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

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Received: 7 March 2021 / Accepted: 13 February 2022 / Published online: 15 March 2022
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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 with 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 h, 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 to 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 observations. Biases of the simulation by the 9-km mesh convection-parameterized model appear to be related to the deficiencies in the representation of convections.

Keywords Convection-permitting model · Extreme precipitation · Regional climate model · Extreme events

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. 2020). 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 km² 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. 2011; 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
Recent 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 represent the convection when simulating the regional climate (Guo et al. 2019). 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. 2019). 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 continues light 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 10 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. 2014). 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. 2020), 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. 2017). The improvement in precipitation characteristics simulated by CPMs is attributed to the fact that the CPMs can generate realistic showers by better representing 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. (2021) simulated precipitation during the warm season (April–September) in China, showing that CPMs can improve the simulated spatial distribution of precipitation in summer. The studies of extreme precipitation indicate the added value of smaller-scale distribution and diurnal cycle by CPMs (Li et al. 2019, 2020a, b). Xiong and Yan (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–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. (2019) with a 6-year warm-season climate simulation, Guo et al. (2019) with a 13-year continuous simulation, and other researchers (Furtado et al. 2018, 2020). 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. 2017; Li et al. 2019, 2020a, b), 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 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 cycle.

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 Sect. 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 Sect. 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 2005–2014 and are used in the analysis. These data were consolidated from the records at 70 automatic weather stations in the Yangtze River Delta region by the National Meteorological Information Center (NMIC) of China Meteorological Administration (CMA). The gauge–satellite merged dataset (AWSC-MORPH; Shen et al. 2014), which is obtained by merging the observations at over 30,000 national and regional automatic weather stations with the above-mentioned NMIC 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 performance of RCM and CPM in terms of simulated rainfall spatial coverage is evaluated by CMORPH hourly precipitation (Fig. 12), other performances are evaluated by site-based rain gauge station datasets.

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) with a 6-hourly update in this study (Fig. 1). In this configuration, deep convection is simulated by Kain-Fritsch convective parameterization scheme (Kain 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 W9k provides lateral boundary conditions to the W1p5k hourly. 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 values of meteorological variables 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 Fig. 1 (see Table 1).

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 Fig. 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 shown in Fig. 2, there are errors in the simulated mean precipitation amount and numbers of wet days and wet hours, compared to observations. Therefore, we focus on assessing simulated extremes and do the corresponding comparison between the two resolutions on the properties of climate variability. 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 10 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.

$$p_{ij} = P\{X = A_i, Y = D_j\}$$

(1)

where

$$p_{ij} \geq 0, \sum_i \sum_j p_{ij} = 1$$

(2)

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 2004) |
| Microphysics         | WSM5  | WSM5 (Hong et al. 2004) |
| Radiation            | Rrtmg | Rrtmg (Iacono et al. 2008) |
| Land surface         | NOAH  | NOAH (Chen and Dudhia 2001) |

Fig. 2 Seasonal cycles of monthly mean a precipitation, b number of wet days and c number of wet hours. Wet days/hours are define as precipitation $\geq 1$ mm day$^{-1}$ or 0.1 mm h$^{-1}$, respectively.
3 Results

In this section, the WRF simulation results are compared with the observations to assess the performance of the CPM (W1p5k) and RCM (W9k).

3.1 The distribution of mean and extreme precipitation

To give a broad picture of precipitation in the study area, Fig. 2 shows the monthly mean precipitation, numbers of 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 them perform 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.

As shown in Fig. 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 mm day$^{-1}$, 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 mm day$^{-1}$. In contrast, the daily precipitation intensity simulated by W9k is about 20% higher than the observations. For hourly precipitation intensity, the simulations 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 (Fig. 7b). 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.

| 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  |
Fig. 3 Biases of the RCM-simulated precipitation intensity compared with the observations on a–f daily and g–l hourly scales
The performances of W9k and W1p5k for simulating precipitation with different intensity thresholds are assessed by analyzing their corresponding frequencies (Fig. 8). W1p5k shows a good representation of the total precipitation hours and light rain hours (Fig. 8a, b) 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\(^{-1}\) (Fig. 8c, f) 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 12:00 (Fig. 9b), and the event with this peak lasts for 3–5 h. This significantly differs from the observations which show that precipitation reaches its peak around 15:00–18:00 and with the durations of 1–3 h. The precipitation diurnal cycle is improved in W1p5k which shows that more intensive precipitation occurs in the afternoon around 12:00–18:00, with the durations of 1–3 h. The observed precipitation generally lasts for no more than 8 h, however the durations of events which start during 0:00–6:00 could last for about 10 h 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.

Previous studies have revealed that the convective precipitation generally lasts for a short time (1–4 h) and tends to be more local (Chan et al. 2014). Thus, the precipitation structure in the study area is further illustrated (Fig. 10). 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 the durations of 2–5 h accounts for nearly 30% of the total precipitation. After that, the proportion decreases with the increase of the...
durations, and tends to be flat for the events longer than 20 h. The maximum precipitation ratio simulated by W9k reaches about 8.5% for the rainfall events with the durations of 4 h, and then the ratio decreases with the increase of the duration. W9k underestimates the precipitation during the events which last less than 3 h. This means that convective

Fig. 5  Biases of the RCM-simulated precipitation amount compared with the observations

Fig. 6  Observed and two RCM simulated frequency distributions of the a daily and b hourly precipitation intensity
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 11 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 at 99.9% or above, the proportion of precipitation events lasting for 4 h 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. Fig. 11d, f). Heavy rain in the 1.5-km RCM is shorter-persistent than in the 9-km RCM, with the probability of rainfall lasting for just one hour being significantly higher for all percentile thresholds ≤ 99.99%, and also with a remarkably lower probability of rainfall lasting 2~5 h for all percentile thresholds ≤ 99.5%. These results indicate that the 1.5-km RCM shows great added value in terms of rainstorm duration characteristics.

3.3 Size of heavy rain cells

To assess the spatial structure, the coverage of rainfall cells exceeding certain intensity thresholds is shown in Fig. 12. Rainfall cell size is the total number of the neighboring rainy grids under one rainfall event. Observations (here is CMORPH) show that heavy precipitation events tend to 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 those rainfall events that exceed 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, Fig. 13a 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 h). W9k produces too few short (1–2 h) medium-intensity (10–20 mm) and high-intensity (>30 mm) events and too many long (2–6 h) 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 (Fig. 13c). 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 h, 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 h.

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 wet days with different convection contributions, which is defined as the ratio of the convective precipitation to the total precipitation. The CF is calculated in W9k at each station, and then the duration and characteristics of
peak intensity are examined at a given range of CF. It should be noted that we are comparing the models on days when the W9k has lots (or little) convection. In the W1p5k, the convection scheme is switched off, so there is no model diagnosis of convection occurrence. However, given the small size of the W1p5k domain, we expect good agreement in the daily meteorological patterns between the W1p5k and the driving W9k, and hence reasonable day-to-day correspondence in the precipitation regime. This assumption is also applied by Kendon et al. (2012).

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 rainfall when CF is high. High-CF days are often associated with more rainfall events with 1–2 h 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 events for high-peak-intensity rainfall. However, longer moderate-intensity precipitation is clearly presented in all the three sets of data (Fig. 14b, d and f). The differences between W1p5k simulation for high CF events and that for middle CF ones in Fig. 14 are similar to the differences between W1p5k and W9k simulations as shown in Fig. 13. 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.

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 1.5 km resolution to produce a 10-year 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-year period of 2005–2014. We
Fig. 14 Differences in the joint probability distribution of rain duration versus peak intensity for different CF ranges. Results are presented in terms of rainfall on high convective fraction (CF ≥ 0.7) days minus rainfall on lower level convective fraction days.
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 also more 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 h) heavy precipitation events, and in a continuous precipitation event precipitation distribution has a significant peak. The short-duration (1–2 h) 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 h) 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 convection parameterization scheme is used for describing the average properties of convections over a grid cell (Kendon et al. 2012), it has a limitation in representing extreme precipitation or concentrated precipitation. 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. 2021; 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 and Yan 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 producing 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 among the first to carry out free running decadal climate simulations over eastern China, with the grid spacing of the model being smaller than 2 KM. And it is also among the first 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 to slightly 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 insufficiently represented overall, and the simulated 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 highlights the needs for 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 the better representation of MCS also needs to be further investigated.

**Supplementary Information** The online version contains supplementary material available at https://doi.org/10.1007/s00382-022-06208-1.
Acknowledgements The authors would like to thank the sponsors of this work: the National Key R&D Program of China (Grant no. 2019YFE0124800), National Natural Science Foundation of China (51761135024 and 41730959), and also Social Development Projects of STCSM (19DZ1201402 and 19DZ1201500). We also thank Dr. Huqiang Zhang from Australia Met office and Prof. Laixiang Sun from Maryland University for their efforts in improving our exposition.

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

Declarations
Conflict of interest The authors declare that they have no conflict of interest.

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