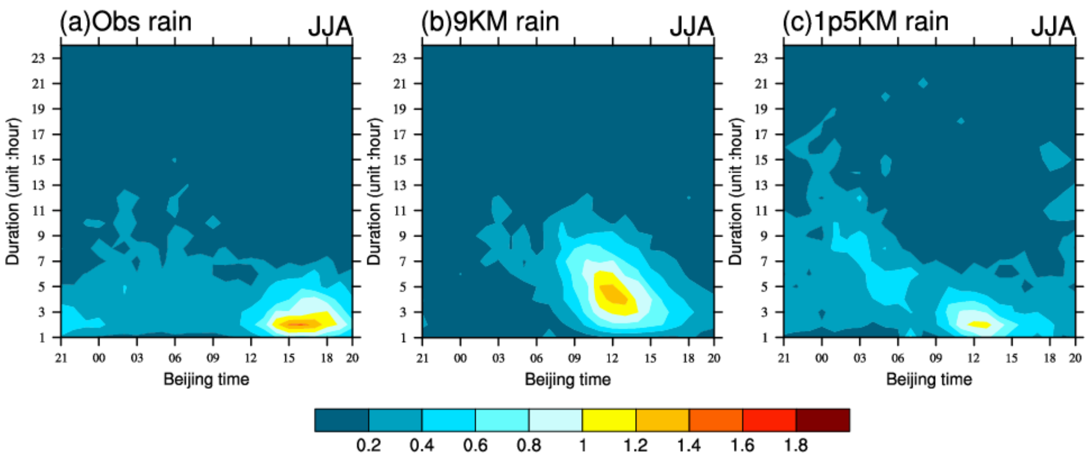

Figure8. The diurnal cycles of different durations of the intensity of precipitation to its total precipitation for the (a) observation, (b) W9k and (c) W1p5K (unit: %) in JJA. The horizontal axis represents the Beijing time, and the vertical axis indicates the duration of the precipitation events and the shaded colors are the corresponding ratios to total precipitation. Note the events longer than 24 hours are not shown.

Previous studies have revealed that the convective precipitation generally lasts for a short time (1–4 hours) and tends to be more local (Chan et al., 2014). Thus, the precipitation structure in the study area is further illustrated (Figure 9). It is found that short-duration precipitation in summer is one of the principal precipitation types in the study domain. Observations show that precipitation with a duration of 2–5 hours accounts for nearly 30% of the total precipitation. After that, the proportion decreases with the increase of the duration, and tends to be flat for the events longer than 20 hours. The maximum precipitation ratio simulated by W9k reaches about 8.5% for the rainfall events with durations of 4 hours, and then the ratio decreases with the increase of the duration. W9k underestimates the precipitation during the events which last less than 3 hours. This means that convective precipitation may be underestimated in W9k. In contrast, the W1p5k shows a more realistic peak duration which corresponds well with the observation.

In order to investigate whether W1p5k can represent the rainstorm with more realistic characteristics in the study domain, special attention has been paid to the rainstorm duration. Figure 10 shows the frequency distribution of precipitation events at different duration thresholds. The horizontal rows correspond to the frequency distribution of precipitation events that exceed a specific precipitation threshold. Each box in the row represents the probability of precipitation events for a certain duration. Observations show that high threshold precipitation usually has short duration. For the precipitation threshold value of 99.9% or above, the proportion of precipitation events lasting for 4 hours or above is very low.In the W9k, rainfall persists too long compared with the observations. The 9-km RCM lacks one-hour precipitation events while abounds two or more hours events. Indeed, the comparison between the 9-km RCM & observations and the 1.5-km & 9-km RCMs look like the inverse of each other (cf. Figure 10d and 10f). Heavy rain in the 1.5-km RCM is shorter-persistent than in the 9-km RCM, the probability of rainfall lasting for just one hour is significantly higher for all percentile thresholds ≤ 99.99%, and also with a remarkably fewer probability of rain lasting 2~5 hours for all percentile thresholds ≤ 99.5%. The 1.5-km RCM shows great added value in terms of rainstorm duration characteristics.

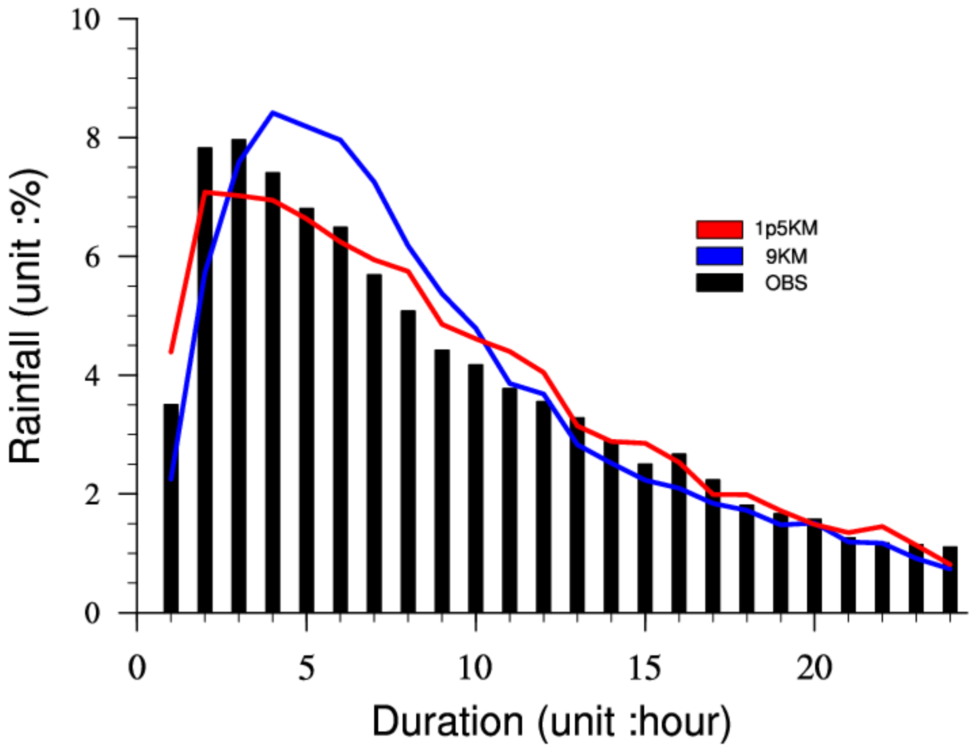

Figure9. Ratio of the precipitation with different durations to the total precipitation (unit: %, events with durations longer than 24 hours are not shown) in the observation (black bar) and the two simulations by W9k (blue solid line) and W1p5k (red solid line) in JJA. The horizontal axis represents the duration of the precipitation event (> 0.1 mm, unit: hour), and the vertical axis represents the proportion of precipitation with different durations to the total precipitation (unit: %).

3.3 Size of heavy rain cells

To assess the spatial structure, the coverage of rainfall cells exceeding certain intensity thresholds is shown in Figure 11. Observations show that heavy precipitation events tendto be more local. The probability of large precipitation cells decreases with the increasing threshold. Heavy precipitation (exceeding the percentile threshold of 99.5) covers a widespread area in the simulation by W9k, while there are too many moderate rainfall cells covering 50–100 grids and extreme rainfall covering a single grid. At the same time, there is a lack of rainfall events covering a single grid in W9k simulations.

In contrast, heavy precipitation simulated by W1p5k is more local than that simulated by W9k, leading to a better agreement with the observation. W1p5k produces more widespread light rainfall cells while W9k tends to produce more widespread heavy rainfall cells. The precipitation simulated by W1p5k seems to be more concentrated, with numerous one-grid light or moderate rainfall events. Considering that the difference between W1p5k and W9k is almost opposite to that of W9k against the observations, it can be concluded that the W1p5k has a better skill in simulating the size of heavy rain cells.

3.4 Rainfall durations versus peak intensity

Considering only some of the rainfall events exceeding a given threshold, there is a limitation that the heaviest rainfall, which usually short-lived and local, will be embedded in a larger scale or longer duration precipitation event with lower intensity (Kendon et al., 2012). To assess this characteristic, Figure 12a shows that precipitation events with a lower peak intensity are short-lived, and moderate-intensity precipitation is more likely to be embedded within relatively longer precipitation events (2–5 hours). W9k produces too few short (1–2 hours) medium-intensity (10–20 mm) and high-intensity (> 30 mm) events and too many long (2–6 hours) low-intensity events. On the other hand, W1p5k tends to agree with the observations quite well when the rainfall intensity exceeds 5 mm h^{-1} (Figure 12c). The differences of the W9k simulation against the observations and that of the W1p5k simulation against the W9k simulation look opposite to each other, indicating that W1p5k is in a better agreement with the observations. Though both W9k and W1p5k underestimate the rainfall with the intensity of 20–30 mm or heavier and lasting 2–6 hours, W1p5k produces a higher precipitation probability than W9k at this condition. It means W1p5k is more skillful in representing short-lived and high-peak-intensity events. Similar improvements can be found for the events with the intensity of 10–20 mm and lasting 1–2 hours.

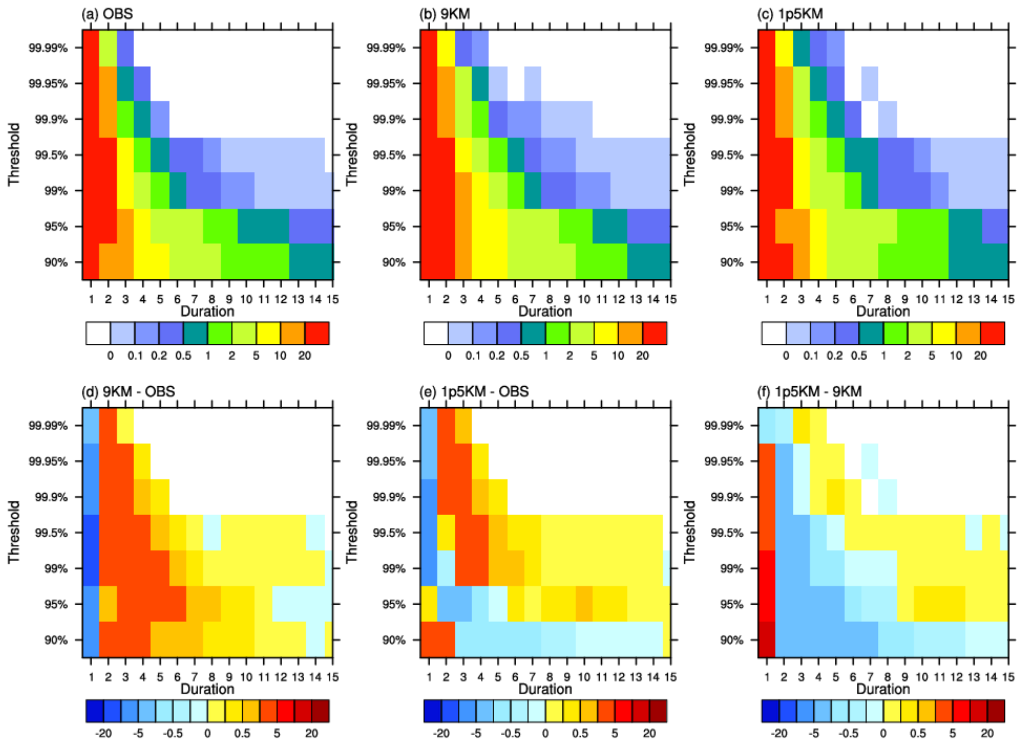

Figure 10. Probability distribution of rainfall duration exceeding intensity percentile thresholds(unit: %) for (a) OBS, (b) W9k, (c) W1p5k, as well as the difference for (d) W9k–OBS, (e) W1p5k–OBS and (f) W1p5k–W9k. The threshold used here is defined in Figure6c (calculated for all the hours).

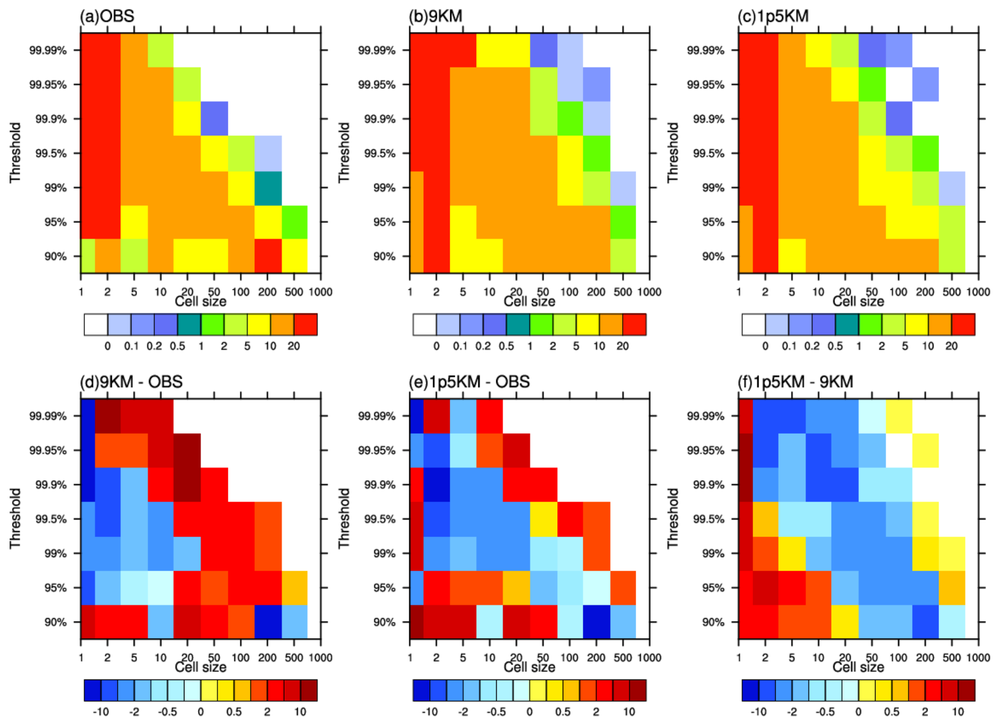

Figure 11. Probability distribution of rain cell size where rainfall over given percentile thresholds (unit: %). The data are interpolated to the gridswith the resolution of 10 km×10 km in the same region. Results are shown for (a) OBS, (b) W9k, (c) W1p5k, as well as the difference for (d) W9k–OBS, (e) W1p5k–OBS and (f) W1p5k–W9k. The threshold used here is defined in Figure6c (calculated for all the hours).

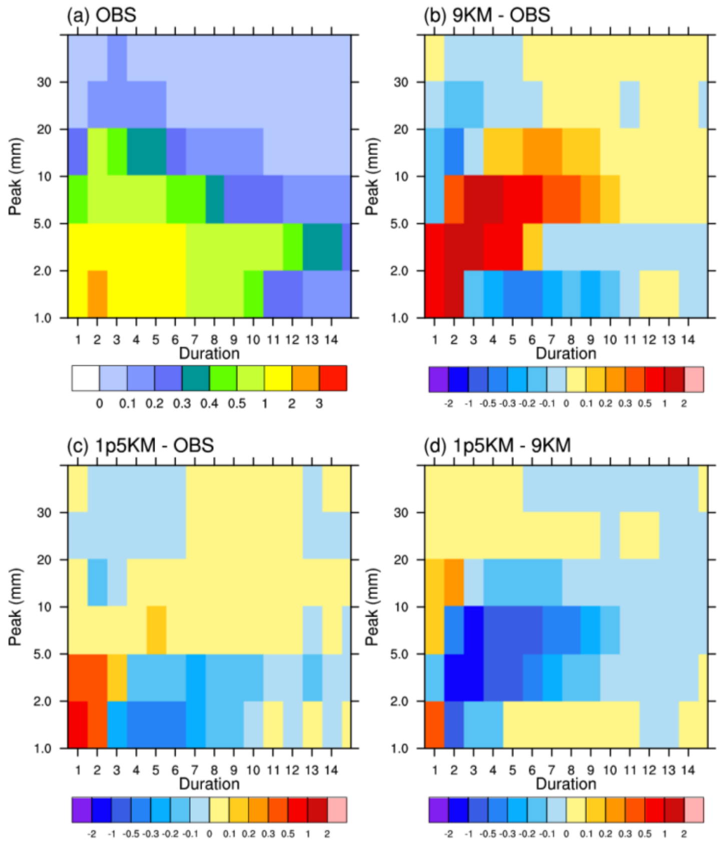

Figure 12. Joint probability distribution of duration versus peak intensity for rainfall ≥ 0.1 mmh^{-1} (unit: %). Results are shown for (a) OBS, (b) W9k–OBS, (c) W1p5k–OBS and (d) W1p5k–W9k.

As W9k and W1p5k are able to show some different characteristics of the simulated precipitation events, it is informative for us to further explore how precipitation in these simulations is related to the convection properties in these phenomena. The convection fraction (CF) is used to distinguish these wet days with different convection contributions. The CF is calculated in W9k at each station, and then the duration and characteristicsof peak intensity are examined at a given range of CF. As the convection scheme is switched off in W1p5k, in this part of the analysis, we assume that CF in W9k is also applicable for W1p5k given the fact that large-scale factors affecting convection should be largely similar in these two resolutions.

Comparing high-CF days (CF > 0.7) with low-CF days (CF < 0.1) in W1p5k, there are much more short-duration high-peak-intensity rain when CF is high. High-CF days areoften associated with more rainfall events with 1–2 hours durations, while longer rainfall events can be seen in other CF categories (without taking the intensity into account). Results are rather different for W9k. High-CF events do not show a different pattern as to other CF category eventsfor high-peak-intensity rainfall. However, longer moderate-intensity precipitation is clearly presented in all the three sets of data (Figures 13 b, 13d and 13f). The differences between W1p5k simulationfor high CF events and thatfor middle CF ones in Figure 13 are similar to the differencesbetween W1p5kand W9k simulations as shown in Figure 12. This suggests that the differences in the model-simulated rainfall duration and intensity characteristics in these two sets of model configurations are mainly due to the improved representation of convections in W1p5k.

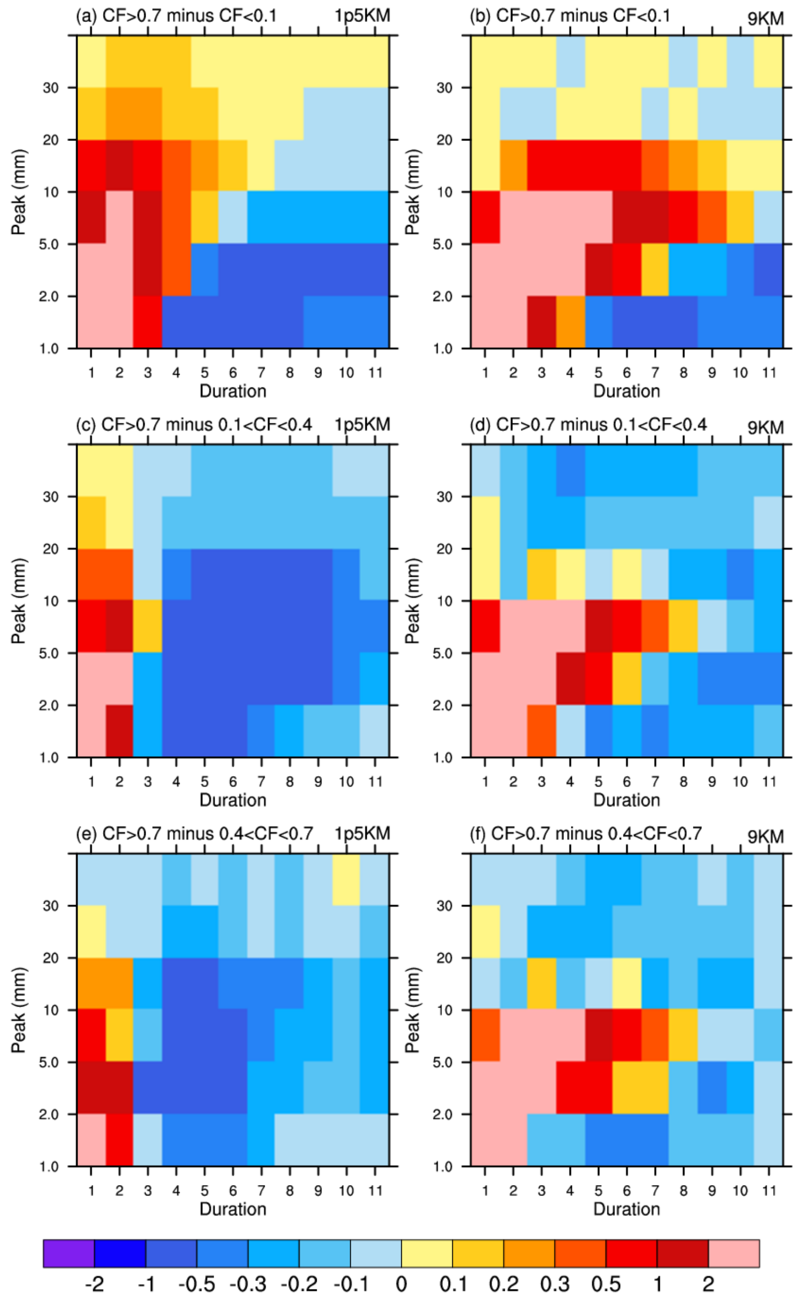

Figure 13. Differences in the joint probability distribution of rain duration versus peak intensity for different CF ranges. Results are high convective fraction (CF ≥ 0.7) days minus lower level convective fraction days.

4 Discussion and conclusions

Many applications of risk assessment and environmental impact assessment (EIA) require detailed information on the local climate at a very fine spatial scale (Wang et al., 2013). There is an increasing need to use high-resolution regional climate models to make more reliable assessments on possible changes of small-scale and high-impact extreme weather events under global warming. Our study is among the first in China to use a convection permitting model at 1.5km resolution to produce a 10-yr simulation so that we can properly explore the sensitivity of modelling rainfall characteristics by considering the model resolutions and physics representations. The knowledge obtained from this study will provide valuable insights to the efforts, and increase our confidence, in providing more reliable and detailed projections of future rainfall at local and regional scales under the condition of global warming.

This paper aims at evaluating the skill of two selected WRF high-resolution experiments (9-km and 1.5-km RCMs) in simulating precipitation extremes over a region in eastern China for the 10-yr period of 2005 to 2014. We have been focused on assessing whether there are added values in the convection-permitting configuration of W1p5k for simulating precipitation extremes. Our results show that the 1.5-km convection-permitting RCM produces more realistic extremes than the W9k.

In the simulations, we found that the incorporation of explicit convection parametrization produces not only smaller wet bias of mean precipitation and a more realistic rainfall diurnal cycle, but alsomore accurate short-duration individual rainfall events which are more consistent with the observations (Chang et al., 2018). W1p5k has a more realistic performance for the precipitation duration simulation, including the proportion of precipitation to total precipitation with different intensities or durations. The observations show that there are many short-duration (1–2 hours) heavy precipitation events, and in a continuous precipitation event precipitation distribution has a significant peak. The short-duration (1–2 hours) precipitation and its peak can be better represented in the W1p5k simulation. In contrast, the heavy-precipitation duration simulated by W9k is longer (2–4 hours) than the observed, and the simulated precipitation tends to be more evenly distributed than the observations during the rainfall period. The average temporal and spatial characteristics of convections can be simulated, but individual rainfall events are not well represented.

Comparing with W9k, W1p5k also has a better performance on the spatial coverage of precipitation. As the convective parameterization scheme is used for dedcribing the average properties of convections over a grid cell (Kendon et al., 2012), it has a limitation in representing extreme precipitation or concentratedprecipitation. Our results show that the precipitation in W9k tend to have a spatially more widespread and temporally long-lasting tendency, while the model deficiency is much improved in W1p5k. The convection-permitting simulation can represent many important processes that control convections, including local dynamics and topographic forcing (such as convergence lines) that lead to the triggering and inhibition of convections, as well as the environmental mixing (Roberts, 2007, cited in Kendon et al., 2012). Therefore, the CPM can represent the spatial-temporal structure of rainfall well. However, the convection is still not properly resolved at the kilometer scale, and the grid spacing is still too coarse to resolve updrafts (Prein et al., 2015). This means that the updraft of some showers will appear on wrong scales, as the turbulent mixing is inherently insufficient. This explains the trend of the vertical velocity, so the intensity of convective showers is too strong in some cases simulated by the kilometer-scale model (Lean et al., 2008).

Our results showed that W9k produces stronger extreme rainfall than W1p5k, as the precipitation simulated by W9k is overestimated to a large extent. Generally, precipitation intensity by coarse-resolution RCMs may be somewhat underestimated (Li et al., 2018; Kendon et al., 2012), which is mainly due to the overestimation of the frequency of light rains. The high intensity presented by W9k in this study is due to the overestimation of rainfall, especially in summer. This could be attributed to the fact that the resolution of 9 km is finer than that of common large-scale models. Previous studies (e.g., Xiong, 2013) found that for the rainfall simulation in the upstream area of the Heihe River Basin in China with concentrated rainfall from May to September at the resolution of 3 km, both the convective parameterization scheme and the convection-permitting scheme overestimate the precipitation. There is a possibility that the 9-km model with the convective parameterization scheme leads to the overestimation of precipitation. As the CPM is more sensitive to produce convective precipitation, theoretically there should be more precipitation produced in CPM, while less precipitation in coarse-resolution RCMs. Such biases in the model may be related to the uncertainty of the study domain, the model or the observation (Isotta et al., 2014). These aspects of the model performance will be further explored in our future analysis based on our 10-yr simulations.

This study is the first decadal long continuous convection-permitting simulations at 1.5 km resolution over eastern China. And it is also a first attempt to look at the added value of CPMs in terms of the temporal and spatial structure of hourly precipitation over eastern China.

Results show that the 1.5-km RCM tend toslightly overestimate the daily rainfall intensity, however, it presents a much better agreement in terms of hourly rainfall frequency and intensity, and also shows better agreements with observations in terms of temporal and spatial structure of hourly rainfall. In the 9-km RCM, the short-duration high peak intensity events are insufficient representation overall, and rainfall tends to be too widespread and persistent. The bias is remarkably reduced by the 1.5 km CPM due to its better account of physical processes related with convection. We note, however, the grid spacing is still too coarse to resolve updrafts that are narrower than several kilometers (Murata et al., 2017; Lean et al., 2008), which suggests higher resolution and more accurate microphysical parameterizations in future. Meanwhile, short-duration high peak intensity events are usually related to mesoscale convective system (MCS) in Eastern China (Luo and Chen, 2015; Luo et al., 2016; He et al., 2017). Whether the better representation of spatial and temporal structure of hourly rainfall of 1.5-km RCM is caused by better representation of MCS also need be further investigated.

Acknowledgments

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Data Availability Statement

The WRF simulation data in this study is publicly available at https://osf.io/nfqt2/files/

References

Arnbjerg-Nielsen, K., Willems, P., Olsson, J., Beecham, S., Pathirana, A., Bülow Gregersen, I., . . . Nguyen, V.-T.-V. (2013), Impacts of climate change on rainfall extremes and urban drainage systems: a review. *Water Science and Technology, 68*(1), 16-28.

Ban, N., Schmidli, J., & Schär, C. (2014), Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. *Journal of Geophysical Research:*

Atmospheres, 119(13), 7889-7907.

Ban, N., Schmidli, J., & Schär, C. (2015), Heavy precipitation in a changing climate: Does short-term summer precipitation increase faster? *Geophysical Research Letters, 42*(4), 1165-1172.

Berthou, S., Rowell, D. P., Kendon, E. J., Roberts, M. J., Stratton, R. A., Crook, J. A., & Wilcox, C. (2019), Improved climatological precipitation characteristics over West Africa at convection-permitting scales. *Climate Dynamics*, *53*, 1991-2011.

Boberg, F., Berg, P., Thejll, P., Gutowski, W. J. , & Christensen, J. H. (2009), Improved confidence in climate change projections of precipitation evaluated using daily statistics from the prudence ensemble. *Climate Dynamics, 32*(7-8), 1097-1106.

Brisson, E., Van Weverberg, K., Demuzere, M., Devis, A., Saeed, S., Stengel, M., & van Lipzig, N. P. (2016), How well can a convection-permitting climate model reproduce decadal statistics of precipitation, temperature and cloud characteristics? *Climate Dynamics*, *47*(9-10), 3043-3061.

Chan, S. C., Kendon, E. J., Fowler, H. J., Blenkinsop, S., Roberts, N. M., & Ferro, C. A. (2014), The value of high-resolution Met Office regional climate models in the simulation of multihourly precipitation extremes. *Journal of Climate*, *27*(16), 6155-6174.

Chang, W., Wang, J., Marohnic, J., Kotamarthi, V. R., & Moyer, E. J. (2018), Diagnosing added value of convection-permitting regional models using precipitation event identification and tracking. *Climate Dynamics*, *55*, 175-192.

Chen, F., & Dudhia, J. (2001), Coupling and advanced land surface-hydrology model with the Penn State-NCAR MM5 modeling system. Part I: model implementation and sensitivity. *Monthly Weather Review, 129*, 569–585

Chen, X., Zhang, F,. Zhao, K. (2016), Diurnal variations of land/sea breeze and its related precipitation over South China. *Journal of the Atmospheric Sciences, 73*(12). https ://doi.org/10.1175/JAS-D-16-0106.1

Donner, L. J., Wyman, B. L., Hemler, R. S., Horowitz, L. W., Ming, Y., Zhao, M., . . . Schwarzkopf, M. D. (2011), The dynamical core, physical parameterizations, and basic simulation characteristics of the atmospheric component AM3 of the GFDL global coupled model CM3. *Journal of Climate*, *24*(13), 3484-3519.

Feser, F., Rockel, B., von Storch, H., Winterfeldt, J., & Zahn, M. (2011), Regional climate models add value to global model data: a review and selected examples. *Bulletin of the American Meteorological Society, 92*(9), 1181-1192.

Fosser, G., Khodayar, S., & Berg, P. (2015), Benefit of convection permitting climate model simulations in the representation of convective precipitation. *Climate Dynamics, 44*(1-2), 45-60.

Fowler, H. J., and M. Ekstrom. (2009), Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *International Journal of Climatology, 29*, 385–416.

He, Z., Zhang, Q., Bai, L., et al. (2016), Characteristics of mesoscale convective systems in centralEast China and their reliance on atmospheric circulation patterns. *International Journal of Climatology, 37*(7), 3276-3290.

Guo, Z., Fang, J., Sun, X., Tang, J., Yang, Y., & Tang, J. (2019a), Decadal long convection-permitting regional climate simulations over eastern China: evaluation of diurnal cycle of precipitation. *Climate Dynamics, 54*(3), 1329-1349.

Guo, Z., Fang, J., Sun, X., Yang, Y., & Tang, J. (2019b), Sensitivity of Summer Precipitation Simulation to Microphysics Parameterization Over Eastern China: Convection-Permitting Regional Climate Simulation. *Journal of Geophysical Research: Atmospheres, 124*(16), 9183-9204.

Helsen, S., van Lipzig, N. P., Demuzere, M., Broucke, S. V., Caluwaerts, S., De Cruz, L., . . . Van Schaeybroeck, B. (2019), Consistent scale-dependency of future increases in hourly extreme precipitation in two convection-permitting climate models. *Climate Dynamics, 54*, 1267-1280.

Hong, S.Y., Dudhia, J., & Chen, S.H. (2004), A revised approach to ice microphysical processes for the bulk parameterization of clouds and precipitation. *Monthly Weather Review, 132*(1), 103-120.

Iacono, M. J., Delamere, J. S., Mlawer, E. J., Shephard, M. W., Clough, S. A., and Collins, W. D. (2008), Radiative forcing by long‐lived greenhouse gases: Calculations with the AER radiative transfer models, *Journal of Geophysical Research Atmospheres, 113*, D13103

Isotta, F. A., Frei, C., Weilguni, V., Perčec Tadić, M., Lassegues, P., Rudolf, B., . . . Ratto, S. M. (2014), The climate of daily precipitation in the Alps: development and analysis of a high-resolution grid dataset from pan-Alpine rain-gauge data. *International Journal of*

Climatology, *34*(5), 1657-1675.

Kain JS. (2004), The Kain–Fritsch convective parameterization: an update. *Journal of Applied Meteorology,* *43*(1), 170–181. https://doi.org/10.1175/1520-0450(2004)043<0170:TKCPAU>2.0.CO;2.

Kendon, E. J., Roberts, N. M., Senior, C. A., & Roberts, M. J. (2012), Realism of rainfall in a very high-resolution regional climate model. *Journal of Climate*, *25*(17), 5791-5806.

Kendon, E. J., Roberts, N. M., Fowler, H. J., Roberts, M. J., Chan, S. C., & Senior, C. A. (2014), Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*, *4*(7), 570.

Kendon, E. J., Stratton, R. A., Tucker, S., Marsham, J. H., Berthou, S., Rowell, D. P., & Senior, C. A. (2019), Enhanced future changes in wet and dry extremes over Africa at convection-permitting scale. *Nature communications*, *10*(1), 1794.

Knist, S., Goergen, K., & Simmer, C. (2018), Evaluation and projected changes of precipitation statistics in convection-permitting WRF climate simulations over Central Europe. *Climate Dynamics*, *55*, 325-341.

Lean, H. W., Clark, P. A., Dixon, M., Roberts, N. M., Fitch, A., Forbes, R., & Halliwell, C. (2008), Characteristics of high-resolution versions of the Met Office Unified Model for forecasting convection over the United Kingdom. *Monthly Weather Review*, *136*(9), 3408-3424.

Lucas-Picher, P., Laprise, R., & Winger, K. (2017), Evidence of added value in North American regional climate model hindcast simulations using ever-increasing horizontal resolutions. *Climate Dynamics*, *48*(7-8), 2611-2633.

Luo, Y., Chen, Y. (2015), Investigation of the predictability andphysical mechanisms of an extreme-rainfall-producing mesoscaleconvective system along the Meiyu front in East China:an ensemble approach. *Journal of Geophysical Research: Atmospheres*, *120*(20), 10593–10618. https ://doi.org/10.1002/2015jd023584

Luo, Y., Wu, M., Ren, F., Li, J., Wong, W. (2016), Synoptic situations ofextreme hourly precipitationover China. *J Climate*, *29*(24), 8703–8719. https ://doi.org/10.1175/jcli-d-16-0057.1

Li, P., Furtado, K., Zhou, T., Chen, H., Li, J., Guo, Z., & Xiao, C. (2018), The diurnal cycle of East Asian summer monsoon precipitation simulated by the Met Office Unified Model at convection-permitting scales. *Climate Dynamics,55*, 131-151.

Murata, A., Sasaki, H., Kawase, H., Nosaka, M. (2017), Evaluation of precipitation over an oceanic region of Japan in convection-permitting regional climate model simulations. *Climate dynamics*, *48*, 1779-1792. https://doi.org/10.1007/s00382-016-3172-x

Prein, A. F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Goergen, K., . . . Feser, F. (2015), A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges. *Reviews of Geophysics*, *53*(2), 323-361.

Qian, T., Zhao, P., Zhang, F., Bao, X. (2015), Rainy-season precipitation over the Sichuan basin and adjacent regions in southwestern China. *Monthly Weather Review, 143*(1), 383–394

Roberts, N. (2007), Meteorological components in forecasts of extreme convective rainfall using 12-km and 1-km NWP models: A tale of two storms. *Met Office Technical Report no. 520.*

Stratton, R. A., Senior, C. A., Vosper, S. B., Folwell, S. S., Boutle, I. A., Earnshaw, P. D., . . . Manners, J. (2018), A pan-African convection-permitting regional climate simulation with the Met Office Unified Model: CP4-Africa. *Journal of Climate*, *31*(9), 3485-3508.

Wang, C. (2013), Using an ultrahigh-resolution regional climate model to predict local climatology. *Quarterly Journal of the Royal Meteorological Society, 139*(677), 1964-1976.

Xiong, Z., & Yan, X. (2013), Building a high-resolution regional climate model for the Heihe River Basin and simulating precipitation over this region. *Chinese Science Bulletin*, *58*(36), 4670-4678.

Yang, Q., Houze Jr, R. A., Leung, L. R., & Feng, Z. (2017), Environments of long-lived mesoscale convective systems over the Central United States in convection permitting climate simulations. *Journal of Geophysical Research: Atmospheres*, *122*(24), 13-288.

Yun, Y., Liu, C., Luo, Y., Liang, X., Huang, L., Chen, F., &Rasmmusen, R. (2019), Convection-permitting regional climate simulation of warm-season precipitation over Eastern China. *Climate Dynamics*, *54*, 1469-1489.

[Journal of Geophysical Research - Atmospheres]

Supporting Information for

[Evaluation of extreme precipitation in the Yangtze River Delta Region of China using a 1.5 km mesh convection-permitting regional climate model]

[Guangtao Dong[1,2], Zhiyu Jiang[3], Ya Wang[4], Zhan Tian[5 *], Junguo Liu[5]]

[[1] Shanghai Climate Center, Shanghai, 200030, China

[2] Key Laboratory of Cities' Mitigation and Adaptation to Climate Change in Shanghai, China Meteorological Administration, Shanghai, 200030, China

[3] School of Atmospheric Sciences, Nanjing University, Nanjing, China, 201400, China

[4] Shanghai Meteorological Disaster Prevention Technology Center, Shanghai, 200030, China

[5] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China]

Contents of this file

Introduction

In order to investigate the reason leading to the overestimation of JJA precipitation by 9-km RCM, we examine the ability of 9-km RCM to reproduce JJA large-scale atmospheric circulations in this Supplementary Material.

Fig. S1 shows the spatial distributions of the ten-year (2005–2014) averaged JJA large-scale atmospheric circulations, including 500 hPa geopotential height, 850 hPa wind field, specific humidity and the moisture flux divergence. As a dominant factor controlling the summer precipitation over the eastern China, the observed western

Pacific subtropical high in boreal summer at 500 hPa dominates the southeastern China (Fig. S1a). However, the WRF lacks the skill for realistically simulating the position and intensity of the western Pacific subtropical high which leads to much of the moisture transport concentrates near Zhejiang province (Fig. S1b). The intensities of 850-hPa wind speed are also overestimated to some extent, which could be responsible for the overestimation of the summer precipitation over the eastern China (Fig. S1d).

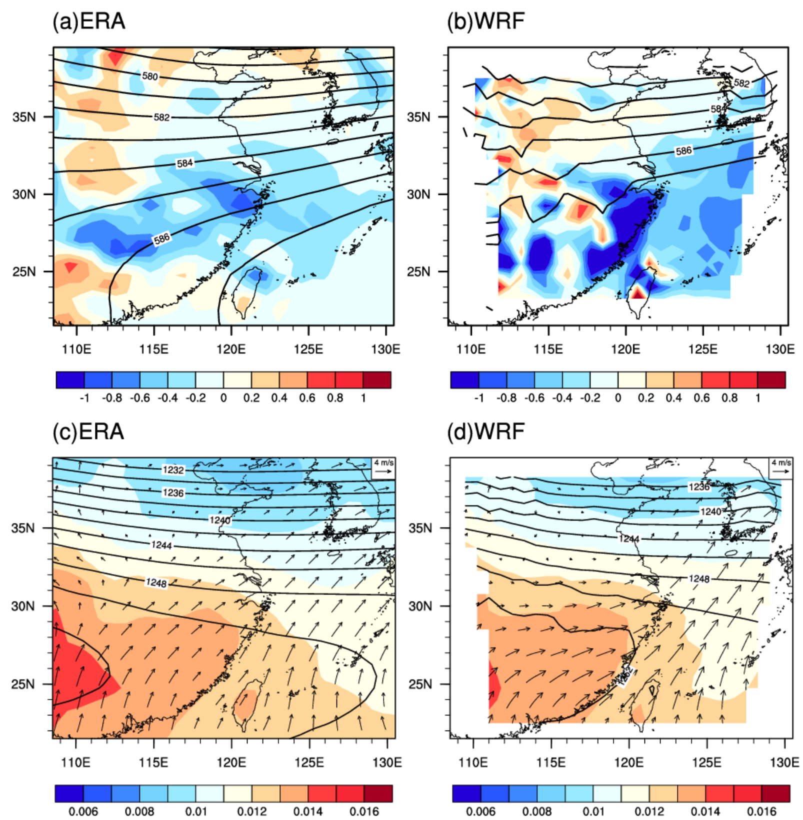

Figure S1. The averaged summer-mean moisture flux divergence (shaded, unit: 10^{-7} g cm^{-2} hPa^{-1} s^{-1}) and 500-hPa geopotential height (contour, unit: dagpm) from (a) ERA-Interim reanalysis data and (b) W9k simulation for the period of 2005-2014, with summer-mean 850-hPa wind filed (vector, unit: m s^{-1}), specific humidity (shaded, unit: kg kg^{-1}) and 200-hPa geopotential height (contour, unit: dagpm) from (c) ERA-Interim reanalysis data and (d) W9k simulation. The spatial correlation of the mean moisture flux divergence between the model simulation and the observation is 0.18, and that of the specific humidity is 0.98. The RMSE of mean moisture flux divergence is 0.59, and that of the specific humidity is 2.6 g/kg..

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[3] School of Atmospheric Sciences, Nanjing University, Nanjing, China, 201400, China

[4] Shanghai meteorological disaster prevention technology center, Shanghai, 200030, China

[5] School of Environmental Science and Engineering, Southern University of Science and Technology, Shenzhen, 518055, China]

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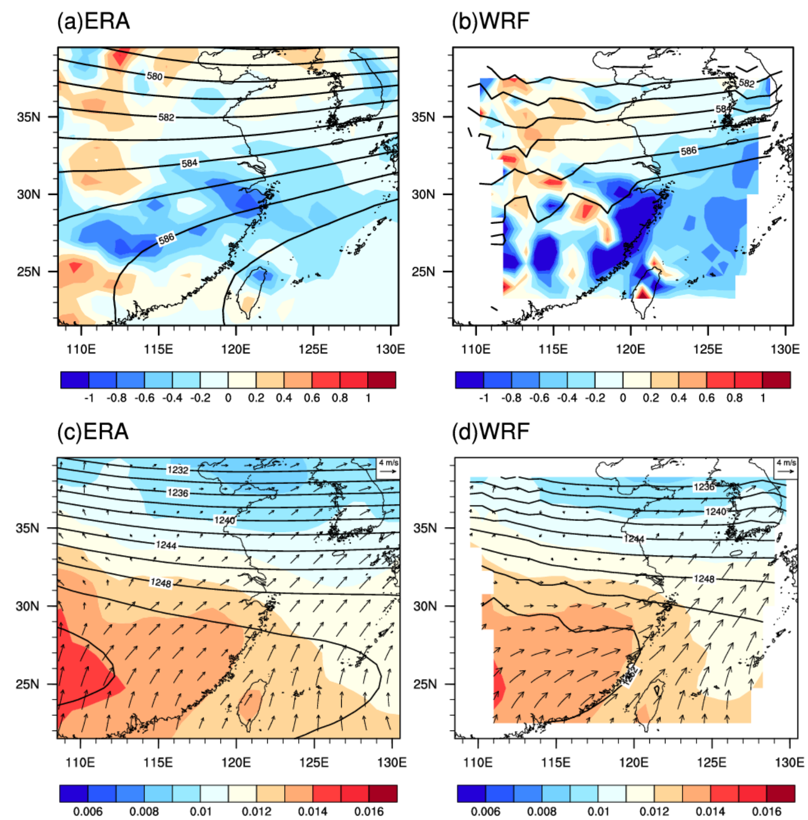

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