Convection-permitting modelling improves simulated precipitation over the central and eastern Tibetan Plateau

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Abstract
The Tibetan Plateau (TP) plays an essential role in influencing the global climate, and precipitation is one of its most important water-cycle components. However, accurately simulating precipitation over the TP is a long-standing challenge. In this study, a convection-permitting model (CPM; with 4 km grid spacing) that covers the entire TP was conducted and compared to two mesoscale models (MSMs; with model horizontal resolutions of 13 and 35 km) over the course of a summer. The results showed that the two MSMs have notable wet biases over the TP and can overestimate the summer precipitation by more than 4.0 mm day$^{-1}$ in some parts of the Three Rivers Source region. Moreover, both MSMs have more frequent light rainfall; increasing horizontal resolution of the MSMs alone does not reduce the excessive precipitation. Further investigation reveals that the MSMs have a spurious early-afternoon rainfall peak, which can be linked to a strong dependence on convective available potential energy (CAPE) that dominates the wet biases. Herein, we highlight that the sensitivity of CAPE to surface temperatures may cause the MSMs to have a spurious hydrological response to surface warming. Users of climate projections should be aware of this potential model uncertainty when investigating future hydrological changes over the TP. In comparison, the CPM removes the spurious afternoon rainfall and thus significantly reduces the wet bias simulated by the MSMs. In addition, the CPM also better depicts the precipitation frequency and intensity, and is therefore a promising tool for dynamic downscaling over the TP.

KEYWORDS
convection parametrization, convection-permitting model, diurnal cycle, precipitation, Tibetan Plateau
1 | INTRODUCTION

The Tibetan Plateau (TP) is the highest and most extensive highland in the world, and is widely known as “the Roof of the World” and “the World Water Tower” (Qiu, 2008; Xu et al., 2008; Wang et al., 2018; Yao et al., 2019). The thermal and mechanical forces of the TP play an essential role in influencing both local and global atmospheric circulations, especially via the formation of the Asian monsoon system (Hahn and Manabe, 1975; Wu and Zhang, 1998; Immerzeel and Bierkens, 2012; Wu et al., 2012).

Precipitation is one of the most critical components of the water cycle on the TP (Li et al., 2010; Liang et al., 2013; Tong et al., 2014; Li, 2018; Sun and Wang, 2018; Yao et al., 2019; Gao et al., 2020). However, accurately simulating precipitation over the TP remains a long-standing worldwide challenge; current state-of-the-art climate models tend to overestimate precipitation over the TP. The ensemble mean of 18 models participating in Phase 3 of the coupled model intercomparison project (CMIP3) overestimated the precipitation by up to 100.0% over the TP as compared with actual observations (Xu et al., 2010), and almost all of the CMIP5 global climate models (GCMs) continue to significantly overestimate the climatological annual mean precipitation over the TP by 62.0–183.0% (Su et al., 2013). Therefore, improvements in simulating precipitation over the TP between CMIP5 and CMIP3 are negligible (Song and Zhou, 2014; Zhou et al., 2018). Note that this wet bias has been shown to exist in widely used reanalysis datasets (You et al., 2015; Zhang and Li, 2016; Wang et al., 2018).

The wet bias in current numerical models could be a combined outcome of moisture transport issues associated with the model’s dynamical core (such as water vapour advection scheme: Yu et al., 2015; Zhang and Li, 2016), inadequate model physical parametrizations (such as the uncertainties in land surface models: Maussion et al., 2011; Gao et al., 2017), and relatively coarse model resolution in both the horizontal and vertical axes (Maussion et al., 2014; Collier and Immerzeel, 2015; Feng and Zhou, 2015; Li et al., 2015; Lin et al., 2018). Lin et al. (2018) demonstrated that climate models with coarse resolutions cannot adequately resolve the small-scale land–atmosphere interactions over steep terrain regions, thus leading to an unrealistic and excessive water vapour transport through the central Himalayas which results in an overestimation of precipitation over the TP. Previous studies have reported that increasing the model horizontal resolution created a better representation of precipitation over the TP (Feng and Zhou, 2015; Li et al., 2015), including better depictions of surface air temperature and boundary wind fields (Gao et al., 2015; Li et al., 2018), which might result from an improvement in resolving orographic drag with inhomogeneous surface forcing, a better representation of land–atmospheric interactions over complex terrain and a more realistic water vapour transport towards the TP in the high-resolution model (Feng and Zhou, 2015; Li et al., 2018; Lin et al., 2018). However, a notable wet bias still exists over the TP in the aforementioned high-resolution simulations (Feng and Zhou, 2015; Gao et al., 2015; Li et al., 2015).

Due to the rapid development of high-performance computing resources, convection-permitting models (CPMs), which explicitly resolve deep convective clouds and remove the need for convection parametrizations (Liang et al., 2004; Dai, 2006; Prein et al., 2015; Zhang and Chen, 2016), have become important tools for climate research (Ban et al., 2014; 2015; Prein et al., 2015; Clark et al., 2016). CPMs with horizontal-grid spacings of less than 5 km are constructed to partially resolve (rather than parametrize) convective heat and moisture transport, and thereby offer a path towards fundamental advances in our understanding of factors influencing clouds and precipitation (Pritchard et al., 2011; Kooperman et al., 2014; Fosser et al., 2015; 2017; Stevens et al., 2020). Many studies have demonstrated the benefits of using CPMs, including simulating the Madden–Julian Oscillation (Miura et al., 2007; Sato et al., 2009), forecasting severe weather (Schwartz et al., 2009; Zhu et al., 2018; Li et al., 2019), depicting precipitation diurnal cycles over the sub tropics (Ban et al., 2015; Fosser et al., 2015; Guo et al., 2019; Li et al., 2020; Yun et al., 2020), and replicating the spatial distribution of precipitation (Grell et al., 2000; Prein et al., 2013; Rasmussen et al., 2014; Gao et al., 2020) and wind over complex terrain (Schmidl and Rotunno, 2010; Schmidl et al., 2011; Belušič et al., 2018).

In the last decade, regional models at convection-permitting scales have also been used to investigate the TP’s surface processes, convective activities, and the hydrological cycle. Sato et al. (2007) showed that a CPM was better at simulating the diurnal variations of clouds, and was therefore able to develop a better depiction of the thermal forcing within the TP over a month-long simulation with a global cloud resolving model (NICAM). Maussion et al. (2011) demonstrated that a Weather Research and Forecasting model (WRF) with 2 km grid spacing exhibited a small improvement in simulated precipitation in October 2008, compared to that of a WRF with 10 km grid spacing. Meanwhile, over the central Himalayas, several studies revealed that a WRF with 1 km grid spacing has some added value in simulating the surface air temperature and daytime convective precipitation (Collier and Immerzeel, 2015), and better reproduces the regional climate (Karki et al., 2017). Lin et al. (2018) found that the WRF with 2 km grid spacing can better resolve orographic drag as well as mountain–valley circulations.
over complex terrain, and therefore can more accurately depict the transport of water vapour through the central Himalayas. Further, the 2 km simulation diminished the positive precipitation bias over the TP. Wang et al. (2020) demonstrated that a WRF with 3 km grid spacing considerably reduced wet biases over the central Himalayas. Lv et al. (2020) used the WRF to conduct a 2-month simulation to test different model physical configurations over the central TP. They found that the simulated precipitation frequency is dominated by the microphysics scheme and the simulated soil moisture is most sensitive to the land surface model. Further, Gao et al. (2020) used the WRF with 4 km grid spacing to simulate the snow cover for a snow season and found that the CPM was better at simulating the hydrology in high-mountain regions.

Previous CPM simulations over the TP, however, usually have a shorter simulation period, or a relatively smaller simulation domain (such as only focusing on the central Himalayas) due to high computation costs, and as most of the previous findings are based on WRF simulations, they have limited validity for other modelling systems. There is little literature on the added value of a season-long CPM simulation used over the TP compared with mesoscale convection-parametrized models. This study addresses this issue by using a non-WRF based approach across three different resolutions that are convection-parametrized (35 km and 13 km) and convection-permitting (4 km) for the summer of 2009. The second aim of this study is to improve the current understanding of the physical causes of wet biases in mesoscale convection-parametrized simulations and how they may influence the uncertainties in simulating historical and future projections of the TP.

The reminder of the article is organized as follows. Section 2 describes the model and experimental design, observation datasets, and analysis methods. Section 3 presents the main results, including added value of the CPM in reproducing the precipitation characteristics over the TP, the late-afternoon to night rainfall, and the associated large-scale circulations in both observation and model simulations, as well as the possible reasons for explaining excessive precipitation over the TP in the two mesoscale convection-parametrized models (mesoscale models; MSMs). Finally, we present a brief summary and a discussion in Section 4.

2  |  DATA AND METHODOLOGY

2.1  |  Model and experiment design

Three continental-scale regional simulations covering an entire warm season from 1 April to 30 September 2009 (with a background of a neutral sea-surface temperature over the tropical Pacific Ocean), were conducted using regional configurations of the Met Office Unified Model (MetUM: Cullen, 1993; Brown et al., 2012), which is based on the high-resolution configurations developed by Lean et al. (2008) and has been described in detail in Pearson et al. (2014). Two MSMs with grid spacings of 0.12° (~13.0 km; MSM-13) and 0.32° (~35.0 km; MSM-35), and a CPM with grid spacing of 0.04° (~4.0 km; CPM) were used. All three simulations have identical simulation domains (17.0°–44.5°N, 70.0°–138.5°E) and cover most of the East Asian Summer Monsoon (EASM) region.

Each model has been initialized from the European Centre for Medium-Range Weather Forecasts (ECMWF) operational analysis (Dee et al., 2011) for 31 March 2009. Wherein, the lateral boundary conditions (LBCs; one way nested) are provided hourly from a global-model simulation with the Met Office Unified Model Global Atmosphere 6.1 (GA6.1: Walters et al., 2017). This global model run is reinitialized on a 6 hr forecast cycle from the ECMWF analysis, providing a convenient way of deriving LBCs between analyses by using a physical model rather than relying on unphysical interpolation in time. The regional model is completely free-running for the 6-month simulation period without any re-initialization required from the analyses. Therefore, the meteorological conditions within the regional model are determined purely by the model’s response to the hourly LBCs.

The land surface model is a configuration of the Joint UK Land Environment Simulator (JULES: Best et al., 2011) that was used in the operational configuration of the Met Office’s convection-permitting UK weather forecast model at the time of running. Soil moisture evolves dynamically on four vertical subterranean levels, and at the land-surface snowpack can accumulate, evaporate and melt within all land-use types defined by JULES (except under the canopies of broadleaf trees). The amount of snow on the ground during the study period is minimal. The ancillary data used for the static land-surface properties are as described in Walters et al. (2017), and the initialized land-surface properties (soil moisture, temperature, and snow-pack depth) are initialized from the same ECMWF analysis as the meteorological fields.

On a subgrid-scale, a non-local mixing scheme is used for the unstable boundary layers of Lock et al. (2000) with some modifications (Boutle et al., 2014; Pearson et al., 2014) involving the grid-box size dependence to make the scheme more applicable to the intermediate “grey-zone”. The cloud microphysics is a mixed-phase scheme that includes four species: cloud, rain, snow and graupel, and is based on the single-moment scheme developed by Wilson and Ballard (1999) with subsequent
extensive modifications by Boutle et al. (2014), Furtado et al. (2015), and Wilkinson (2017).

The most significant difference between the CPM and MSM is the treatment of deep convection. The dynamical core is non-hydrostatic at all resolutions; therefore, if the resolution is high enough, it will partially resolve the vertical motions associated with cumulonimbus clouds (Walters et al., 2017). In the MSMs, the deep convection scheme is based on the Gregory and Rowntree (1990) scheme with a stability-dependent (convective available potential energy; CAPE) closure and a relaxation time-scale of 30 min. Meanwhile, in the CPM simulation, the closure time-scale of the deep convection is increased for high CAPE, therefore the deep convection scheme is effectively switched off (Lean et al., 2008; Birch et al., 2014; Pearson et al., 2014), and the CPM can run with “explicit” deep convection. The simulation cost of the CPM was approximately 350,000 node hours. The CPM simulation took approximately 3 weeks to complete (including queuing time) on 288 nodes on the Met Office’s supercomputer Cray XC40.

The overall configurations of the three simulations are summarized in Table 1 and more details can be found in Pearson et al. (2014) and Li et al. (2020). In this study, the first month is treated as a spin-up period and only the output of the boreal summer monsoon season (June–July–August; JJA) is analysed.

2.2 Observation data and reanalysis datasets

We use the following network of in situ measurements and two observationally based gridded precipitation products to reveal the observed precipitation characteristics over the TP:

1. Surface hourly rain-gauge data from 2,420 stations that were developed by the National Meteorological Information Center (NMIC) of the China Meteorological Administration (CMA). The precipitation measurements in each tipping-bucket rain-gauge instrument were automatically collected by computers and were already under quality control by the NMIC (Zhang et al., 2016). We used the quality-controlled surface hourly rain-gauge data to reveal the observational precipitation characteristics, as well as their diurnal cycle.

2. The density of the rain-gauge stations is relatively sparse over the TP. Specifically, there are 40 rain-gauge stations over the central and eastern TP (which is also commonly referred to as the Three Rivers Source region; Figure 1), and most in situ rain-gauge stations are located in valleys (Li, 2018; Ou et al., 2020). In order to better understand the observed spatial distributions of precipitation characteristics, as well as their diurnal cycle, we used a merged rain-gauge–satellite gridded hourly precipitation dataset for China with the horizontal resolution of 0.1° (Shen et al., 2014) that was developed by the NMIC. This product was created with the probability density function optimal interpolation (PDF-OI) merging method, in which 30,000 hourly surface rainfall measurements from CMA’s rain-gauge network are combined with the Climate Prediction Center’s morphing technique (CMORPH: Joyce et al., 2004) precipitation product. The CMORPH satellite-based precipitation estimates are first corrected for bias by matching their PDF with those of the surface hourly rain-gauge product (Yu et al., 2013). Then the bias-corrected CMORPH precipitation estimates are merged with the rain-gauge records to create a new merged precipitation product using the OI method (Shen et al., 2014). The new merged precipitation dataset effectively reduces the systematic bias (with an overestimation of weak precipitation but an underestimation of heavy precipitation) in the original CMORPH precipitation estimates over China (Shen et al., 2014).

3. A gridded quality-controlled daily precipitation dataset over China with the horizontal resolution of 0.25° (CN05.1: Wu and Gao, 2013) was also used. The CN05.1 dataset is based on the “anomaly approach” interpolation method (New et al., 2000) from more than 2,400 rain-gauge stations across China. The climatology from the rain-gauge stations is first interpolated using the thin-plate smoothing splines method. Then, a 0.25°×0.25° gridded daily anomaly derived from the angular distance weighting approach is added to the aforementioned climatology, which forms the final dataset. Wu and Gao (2013) emphasized that users should be aware of potential uncertainties when investigating precipitation over largely uninhabited areas (such as the western and northwestern parts of the TP, as well as some parts of northwestern China). Herein, we used CN05.1 to reveal the spatial distribution of summer precipitation over the TP. The differences between the CN05.1 and the merged rain-gauge–satellite precipitation product in representing summer mean precipitation over the TP were taken to indicate the uncertainties among different observations.

Previous studies (Sun and Wang, 2018; 2019) showed that the results regarding precipitation variability over the Three Rivers Source (TRS) region (31.5°–36.5°N, 89.5°–102.5°E, the red dash rectangle indicated in Figure 1) of the CN05.1 are consistent with the results
TABLE 1 Model description of mesoscale convection-parametrized model (MSM) and convection-permitting model (CPM)

|                      | MSM                                      | CPM                                      |
|----------------------|------------------------------------------|------------------------------------------|
| Simulation domain    | 17.0° ~ 44.5°N, 70.0° ~ 138.5°E; the same as that described in Li et al. (2020) |                                           |
| Rotated pole system  | Lat0: 57.54°, Lon0: 284.22°; Arakawa C staggering |                                           |
| Vertical coordinate  | Terrain-height hybrid coordinate (Davies et al., 2005) |                                           |
| Horizontal resolution| 0.12° (~13.0 km) 0.32° (~35.0 km) 0.04° (~4.0 km) |                                           |
| Model dynamics time step | 60s                                      | 20s                                      |
| Deep convection scheme | Gregory and Rowntree (1990)             | Explicit                                 |
| Shallow convection scheme | Similar to the Gregory–Rowntree Scheme, but with some modifications following Grant (2001) |                                           |
| Microphysics scheme  | Based on the mixed-phase cloud microphysics (Wilson and Ballard, 1999) |                                           |
| Sea-surface temperature | OSTIA (Donlon et al., 2012)           |                                           |

FIGURE 1 Surface elevation (shaded; unit: m) and location (blue dots) of national rain-gauge stations over the Tibetan Plateau and its surrounding regions. The dashed blue rectangle (28.0°–39.75°N, 80.25°–103.0°E) indicates the region over which pattern correlation coefficients (PCCs) and root mean square errors (RMSEs) are computed across the three simulations. The dashed red rectangle (31.5°–36.5°N, 89.5°–102.5°E) indicates the Three Rivers Source (TRS) region. The small blue (big red) dots indicate the location of national rain-gauge stations (which are located in the TRS region). The blue lines indicate the Yellow River (top), the Yangtze River (middle) and the Lancang River (bottom).

of the rain-gauge stations, the Global Precipitation Climatology Project (GPCP), and the Climatic Research Unit (CRU) data. Here the definition of the TRS region is the same as that described in Sun and Wang (2018; 2019). The TRS region (also named “Sanjiangyuan” in China) is located in the central and eastern TP. The TRS region has a unique ecosystem and is widely considered to be the key region over the TP because it is the headwater area where the Yellow River, the Yangtze River, and the Lancang River originate (Sun and Wang, 2018; 2019).

We used surface pressure, zonal wind, meridional wind, omega, air temperature and specific humidity derived from the ERA5 reanalysis dataset for summer 2009 to reveal the diurnal variations of atmospheric circulations over the TP. ERA5 is the fifth generation of the ECMWF atmospheric reanalysis of the global climate, which was developed through the Copernicus Climate Change Service (http://climate.copernicus.eu/products/climate-reanalysis). The ERA5 dataset was produced using 4D-Var data assimilation in CY41R2 of ECMWF’s Integrated Forecast System (IFS), with 137 hybrid (sigma/pressure) model levels in the vertical (top level at 0.01 hPa). The released ERA5 data cover the period from 1979 to near real time. In this study, we used the ERA5 high-resolution realization dataset, which has a horizontal resolution of 31 km and a 1 hr time interval.
FIGURE 2  Spatial distributions of summer (June to August) precipitation in 2009 among different observations and model simulations (unit: mm·day\(^{-1}\)) over the Tibetan Plateau: (a) rain-gauge observation; (b) CMORPH merged with rain-gauge observation; (c) CN05.1 observation; (d) convection-permitting model (CPM) simulations; (e) 13.0 km mesoscale convection-parametrized model (MSM-13) simulations; (f) MSM-35 simulations. The red dash rectangle (31.5\(^\circ\)–36.5\(^\circ\)N, 89.5\(^\circ\)–102.5\(^\circ\)E) indicates the TRS region. The black contour indicates the main body of the Tibetan Plateau, where the topography exceeds 2,800 m.

2.3 Analysis methods

In this study, we focus on the performance of the MSMs and CPM regarding JJA precipitation over the TP. Following previous studies (Dai et al., 1999; Chen and Dai, 2018), precipitation frequency is defined as the percentage of total hours in the summer with measurable precipitation (≥0.1 mm·hr\(^{-1}\)), and precipitation intensity is defined as the average precipitation rate over the precipitating hours. The estimated precipitation frequency and intensity highly depend on the horizontal data resolution (Chen and Dai, 2018). Chen and Dai (2018) also highlighted that different products should have similar horizontal resolution when making a direct comparison. Therefore, to minimize the effects of different data resolutions, we first average the station data onto the observational grid (0.10\(^\circ\) grid; the grid of the merged rain-gauge–satellite product), then mask out the grid cells which do not contain rain-gauge stations to produce a gridded dataset. We also convert the CPM data (0.04\(^\circ\)), MSM-13 data (0.12\(^\circ\)) and MSM-35 data (0.32\(^\circ\)) onto the observational grid by using the local area-conservative binning method. Then, we calculate precipitation characteristics (precipitation frequency and intensity) and make all quantitative comparisons between observation and simulations. Similar analysis methods and their details can be found in Chen and Dai (2018) and Li et al. (2020). For visual clarity, we use a scatter plot to display the results from the rain-gauge stations (Figure 2, Figures 4 and 5).

To reveal the relationship between large-scale atmospheric circulation diurnal variations and the diurnal cycle of precipitation over the TP, we calculate the convergence...
of the vertically integrated water vapour transport flux in both the ERA5 reanalysis and model simulations based on the following equation:

\[
- \nabla \cdot < q \mathbf{V} > = \frac{1}{g} \nabla \cdot \int_{p_s}^{p_f} q \mathbf{V} \, dp,
\]

where \( - \nabla \cdot < q \mathbf{V} > \) is the convergence of the vertically integrated moisture flux, “\(<\)” denotes a vertical mass integration through the whole troposphere, from surface to tropopause, \( \mathbf{V} \) is the differential operator, \( g \) denotes gravitationa l acceleration, \( p_f \) is the pressure of the tropopause (taken as 100 hPa), \( p_s \) is the surface pressure, \( q \) is specific humidity, and \( \mathbf{V} \) is the wind vector.

To investigate the possible reasons for the excessive precipitation reported in the MSMs, we analyse the relationship between atmospheric instability (CAPE) and precipitation in simulations and observations over the TRS region. The CAPE is defined as the accumulated buoyant energy from the level of free convection (LFC) to the equilibrium level (EL):

\[
\text{CAPE} = g \int_{\text{LFC}}^{\text{EL}} \left( \theta(z) - \bar{\theta}(z) \right) dz,
\]

where \( \theta(z) \) is the potential temperature of the parcel as it ascends moist adiabatically, and \( \bar{\theta}(z) \) is the potential temperature of the environment \( (\text{Rose et al., 2002}) \). The Gregory–Rowntree deep convection scheme used in the MSMs assumes CAPE closure, while a convectively unstable atmosphere is expected if a higher CAPE occurs.

In addition, the convection triggering procedure in the Gregory and Rowntree (1990) scheme is simply related to the instability of the lowest convective layers by the empirical equation \( (\text{equation 3 in Gregory and Rowntree, 1990}) \). Hence, local-parcel buoyancy is the only criterion determining the development of convection. This is in contrast to schemes that assume a quasi-equilibrium between convection and large-scale forcing \( (\text{e.g. the Arakawa–Schubert scheme and its descendants: Arakawa, 2004}) \). In these aforementioned convection schemes, “if no large-scale forcing is present to destabilize the thermodynamic profile, however, then no convection occurs even though a parcel ascent may be buoyant” \( (\text{Gregory and Rowntree, 1990}) \). According to the Gregor y and Rowntree (1990) convection scheme. This kind of closure hypothesis used in the Gregory–Rowntree convection scheme is a realistic model of convection over tropical oceans; however, convection over subtropical land is often influenced by a range of other factors \( (\text{e.g. large-scale convergence}) \).

Before comparing the results of the three regional simulations with the ERA5 reanalysis, the simulated atmospheric variables, including surface pressure, zonal and meridional wind, omega, specific humidity and air temperature, are converted onto the same grid as the ERA5 reanalysis \( (0.30^\circ \text{grid}) \). In this study, we use local solar time \( (\text{LST}) \) to investigate the diurnal cycle of precipitation characteristics and associated large-scale circulation.

3 RESULTS

3.1 Added value of CPM in reproducing precipitation characteristics over the TP

Generally, the three observational precipitation datasets agree with each other regarding the spatial distributions of precipitation over the TP \( (\text{Figure 2a–c}) \). Summer precipitation decreases from the southeastern flank of the TP \( (8.0–9.0 \text{ mm day}^{-1}) \) to the central western part of the TP \( (\text{Qiangtang Plateau; less than 1.0 mm day}^{-1}) \). Note that there are also some uncertainties exhibited among different observations. The spatial pattern of precipitation in CN05.1 is smoother compared with those in the merged rain-gauge–satellite product \( (\text{Figure 2b,c}) \). Meanwhile, over the western and northwestern parts of the TP, the accumulated precipitation amount is extremely low \( (\text{below 1.0 mm day}^{-1}) \) in the surface hourly rain-gauge product and merged rain-gauge–satellite product \( (\text{Figure 2a,b}) \), and there are few rain-gauge stations in these uninhabited areas. In CN05.1, however, there is some precipitation \( (1.0–3.0 \text{ mm day}^{-1}) \) because the precipitation in this area is interpolated from the values of the surrounding rain-gauge stations \( (\text{Figure 2c}) \). Over the TRS region, CN05.1 is 0.5–1.5 mm day\(^{-1}\) wetter than the merged rain-gauge–satellite product \( (\text{Figure 2b,c}) \).

Next, we evaluate the performance of each simulation based on its ability to reproduce summer precipitation characteristics over the TP. Overall, both MSMs and the CPM are able to simulate the spatial distribution of summer precipitation \( (\text{Figure 2d–f}) \). Compared with the merged rain-gauge–satellite product \( (\text{CN05.1}) \), the CPM, MSM-13 and MSM-35 have pattern correlation coefficients \( (\text{PCCs}) \) of 0.72 \( (0.69) \), 0.65 \( (0.65) \) and 0.64 \( (0.63) \), and root mean square errors \( (\text{RMSEs}) \) of 2.70 \( (2.50) \), 3.76 \( (3.23) \) and 3.95 \( (3.46) \) mm day\(^{-1}\) respectively, over the main body of the TP \( (28.0^\circ–39.75^\circ \text{N}, 80.25^\circ–103.0^\circ \text{E}) \), which is indicated by the dashed blue lines in Figure 1). Note that the two observations we used here, as well as the three model simulations, were converted onto the same observational grid \( (0.10^\circ) \), before we calculated the PCC and RMSE of each simulation. Therefore, the CPM has the highest PCCs and
the lowest RMSEs compared with the observed summer precipitation over the TP (Figure 2d).

Then, we check the difference in spatial distribution of summer precipitation between the observations and model simulations (Figure 3). Here, we consider a mean of the merged rain-gauge–satellite product and CN05.1 as the observation, using the results to evaluate model performance. CN05.1 is found to be wetter than the merged rain-gauge–satellite product with differences (between CN05.1 and the “mean observation”) larger than 1.0 mm day$^{-1}$ occurring over the TRS region (Figure 3a). Further, a wet bias over the TP is shown in the two MSMs (Figures 2e,f and 3c,d). Both MSMs overestimate the summer precipitation over the main body of the TP, including the eastern Himalayas and the TRS region. In particular, they overestimate the regional mean summer precipitation by 2.72 (1.70) mm day$^{-1}$ and 2.67 (1.65) mm day$^{-1}$, respectively, compared with the merged rain-gauge–satellite product (CN05.1) over the TRS region. This excessive simulated precipitation can exceed 4.0 mm day$^{-1}$ in some parts of the TRS region (Figure 3c,d). Increasing the MSM horizontal resolution from 35 to 13 km can reduce the excessive precipitation over the eastern Himalayas. This improvement might result from a more realistic simulated water vapour transport towards the TP as the model’s horizontal resolution increases, which is concurrent to the findings of a previous study (Lin et al., 2018). However, the wet bias over the TRS region remains in these two high-resolution regional simulations (Figure 3c,d). In comparison, the CPM significantly reduces the wet bias simulated by the MSMs (Figure 3b). For instance, it overestimates the regional mean precipitation by only 1.32 (0.11) mm day$^{-1}$ over the TRS region. Although the CPM is better at reproducing summer precipitation over the TRS region, it has some notable model biases over the TP, including overestimating the precipitation over the eastern Himalayas, and the continued wet bias at higher altitudes over the southeastern flank of the TP (an overestimation of the precipitation can exceed 5.0 mm day$^{-1}$ in some parts of this region; Figure 3b).

The performance in simulating the summer precipitation frequency and intensity over the TP is shown in Figure 4, wherein the two different types of observational datasets exhibit similar spatial distributions of the precipitation frequency and intensity over the TP, although the rain-gauge stations have a relatively larger precipitation frequency (Figure 4a) and stronger precipitation intensity (Figure 4e) compared with the merged rain-gauge–satellite product (Figure 4b,f). The observed precipitation frequency (Figure 4a,b) has a similar spatial pattern compared with the observed precipitation amount (Figure 2a,b). The precipitation intensity over the TP is weaker (Figure 4f,g) compared with that in the surrounding regions (e.g. Sichuan valley, located in the eastern periphery of the TP). MSM-13 and MSM-35 overestimate the precipitation frequency, especially in the eastern Himalayas and the TRS region (Figure 4d,e), but they underestimate the precipitation intensity (Figure 4i,j). Therefore, the MSMs have considerably more frequent light rainfall over the TP than the observations. Although increasing the MSM horizontal resolution from 35 to 13 km results in a better simulation of precipitation frequency and intensity, the MSM-13 still overestimates the frequency (Figure 4d) and underestimates the intensity (Figure 4i). In comparison, the CPM reasonably reproduces the observed precipitation characteristics over the TP (Figure 4c,h), it better simulates the precipitation intensity over the TP (Figure 4h), but it also overestimates the precipitation frequency over the eastern Himalayas and the southeastern flank of the TP (Figure 4c). The precipitation frequency can exceed 40.0% at higher altitudes over the southeastern flank of the TP; too frequent convection in the CPM (Figure 4c) results in a wet bias over higher altitudes over this complex terrain region (Figure 3b).

3.2 Late-afternoon to night summertime rainfall over the TP and associated large-scale circulations

Previous studies have documented that precipitation over the TP mainly exhibits two late-afternoon and midnight diurnal peaks (Yu et al., 2014; Li, 2018). To evaluate this, we examine the diurnal variation of summertime precipitation in both the observations and model simulations (Figure 5).

Regarding observations, summer rainfall over the TP frequently occurs in the afternoon to evening (Figure 5b,c); specifically, precipitation over the TRS region is inhibited from early morning (0600 LST) to noon (1200 LST), then begin to develop and peaks around late afternoon (1800 LST) to night-time (2000 LST; Figure 5a). Both the MSMs and CPM could successfully reproduce the late-afternoon to night rainfall over the TRS region, although the amplitude was underestimated (Figure 5a). However, the MSMs (indicated by the orange and light-blue lines in Figure 5a) showed a spurious afternoon rainfall peak (at approximately 1400 LST) that inhibited their ability to accurately simulate the phase and magnitude of the precipitation diurnal variations (Figure 5a). Conversely, the CPM (indicated by the red line) effectively reduced the spurious afternoon rainfall peak, and better reproduced the diurnal variation of precipitation (Figure 5a).

The diurnal variations of monsoonal flow (including the sea–land breeze, surface wind, boundary-layer flow and low-level jet) are the key factors that influence
FIGURE 3  Difference between observations and model simulations over the Tibetan Plateau and its surrounding regions (unit: mm·day⁻¹): (a) difference between CN05.1 and a mean of CN05.1 and CMORPH merged with rain-gauge product (the mean value of both product is also considered as the “observation”), and the differences between the observation and (b) the CPM simulation, (c) the MSM-13 simulation, and (d) the MSM-35 simulation. Here the red dash rectangle indicates the TRS region.

The diurnal cycle of precipitation over the EASM region (Chen et al., 2009; Yu et al., 2014). We further investigate the diurnal variations of atmospheric circulations over the TRS region in the ERA5 reanalysis and model simulations (Figure 6). The horizontal wind field in the mid-troposphere (500 hPa; near the boundary layer from the surface) exhibits a clear inertial oscillation (Figure 6), due to the combined influence of the diurnal variations of the boundary-layer friction and the surface thermal forcing (Du et al., 2014; 2015a; 2015b). In the ERA5 reanalysis (black line), the zonal wind (at 500 hPa) over the TRS region remains positive throughout the day, indicating that the TP is under prevailing westerly winds in the mid-troposphere. The zonal wind peaks to a maximum in the early morning (0600–0800 LST) and reaches a minimum in the evening (2100–2200 LST). Compared with the ERA5, the CPM (red line) has a stronger zonal wind, while both the MSMs (light-blue and orange lines) have weaker zonal winds and exhibit negative values (i.e. easterly wind) in the evening. Li et al. (2018) demonstrated that the land surface model and momentum transport in the boundary-layer scheme have impacts on the simulated near-surface wind and result in an overestimation of the zonal wind in their WRF simulation. In our analysis, the main difference of the horizontal wind field in the mid-troposphere (500 hPa) between ERA5 and model simulations is also the strength of the zonal wind. Previous studies have documented that the land surface processes are essential for modulating the near-surface wind speed over the TP (Li et al., 2018; Lin et al., 2018; Fu et al., 2020). The mechanisms for explaining the difference of near-surface winds between the CPM and MSMs regarding land–atmosphere interactions and boundary-layer processes warrant further study.

The regional-averaged meridional wind achieves a maximum at midnight (0200 LST), before it gradually weakens and changes direction from southerly to northerly at approximately 1400 LST (Figures 6 and 7a). Note that the zonal wind over the TRS region also gradually weakens during that time (Figure 6). More importantly, the diurnal variation of the horizontal wind field is highly consistent with the diurnal cycle of upward motion. The convergence of the horizontal-wind field in the mid-troposphere from 1400 LST to 2000 LST is beneficial to the development of ascending motion, which strengthens and reaches a maximum between late afternoon and early evening (1600–1900 LST; Figure 7b). Meanwhile, the convergence of the integrated water-vapour transport provides a moisture source for convection and precipitation (Figure 7c). Therefore, the precipitation over
FIGURE 4  Spatial distributions of summer (June, July, August) precipitation frequency (a–e; unit: %) and precipitation intensity (f–j; unit: mm·hr$^{-1}$) in 2009 among different observations and model simulations over the Tibetan Plateau: (a,f) rain-gauge observations; (b,g) CMORPH merged with rain-gauge observations; (c,h) the CPM simulations; (d,i) the MSM-13 simulations; and (e,j) the MSM-35 simulations

the TRS region exhibits a late-afternoon to night-time maximum (Figure 5a).

Overall, both the MSMs and CPM can simulate the inertial oscillation of mid-level horizontal winds (Figure 6), the diurnal variations of the upward motion (Figure 7b), and the associated convergence of integrated water-vapour transport (Figure 7c). Accordingly, both the MSMs and CPM can simulate the late-afternoon to night precipitation over the TRS region (Figure 5a). However, there are also some notable differences between the simulations and observations. For instance, the MSMs have stronger cyclonic circulations during late afternoon to
night-time (1800–2400 LST; Figure 8e–h) over the TP, and an enhanced convergence of integrated water vapour transport (Figure 7c) in the late afternoon, which provides favorable conditions for convection and precipitation, therefore causing larger late-afternoon to night precipitation (Figure 8e–h). Although convergence of the water vapour transport in the CPM is closer to that of the ERA5 (Figure 7c), there is larger precipitation associated with stronger cyclonic circulations over the northern part of the TRS region during late afternoon to night-time in the CPM (Figure 8f).

3.3 Possible reasons for excessive precipitation over the TP in MSMs

As previously mentioned, although the MSMs could reproduce the late-afternoon to evening precipitation over the TRS region (but overestimate the magnitude of precipitation), they also have a spurious afternoon rainfall peak (Figure 5a). In addition, after increasing the MSM horizontal resolution from 35.0 to 13.0 km, the false simulated afternoon rainfall peak still existed in the MetUM (Figure 5a).

To investigate the reason for this phenomenon, we further sort the total precipitation into convective and large-scale stratiform precipitation (Figure 9). We found that convective precipitation produced by the deep-convection scheme contributes most of the total precipitation and dominates the diurnal cycle in the MSMs (Figure 9). As the local-parcel buoyancy is the only factor that determines the triggering of convection in the Gregory–Rowntree scheme, the convective precipitation in the MSMs is initiated too early and starts to increase after sunrise (approximately 0700 LST) as well as peaks in the afternoon (1300–1400 LST; Figure 9), without...
The presence of large-scale convergence in the morning (Figure 8a,c,d). Therefore, the spurious and excessive afternoon convective precipitation induced by the deep convection scheme (Figure 9) plays a major role in inducing the wet bias in the two MSMs (Figures 3c,d and 8c,d).

Previous studies indicated that the Gregory–Rowntree scheme used in the MetUM responds to the local instability and is unable to organize convection into the evening over a region of the United Kingdom (Roberts and Lean, 2008; Kendon et al., 2012; Clark et al., 2016). Therefore, we investigated the relationship between precipitation and atmospheric instability over the TRS region in the observations and model simulations (Figure 10). The diurnal variations of CAPE are shown in Figure 10a, wherein we see that instability over the TRS region is enhanced after sunrise (0700–0800 LST), and both the MSMs and CPM can capture the diurnal variations of CAPE (Figure 10a), but the simulated precipitation in different models (convection-permitting vs. convection-parametrized) exhibits a distinct response to the increased CAPE (Figure 10c–e).

Over the TRS region, the observed precipitation from approximately noon to afternoon (1100–1600 LST) is not obviously correlated with CAPE (Figure 10b). This relationship could only be simulated by the model when deep convection is explicitly resolved (Figure 10c). In comparison, both MSMs inaccurately simulated a positive correlation between CAPE and precipitation (Figure 10d,e). The convection is triggered too frequently in the MSMs, there is considerable light precipitation (lower than 2.0 mm hr$^{-1}$) during morning to noon time (from 0800 to 1400 LST) over the TRS region (Figure 11a,c), as a response to the increased CAPE (Figure 10a). Conversely, the early onset of convection (produced by the deep convection scheme) in the MSMs may act to release local instability, thus preventing CAPE from accumulating in the morning.
FIGURE 8  The spatial distribution of early-morning to noon (from 0600 to 1400 LST; a–d) and late-afternoon to night (from 1800 LST to 2400 LST; e–h) precipitation (unit: mm-day\(^{-1}\)) and horizontal wind field (unit: m\(\cdot\)s\(^{-1}\)) at 500 hPa over the Tibetan Plateau and its surrounding regions: (a,e) CMORPH merged with rain-gauge observations and ERA5 reanalysis datasets; (b,f) CPM simulations; (c,g) MSM-13 simulations; and (d,h) MSM-35 simulations. The black solid rectangle indicates the TRS region.

to early afternoon based on the findings in previous studies (Brockhaus et al., 2008; Ban et al., 2014). In our analysis, the CAPE from morning to afternoon (0800–1700 LST) in the two MSMs is also lower than that of the ERA5 and CPM (Figure 9a).

Therefore, the wet biases in the MSMs over the TRS region are the results of: (a) overestimating the magnitude of late-afternoon to night precipitation due to a stronger cyclonic circulation (Figure 8e,g,h), associated with an overestimation of convergence of the integrated water vapour transport (Figure 7c), and (b) more importantly, the early onset of convective precipitation in response to the increased CAPE after sunrise and the spurious afternoon precipitation (Figures 5a, 8c,d, 9, 10d,e and 11a,c), which is traced to a strong dependence on CAPE in the Gregory and Rowntree scheme, lead to significant wet biases in the MSMs (Figure 8c,d). The latter dominates the wet biases in the two MSMs.
Conversely, the CPM provides a better simulation of the diurnal variations of CAPE (Figure 10a), is better at depicting the relationship between CAPE and precipitation (Figure 10c), and produces a more realistic precipitation “frequency–intensity” structure compared with both merged rain-gauge–satellite product and hourly rain-gauge stations during morning to noon time (0800–1400 LST; Figure 11a,c). Therefore, the CPM significantly reduces the spurious afternoon precipitation simulated by the MSMs (Figure 9) and gives a better representation of the precipitation over the TRS and its surrounding regions (Figures 2d and 3b). But it should be noted that there still exhibits a notable wet bias at higher altitudes over the southeastern flank in the CPM simulation.

4 | CONCLUSIONS AND DISCUSSION

4.1 | Conclusions

The overestimation of summer precipitation over the TP is a long-standing challenge for most climate models. In this study, two continental-scale MSMs and a CPM covering an entire warm season were compared to evaluate their ability to simulate summer precipitation over the TP. We investigated the added value of the CPM in simulating precipitation characteristics and addressed the possible reasons for the excessive precipitation in the MSMs over the TP.
FIGURE 10 (a) Diurnal variations of convective available potential energy (CAPE; unit: J·kg\(^{-1}\)) averaged over the TRS region among ERA5 reanalysis and simulations. Relationship between noon-to-afternoon (1100 to 1600 LST) hourly precipitation and CAPE averaged over the TRS region among (b) observation and ERA5 reanalysis, (c) the CPM, (d) the MSM-13, and (e) the MSM-35 simulation.

4.2 Discussion

Many state-of-the-art climate models use deep convection schemes, which are based on similar principles to the models used in this study. Such parametrizations are widely regarded as a large source of uncertainty in precipitation simulation (Liang et al., 2004; Dai, 2006; Stevens and Bony, 2013; Zhang and Chen, 2016). Previous studies using the MSM configuration have shown biases in reproducing the diurnal cycle of summer precipitation over eastern China (Li et al., 2020). In this study, we demonstrated that the unrealistic representation of the precipitation diurnal cycle can induce the excessive precipitation over the TP.

Although determining whether the deep convection scheme can be further modified to reduce current model
biases is beyond the scope of this article, it should be mentioned that extensive efforts have been focused on improving current convection parametrizations. For instance, Zheng et al. (2016) have modified the Kain–Fritsch (KF) convection scheme with a dynamic formulation of the adjustment time-scale, an entrainment rate for convective plumes, and a cloud depth-averaged vertical velocity that involves grid resolution dependence, to improve the performance of the high-resolution WRF model. They have found that the new scale-awareness KF scheme does result in a better simulation of the spatial distribution and the intensity of summer precipitation over the US Great Plains. Ou et al. (2020) have shown that the scale-awareness KF scheme indeed outperforms other convection schemes in reproducing summer mean precipitation intensity and the diurnal cycle of precipitation over the TP at the grey-zone horizontal scale (9 km). In addition, Stratton and Stirling (2012) have used the ensemble mean entrainment of the CPM (with 1 km grid spacing or higher) as a reference, and modified the deep entrainment rate decrease with the increasing lifting condensation level height in the global MetUM. They have found that these modifications to the convection scheme result in an improved precipitation diurnal cycle (both the amplitude and the peaking phase) over tropical land. Nonetheless, a previous study has documented that increasing resolution alone has little benefit on reducing the bias of the simulated precipitation diurnal cycle in IFS (a bulk convection scheme has been applied in IFS), and bulk mass flux convection schemes tend to be highly dependent on CAPE for triggering and development of the convection (Dirmeyer et al., 2012). Conversely, the CPMs (at both regional and even global scales) can resolve moist convection with non-hydrostatic dynamics at kilometre scales and get rid of the uncertainty and ambiguity arising from convection parametrizations. Thus they can offer a sound and physical basis for simulating clouds and precipitation, and provide opportunities for a better understanding of climate and climate change (Satoh et al., 2019; Stevens et al., 2020).
An increase in CAPE due to historical warming and moistening over the TP has also been noted in previous studies (Yang et al., 2012; 2014; Wang et al., 2018; Yao et al., 2019). Moreover, CAPE is projected to continue increasing due to the higher capacity of warmer-future atmospheres for storing water vapour (i.e. based on the Clausius–Clapeyron relationship), which makes reliable projections of how regional precipitation responds to climate warming even more challenging, because precipitation is sensitive to both dynamical and thermodynamic processes. Our study suggests that models with parametrized convection will overestimate future precipitation increases over the TP, because they falsely link precipitation with CAPE. Users of climate projections should be aware of this potential source of uncertainty when investigating future changes in the hydrology of the TP. Further, more work is necessary by developers of climate-projection systems to improve predictions of variability and change in rainfall processes over the TP. We have shown that convection-permitting regional climate modelling is a promising tool for addressing such questions.

Although the CPM better simulates precipitation characteristics and significantly reduces the wet bias simulated by the MSMs over the TRS region, it should be noted that the CPM is not a cure for reducing all kinds of model biases, as it still contains notable biases over the TP and its surrounding regions. For instance, the CPM overestimates the precipitation over the eastern Himalayas, producing too much rainfall at higher altitudes over the southeastern flank of the TP, while, at the same time, exhibiting a dry bias over the Sichuan valley (downstream of the TP; Figure 3b). Further, previous studies have documented that the land-surface processes and cloud-precipitation processes are crucial for understanding the physical mechanisms of the hydrological cycle and forecasting weather and climate systems over the TP and other mountainous regions (Suni et al., 2015; Rhoades et al., 2018; Fu et al., 2020). More sensitivity experiments to further investigate the CPM’s uncertainty induced by land-surface model, cloud microphysics scheme, boundary-layer scheme and other physical processes should be performed to improve the performance of the CPMs in the future. In this study, we investigate the differences between the CPM and the MSMs in simulating precipitation over the TP through a set of season-long simulations (which cover only one summer), due to the high computational cost of the CPM. More decadal-long CPM simulations are needed in the future to investigate the added value and weakness of the CPM in simulating the water cycle over the TP from a climatology aspect.

As previously mentioned, all three precipitation products agree with each other regarding the spatial distributions of summer precipitation over the TP, as well as the precipitation frequency and intensity, but the uncertainties among different observations are still worthy to be considered. For example, rain-gauge stations exhibit a later peak of the precipitation diurnal cycle, compared with the merged rain-gauge–satellite product (Figure 5a–c). Previous studies have shown that most of the rain-gauge stations over the TP have relatively lower locations (mostly situated in valleys) compared to their surroundings (Chen et al., 2012; Li, 2018), and the “mountain–valley” local-scale circulations result in a later peak of evening to night-time precipitation in these rain-gauge stations (Chen et al., 2012; Li, 2018; Ou et al., 2020). Conversely, satellite retrievals tend to represent the afternoon to late-afternoon rainfall peak observed by rain-gauge stations on mountain slopes (Chen et al., 2012; Ou et al., 2020). These can partially explain the difference of precipitation characteristics (precipitation frequency and intensity, as well as their diurnal cycles) between rain-gauge stations and satellite retrievals. More high-quality precipitation products in high spatio-temporal resolution over the TP are needed to provide a solid basis for evaluating high-resolution simulations in the near future.

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REFERENCES

Arakawa, A. (2004) The cumulus parameterization problem: past, present, and future. Journal of Climate, 17(13), 2493–2525. https://doi.org/10.1175/1520-0442(2004)017<2493:RATCPP>2.0.CO;2.

Ban, N., Schmidl, J. and Schürr, C. (2014) Evaluation of the convection-resolving regional climate modeling approach in decade-long simulations. Journal of Geophysical Research: Atmospheres, 119(13), 7889–7907. https://doi.org/10.1002/2014JD021478.
Ban, N., Schmidli, J. and Schär, C. (2015) Heavy precipitation in a changing climate: does short-term summer precipitation increase faster? Geophysical Research Letters, 42(4), 1165–1172. https://doi.org/10.1002/2014GL062588.

Belušić, A., Prtenjak, M.T., Gütterl, I., Ban, N., Leutwyler, D. and Schär, C. (2018) Near-surface wind variability over the broader Adriatic region: insights from an ensemble of regional climate models. Climate Dynamics, 50(11–12), 4455–4480. https://doi.org/10.1007/s00382-017-3885-5.

Best, M.J., Pryor, M., Clark, D.B., Rooney, G.G., Essery, R.L.H., Chen, D. and Dai, A. (2018) Dependence of estimated precipitation on orography. Climate Dynamics, 50(9–10), 3625–3647. https://doi.org/10.1007/s00382-017-3830-7.

Brown, A., Milton, S., Cullen, M.J.P., Golding, B., Mitchell, J. and Davies, T., Cullen, M.J.P., Malcolm, A.J., Mawson, M., Staniforth, A., White, A. and Wood, N. (2005) A new dynamical core for the Met Office’s global and regional modelling of the atmosphere. Quarterly Journal of the Royal Meteorological Society, 131(608), 1759–1782. https://doi.org/10.1256/qj.04.101.

Birch, C.E., Parker, D.J., Marsham, J.H., Cospay, D. and Garcia-Carreras, L. (2014) A seamless assessment of the role of convection in the water cycle of the West African Monsoon. Journal of Geophysical Research: Atmospheres, 119(6), 2890–2912. https://doi.org/10.1002/2013JD020887.

Boutle, I.A., Abel, S.J., Hill, P.G. and Morcrette, C.J. (2014) Spatial variability of liquid cloud and rain: observations and microphysical effects. Quarterly Journal of the Royal Meteorological Society, 140(679), 583–594. https://doi.org/10.1002/qj.2140.

Brookhaus, P., Luthi, D. and Schär, C. (2008) Aspects of the diurnal cycle in a regional climate model. Meteorologische Zeitschrift, 17(4), 433–443. https://doi.org/10.1127/0941-2948/2008/0316.

Brown, A., Milton, S., Cullen, M.J.P., Golding, B., Mitchell, J. and Shelly, A. (2012) Unified modeling and prediction of weather and climate: a 25-year journey. Bulletin of the American Meteorological Society, 93(12), 1865–1877. https://doi.org/10.1175/BAMS-D-12-00018.1.

Chen, G., Sha, W. and Iwasaki, T. (2009) Diurnal variation of precipitation over southeastern China: 2. Impact of the diurnal monsoon variability. Journal of Geophysical Research, 114, D21105. https://doi.org/10.1029/2009JD012181.

Chen, H., Yuan, W., Li, J. and Yu, R. (2012) A possible cause for different diurnal variations of warm season rainfall as shown in station observations and TRMM 3B42 data over the southeastern Tibetan Plateau. Advances in Atmospheric Sciences, 29(1), 193–200. https://doi.org/10.1007/s00376-011-0218-1.

Chen, D. and Dai, A. (2018) Dependence of estimated precipitation frequency and intensity on data resolution. Climate Dynamics, 50(9–10), 3625–3647. https://doi.org/10.1007/s00382-017-3830-7.

Clark, P., Roberts, N., Lean, H., Ballard, S.P. and Charlton-Perez, C. (2016) Convection-permitting models: a step-change in rainfall forecasting. Meteorological Applications, 23(2), 165–181. https://doi.org/10.1002/met.1538.

Collier, E. and Immerzeel, W.W. (2015) High-resolution modeling of atmospheric dynamics in the Nepalese Himalaya. Journal of Geophysical Research: Atmospheres, 120(19), 9882–9896. https://doi.org/10.1002/2015JD023266.

Cullen, M.J.P. (1993) The unified forecast/climate model. Meteorological Magazine, 122(1449), 81–94.

Dai, A., Giorgi, F. and Trenberth, K.E. (1999) Observed and model-simulated diurnal cycles of precipitation over the contiguous United States. Journal of Geophysical Research, 104(D6), 6377–6402. https://doi.org/10.1029/98JD02720.

Dai, A. (2006) Precipitation characteristics in eighteen coupled climate models. Journal of Climate, 19(18), 4605–4630. https://doi.org/10.1175/JCLI3884.1.

Davies, T., Cullen, M.J.P., Malcolm, A.J., Mawson, M., Staniforth, A., White, A. and Wood, N. (2005) A new dynamical core for the Met Office’s global and regional modelling of the atmosphere. Quarterly Journal of the Royal Meteorological Society, 131(608), 1759–1782. https://doi.org/10.1256/qj.04.101.

Dee, D.P., Uppala, S.M., Simmons, A.J., Berrisford, P., Poli, P., Kobayashi, S., Andrae, U., Balsamo, G., Bauer, P., Bechtold, P., Beljaars, A.C.M., van de Berg, L., Bidlot, J., Bormann, N., Delsol, C., Dragani, R., Fuentes, M., Geer, A.J., Haimberger, L., Healy, S.B., Hersbach, H., Holm, E.V., Isaksen, L., Källberg, P., Köhler, M., Matricardi, M., McNally, A.P., Monge-Sanz, B.M., Morcrette, J.-J., Park, B.-K., Peubey, C., de Rosnay, P., Tavolato, C., Thépaut, J.-N. and Vitart, F. (2011) The ERA-Interim reanalysis: configuration and performance of the data assimilation system. Quarterly Journal of the Royal Meteorological Society, 137(656), 553–597. https://doi.org/10.1002/qj.828.

Dirmeyer, P., Cash, B., Kinter, J., Jung, T., Marx, L., Sato, M., Stan, C., Tomita, H., Towers, P., Wedi, N., Achutavarier, D., Adams, J., Altschuler, E., Huang, B., Jin, E. and Manganello, J. (2012) Simulating the diurnal cycle of rainfall in global climate models: resolution versus parameterization. Climate Dynamics, 39(1–2), 399–418. https://doi.org/10.1007/s00382-011-1127-9.

Donlon, C.J., Martin, M., Stark, J., Roberts-Jones, J., Fiedler, E. and Wimmer, W. (2012) The operational sea surface temperature and sea ice analysis system (OSTIA) system. Remote Sensing of Environment, 116, 140–158. https://doi.org/10.1016/j.rse.2010.01.2011.

Du, Y., Zhang, Q., Chen, Y.L., Zhao, Y. and Wang, X. (2014) Numerical simulations of spatial distributions and diurnal variations of low-level jets in China during early summer. Journal of Climate, 27(15), 5747–5767. https://doi.org/10.1175/JCLI-D-13-00571.1.

Du, Y., Chen, Y.L. and Zhang, Q. (2015a) Numerical simulations of the boundary layer jet off the southeastern coast of China. Monthly Weather Review, 143(4), 1212–1231. https://doi.org/10.1175/mwr-d-14-00348.1.

Du, Y., Rotunno, R. and Zhang, Q. (2015b) Analysis of WRF-simulated diurnal boundary layer winds in eastern China using a simple 1D mode. Journal of the Atmospheric Sciences, 72(2), 714–727. https://doi.org/10.1175/JAS-D-14-0186.1.

Feng, L. and Zhou, T. (2015) Simulation of summer precipitation and associated water vapor transport over the Tibetan Plateau by Meteorological Research Institute model (in Chinese with an English abstract). Chinese Journal of Atmospheric Sciences, 39(2), 385–396. https://doi.org/10.3878/j.issn.1006-9895.1406.14125.

Fosser, G., Khodayar, S. and Berg, P. (2015) Benefit of convection-permitting climate model simulations in the representation of convective precipitation. Climate Dynamics, 44(1–2), 45–60. https://doi.org/10.1007/s00382-014-2242-1.

Fosser, G., Khodayar, S. and Berg, P. (2017) Climate change in the next 30 years: what can a convection-permitting model tell us that we did not already know? Climate Dynamics, 48(5–6), 1987–2003. https://doi.org/10.1007/s00382-016-3186-4.

Fu, Y., Ma, Y., Zhong, L., Yang, Y., Guo, X., Wang, C., Xu, X., Yang, K., Xu, X., Liu, P., Fan, G., Li, Y. and Wang, D. (2020) Land surface processes and summer cloud-precipitation characteristics in the Tibetan Plateau and their effects on downstream weather: a
review and perspective. National Science Review, 7(3), 500–515. https://doi.org/10.1093/nsr/nwz226.

Furtado, K., Field, P.R., Cotton, R. and Baran, A.J. (2015) The sensitivity of simulated high clouds to ice crystal fall speed, shape and size distribution. Quarterly Journal of the Royal Meteorological Society, 141(690), 1546–1559. https://doi.org/10.1002/qj.2457.

Gao, Y., Xu, J. and Chen, D. (2015) Evaluation of WRF mesoscale climate simulations over the Tibetan Plateau during 1979–2011. Journal of Climate, 28(7), 2823–2841. https://doi.org/10.1175/JCLI-D-14-00300.1.

Gao, Y., Xiao, L., Chen, D., Chen, F., Xu, J. and Xu, Y. (2017) Quantification of the relative role of land-surface processes and large-scale forcing in dynamic downscaling over the Tibetan Plateau. Climate Dynamics, 48(5–6), 1705–1721. https://doi.org/10.1007/s00382-016-3168-6.

Gao, Y., Chen, F. and Jiang, Y. (2020) Evaluation of a dynamical downscaling based on WRF model. Journal of Advances in Modeling Earth Systems, 12(7), 3408–3424. https://doi.org/10.1029/2019MS001561.

Grant, A.L.M. (2001) Cloud-base fluxes in the cumulus-capped boundary layer. Quarterly Journal of the Royal Meteorological Society, 127(572), 407–421. https://doi.org/10.1002/qj.49712757209.

Gregory, D. and Rowntree, P. (1990) A mass flux convection scheme with representation of cloud ensemble characteristics and stability-dependent closure. Monthly Weather Review, 118(7), 1483–1506. https://doi.org/10.1175/1520-0493(1990)118<1483:AMFCSW>2.0.CO;2.

Grell, G.A., Schade, L., Knoche, R., Pfeiffer, A. and Egger, J. (2000) Nonhydrostatic climate simulations of precipitation over complex terrain. Journal of Geophysical Research, 105(D24), 29595–29608. https://doi.org/10.1029/2000JD900445.

Guo, Z., Fang, J., Sun, X., Yang, Y. and Tang, J. (2019) Sensitivity of summer precipitation simulation to microphysics parameterization over eastern China: convection-permitting regional climate model. Journal of Geophysical Research: Atmospheres, 124(16), 9183–9204. https://doi.org/10.1029/2019JD030295.

Hahn, D.G. and Manabe, S. (1975) The role of mountains in the South Asian monsoon circulation. Journal of the Atmospheric Sciences, 32(8), 1515–1541. https://doi.org/10.1175/1520-0469(1975)032<1515:TROMIT>2.0.CO;2.

Joyce, R.J., Janowiak, J.E., Arkin, P.A. and Xie, P. (2004) CMORPH: a method that produces global precipitation estimates from passive microwave and infrared data at high spatial and temporal resolution. Journal of Hydrometeorology, 5(3), 487–503. https://doi.org/10.1175/1525-7541(2004)005<0487:CAMORPG>2.0.CO;2.

Immerzeel, W. and Bierkens, M. (2012) Asia’s water balance. Journal of Hydrometeorology, 13(5), 1705–1721. https://doi.org/10.1175/JHM-D-11-00562.1.

Karki, R., Gerlitz, L., Schickhoff, U., Scholten, T. and Böhner, J. (2017) Quantifying the added value of convection-permitting climate simulations in complex terrain: a systematic evaluation of WRF over the Himalayas. Earth System Dynamics, 8, 507–528. https://doi.org/10.5194/esd-8-507-2017.

Kendon, E.J., Roberts, N.M., Senior, C.A. and Roberts, M.J. (2012) Realism of rainfall in a very high-resolution regional climate model. Journal of Climate, 25(17), 5791–5806. https://doi.org/10.1175/JCLI-D-11-00562.1.

Kooperman, G.J., Pritchard, M.S. and Somerville, R.C. (2014) The response of US summer rainfall to quadrupled CO2 climate change in conventional and superparameterized versions of the NCAR community atmosphere model. Journal of Advances in Modeling Earth Systems, 6(3), 859–882. https://doi.org/10.1002/2014MS000306.

Lean, H.W., Clark, P.A., Dixon, M., Roberts, N.M., Fitch, A., Forbes, R. and 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. https://doi.org/10.1175/2008MWR2332.1.

Li, J. (2018) Hourly station-based precipitation characteristics over the Tibetan Plateau. International Journal of Climatology, 38(3), 1560–1570. https://doi.org/10.1002/joc.5281.

Li, J., Yu, R., Yuan, W., Chen, H., Sun, W. and Zhang, Y. (2015) Precipitation over East Asia simulated by NCAR CAM5 at different horizontal resolutions. Journal of Advances in Modeling Earth Systems, 7(2), 774–790. https://doi.org/10.1002/2014MS000414.

Li, P., Guo, Z., Furtado, K., Chen, H., Li, J., Milton, S., Field, P.R. and Zhou, T. (2019) Prediction of heavy precipitation in the eastern China flooding events of 2016: added value of convection-permitting simulations. Quarterly Journal of the Royal Meteorological Society, 145(724), 3300–3319. https://doi.org/10.1002/qj.3621.

Li, P., Furtado, K., Zhou, T., Chen, H., Li, J., Guo, Z. and Xiao, C. (2020) 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. https://doi.org/10.1007/s00382-018-4368-z.

Li, X., Gao, Y., Pan, Y. and Xu, Y. (2018) Evaluation of near-surface wind speed simulations over the Tibetan Plateau from three dynamical downscalings based on WRF model. Theoretical and Applied Climatology, 134(3), 1399–1411. https://doi.org/10.1007/s00704-017-2353-9.

Li, Y., Li, D., Yang, S., Liu, C., Zhong, A. and Li, Y. (2010) Characteristics of the precipitation over the eastern edge of the Tibetan Plateau. Meteorology and Atmospheric Physics, 106(1–2), 49–56. https://doi.org/10.1007/s00703-009-0048-1.

Liang, L., Li, L., Liu, C. and Cuo, L. (2013) Climate change in the Tibetan plateau Three Rivers Source region: 1960–2009. International Journal of Climatology, 33(13), 2900–2916. https://doi.org/10.1002/joc.3642.

Liang, X.Z., Li, L., Dai, A. and Kunkel, K.E. (2004) Regional climate model simulation of summer precipitation diurnal cycle over the United States. Geophysical Research Letters, 31(24), L24208. https://doi.org/10.1029/2004GL021054.

Lin, C., Chen, D., Yang, K. and Ou, T. (2018) Impact of model resolution on simulating the water vapor transport through the central Himalayas: implication for models’ wet bias over the Tibetan Plateau. Climate Dynamics, 51(9–10), 3195–3207. https://doi.org/10.1007/s00382-018-4074-x.

Lock, A.P., Brown, A.R., Bush, M.R., Martin, G.M. and Smith, R.N.B. (2000) A new boundary layer mixing scheme. Part I: Scheme description and single-column model tests. Monthly Weather Review, 128(9), 3187–3199. https://doi.org/10.1175/1520-0493(2000)128<3187:ANBLMS>2.0.CO;2.

Lv, M., Xu, Z. and Yang, Z.-L. (2020) Cloud resolving WRF simulations of precipitation and soil moisture over the central Tibetan Plateau: an assessment of various physics options. Earth
Space Science, 7(2), e2019EA000865. https://doi.org/10.1029/2019EA000865.

Maussion, F., Scherer, D., Finkelnburg, R., Richters, J., Yang, W. and Yao, T. (2011) WRF simulation of a precipitation event over the Tibetan Plateau, China – an assessment using remote sensing and ground observations. Hydrology Earth System Sciences, 15(6), 1795–1817. https://doi.org/10.5194/hess-15-1795-2011.

Maussion, F., Scherer, D., Mölg, T., Collier, E., Curio, J. and Finkelnburg, R. (2014) Precipitation seasonality and variability over the Tibetan Plateau as resolved by the High Asia Reanalysis. Journal of Climate, 27(5), 1910–1927. https://doi.org/10.1175/JCLI-D-13-00282.1.

Miura, H., Satoh, M., Nasuno, T., Noda, A.T. and Oouchi, K. (2007) A Madden–Julian Oscillation event realistically simulated by a global cloud-resolving model. Science, 318(5857), 1763–1765. https://doi.org/10.1126/science.1148443.

New, M., Hulme, M. and Jones, P. (2000) Representing twentieth-century space-time climate variability. Part II: Development of 1901–96 monthly grids of terrestrial surface climate. Journal of Climate, 13(13), 2217–2238. https://doi.org/10.1175/1520-0442(2000)013<2217:RTCTCM>2.0.CO;2.

Ou, T., Chen, D., Chen, X., Lin, C., Yang, K., Lai, H. and Zhang, F. (2020) Simulation of summer precipitation diurnal cycles over the Tibetan Plateau at the gray-zone grid spacing for cumulus parameterization. Climate Dynamics, 54, 3525–3539. https://doi.org/10.1007/s00382-020-05181-x.

Pearson, K., Lister, G., Birch, C., Allan, R., Hogan, R. and Woolnough, S. (2014) Modelling the diurnal cycle of tropical convection across the ‘grey zone’. Quarterly Journal of the Royal Meteorological Society, 140(679), 491–499. https://doi.org/10.1002/qj.2145.

Prein, A., Golbi, A., Suklitsch, M., Truhetz, H., Awan, N., Keuler, K. and Georgievski, G. (2013) Added value of convection-permitting seasonal simulations. Climate Dynamics, 41(9–10), 2655–2677. https://doi.org/10.1007/s00382-013-1744-6.

Prein, A.F., Langhans, W., Fosser, G., Ferrone, A., Ban, N., Gorgens, K., Keller, M., Tölle, M., Gutjahr, O. and Feser, F. (2015) A review on regional convection-permitting climate modeling: demonstrations, prospects, and challenges. Reviews of Geophysics, 53(2), 323–361. https://doi.org/10.1002/2014RG000475.

Pritchard, M.S., Moncrieff, M.W. and Somerville, R.C. (2011) Orographic propagating precipitation systems over the United States in a global climate model with embedded explicit convection. Journal of the Atmospheric Sciences, 68(8), 1821–1840. https://doi.org/10.1175/2011JAS3699.1.

Qiu, J. (2008) China: the third pole. Nature, 454, 393–396. https://doi.org/10.1038/454393a.

Rasmussen, R., Ikeda, K., Liu, C., Gochis, D., Clark, M., Dai, A., Gutmann, E., Chen, F. and Barlage, M. (2014) Climate change impacts on the water balance of the Colorado headwaters: high-resolution regional climate model simulations. Journal of Hydrometeorology, 15(3), 1091–1116. https://doi.org/10.1175/JHM-D-13-0118.1.

Rhoades, A.M., Ulrich, P.A., Zarzycki, C.M., Johansen, H., Margulis, S.A., Morrison, H., Xu, Z. and Collins, W.D. (2018) Sensitivity of mountain hydroclimate simulations in variable-resolution CESM to microphysics and horizontal resolution. Journal of Advances in Modeling Earth Systems, 10(6), 1357–1380. https://doi.org/10.1029/2018MS001326.

Roberts, N.M. and Lean, H.W. (2008) Scale-selective verification of rainfall accumulations from high-resolution forecasts of convective events. Monthly Weather Review, 136(1), 78–97. https://doi.org/10.1175/2007MWR2123.1.

Rose, S.F., Hobbis, P.V., Locatelli, J.D. and Stoelinga, M.T. (2002) Use of a mesoscale model to forecast severe weather associated with a cold front aloft. Weather and Forecasting, 17(4), 755–773. https://doi.org/10.1175/1520-0434(2002)017<0755:UOMMT>2.0.CO;2.

Sato, T., Miura, H. and Satoh, M. (2007) Spring diurnal cycle of clouds over Tibetan Plateau: global cloud-resolving simulations and satellite observations. Geophysical Research Letters, 34(18), L18816. https://doi.org/10.1029/2007GL030782.

Sato, T., Miura, H., Satoh, M., Takayabu, Y.N. and Wang, Y. (2009) Diurnal cycle of precipitation in the Tropics simulated in a global cloud-resolving model. Journal of Climate, 22(18), 4809–4826. https://doi.org/10.1175/2009JCLI2890.1.

Satoh, M., Stevens, B., Judt, F., Khairoutdinov, M., Lin, S.J., Putman, W.M. and Düben, P. (2019) Global cloud-resolving models. Current Climate Change Reports, 5(3), 172–184. https://doi.org/10.1007/s40641-019-00131-0.

Schmidli, J., Billings, B., Chow, F.K., de Wekker, S.F., Doyle, J., Grubišić, V., Holt, T., Jiang, Q., Lundquist, K.A. and Sheridan, P. (2011) Intercomparison of mesoscale model simulations of the daytime valley wind system. Monthly Weather Review, 139(5), 1389–1409. https://doi.org/10.1175/2011MWR3523.1.

Schmidli, J. and Rotunno, R. (2010) Mechanisms of along-valley winds and heat exchange over mountainous terrain. Journal of the Atmospheric Sciences, 67(9), 3033–3047. https://doi.org/10.1175/2010JAS3473.1.

Schwartz, C.S., Kain, J.S., Weiss, S.J., Xue, M., Bright, D.R., Kong, F., Thomas, K.W., Levit, J.J. and Coniglio, M.C. (2009) Next-day convection-allowing WRF model guidance: a second look at 2-km versus 4-km grid spacing. Monthly Weather Review, 137(10), 3351–3372. https://doi.org/10.1175/2009MWR2924.1.

Shen, Y., Zhao, P., Pan, Y. and Yu, J. (2014) A high spatiotemporal gauge-satellite merged precipitation analysis over China. Journal of Geophysical Research: Atmospheres, 119(6), 3063–3075. https://doi.org/10.1002/2013JD020666.

Song, F. and Zhou, T. (2014) The climatology and interannual variability of East Asian summer monsoon in CMIP5 coupled models: does air–sea coupling improve the simulations? Journal of Climate, 27(23), 8761–8777. https://doi.org/10.1175/JCLI-D-14-00396.1.

Stevens, B. and Bony, S. (2013) What are climate models missing? Science, 340(6136), 1053–1054. https://doi.org/10.1126/science.1237554.

Stevens, B., Acquistapace, C., Hansen, A., Heinze, R., Klinger, C., Klocke, D., Schubotz, W., Windmiller, J., Adamidis, P., Arka, I., Barlakas, V., Biercamp, J., Brueck, M., Brune, S., Buehler, S., Burkhardt, U., Cioni, G., Costa-Sursos, M., Crewell, S., Créger, S., Denekte, H., Friedrichs, P., Henken, C.C., Hohenegger, C., Jacob, M., Jakub, F., Kalthoff, N., Köhler, M., Van Laar, T.W., Li, P., Läuhnert, U., Macke, A., Madenbach, N., Mayer, B., Nam, C., Naumann, A.K., Peters, K., Poll, S., Quaas, J., Röber, N., Rochetin, N., Scheupflüg, L., Schemmann, V., Schnitt, S., Seifert, A., Senf, F., Shapkalijo, M., Simmer, C., Singh, S., Souboulal, O., Spickermann, D., Strandgren, J., Tessiot, O., Vercauteren, N., Vial, J., Voigt, A. and Zängl, G. (2020) The added value of large-eddy simulations: does air–sea coupling improve the simulations? Journal of Climate, 33(18), 5833–5854. https://doi.org/10.1175/JCLI-D-19-0456.1.
and storm-resolving models for simulating clouds and precipitation. *Journal of the Meteorological Society of Japan, Series II*, 98(2), 395–435. https://doi.org/10.2151/jmsj.2020-021.

Stratton, R.A. and Stirling, A.J. (2012) Improving the diurnal cycle of convection in GCMs. *Quarterly Journal of the Royal Meteorological Society*, 138(666), 1121–1134.

Su, F., Duan, X., Chen, D., Hao, Z. and Cuo, L. (2013) Evaluation of the global climate models in the CMIP5 over the Tibetan Plateau. *Journal of Climate*, 26(10), 3187–3208. https://doi.org/10.1175/JCLI-D-12-00321.1.

Sun, B. and Wang, H. (2018) Interannual variation of the spring and summer precipitation over the Three River Source region in China and the associated regimes. *Journal of Climate*, 31(18), 7441–7457. https://doi.org/10.1175/JCLI-D-17-0680.1.

Sun, B. and Wang, H. (2019) Enhanced connections between summer precipitation over the Three-River-Source region of China and the global climate system. *Climate Dynamics*, 52(5), 3471–3488. https://doi.org/10.1007/s00382-018-4326-9.

Suni, T., Guenther, A., Hansson, H.C., Kulmala, M., Andreae, M.O., Arneth, A., Artaxo, P., Blyth, E., Brus, M., Gazevedo, L., Kabat, P., Noblet-Ducoudré, N., Reichstein, M., Reissell, A., Rosenfeld, D. and Kabat, P. (2015) The significance of land–atmosphere interactions in the Earth system – ILEAPS achievements and perspectives. *Anthropocene*, 12, 69–84. https://doi.org/10.1016/j.ancene.2015.12.001.

Tong, K., Su, F., Yang, D., Zhang, L. and Hao, Z. (2014) Tibetan Plateau precipitation as depicted by gauge observations, reanalyses and satellite retrievals. *International Journal of Climatology*, 34(2), 265–285. https://doi.org/10.1002/joc.3682.

Walters, D., Brooks, M., Boutle, I., Melvin, T., Stratton, R., Vosper, S., Wells, H., Williams, K., Wood, N., Allen, T., Bushell, A., Copsey, D., Earnshaw, P., Edwards, J., Gross, M., Hardiman, S., Harris, C., Heming, J., Klingaman, N., Levine, R., Manners, J., Martin, G., Milton, S., Mittermaier, M., Morcrette, C., Riddick, T., Roberts, M., Sanchez, C., Selwood, P., Stirling, A., Smith, C., Suri, D., Tennant, W., Vidale, P.L., Wilkinson, J., Willett, M., Woolnough, S. and Xavier, P. (2017) The Met Office Unified Model Global Atmospheric 6.0/6.1 and JULES Global Land 6.0/6.1 configurations. *Geoscientific Model Development*, 10(4), 1487–1520. https://doi.org/10.5194/gmd-10-1487-2017.

Wang, X., Pang, G. and Yang, M. (2018) Precipitation over the Tibetan Plateau during recent decades: a review based on observations and simulations. *International Journal of Climatology*, 38(3), 1116–1131. https://doi.org/10.1002/joc.5246.

Wang, Y., Yang, K., Zhou, X., Chen, D., Lu, H., Ouyang, L., Chen, Y. and Wang, B. (2020) Synergy of orographic drag parameterization and high resolution greatly reduces biases of WRF-simulated precipitation in central Himalaya. *Climate Dynamics*, 54(3–4), 1729–1740. https://doi.org/10.1007/s00382-019-05080-w.

Wilkinson, J.M. (2017) A technique for verification of convection-permitting NWP model deterministic forecasts of lightning activity. *Weather and Forecasting*, 32(1), 97–115. https://doi.org/10.1175/WAF-D-16-0106.1.

Wilson, D.R. and Ballard, S.P. (1999) A microphysically based precipitation scheme for the UK Meteorological Office Unified Model. *Quarterly Journal of the Royal Meteorological Society*, 125(557), 1607–1636. https://doi.org/10.1002/qj.49712555707.

Wu, G., Liu, Y., He, B., Bao, Q., Duan, A. and Jin, F.-F. (2012) Thermal controls on the Asian summer monsoon. *Scientific Reports*, 2, 404. https://doi.org/10.1038/srep00404.

Wu, G. and Zhang, Y. (1998) Tibetan Plateau forcing and the timing of the monsoon onset over South Asia and the South China Sea. *Monthly Weather Review*, 126(4), 913–927. https://doi.org/10.1175/1520-0493(1998)126<0913:TPTFOT>2.0.CO;2.

Wu, J. and Gao, X. (2013) A gridded daily observation dataset over China region and comparison with the other datasets (in Chinese with an English abstract). *Chinese Journal of Geophysics*, 56, 1102–1111. https://doi.org/10.6038/cjg20130406.

Xu, X., Lu, C., Shi, X. and Gao, S. (2008) World water tower: an atmospheric perspective. *Geophysical Research Letters*, 35(20), L20815. https://doi.org/10.1029/2008GL035867.

Xu, Y., Gao, X. and Giorgi, F. (2010) Upgrades to the reliability ensemble averaging method for producing probabilistic climate-change projections. *Climate Research*, 41(1), 61–81. https://doi.org/10.3354/cr00835.

Yang, K., Ding, B., Qin, J., Tang, W., Lu, N. and Lin, C. (2012) Can aerosol loading explain the solar dimming over the Tibetan Plateau? *Geophysical Research Letters*, 39(20), L20710. https://doi.org/10.1029/2012GL053733.

Yang, K., Wu, H., Qin, J., Lin, C., Tang, W. and Chen, Y. (2014) Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. *Global Planetary Change*, 112, 79–91. https://doi.org/10.1016/j.gloplacha.2013.12.001.

Yao, T., Yue, Y., Chen, D., Chen, F., Thompson, L., Cui, P., Koike, T., Lau, W.K.M., Lettenmaier, D., Mosbrugger, V. and Zhang, R. (2019) Recent Third Pole’s rapid warming accompanies cryospheric melt and water cycle intensification and interactions between monsoon and environment: multidisciplinary approach with observations, modeling, and analysis. *Bulletin of the American Meteorological Society*, 100(3), 423–444. https://doi.org/10.1175/BAMS-D-17-0057.1.

You, Q., Min, J., Zhang, W., Pepin, N. and Kang, S. (2015) Comparison of multiple datasets with gridded precipitation observations over the Tibetan Plateau. *Climate Dynamics*, 45(3–4), 791–806. https://doi.org/10.1007/s00382-014-2310-6.

Yu, J., Shen, Y., Pan, Y., Zhao, P. and Zhou, Z. (2013) Improvement of satellite-based precipitation estimates over China based on probability density function matching method (in Chinese with an English abstract). *Journal of Applied Meteorological Science*, 24(5), 544–553. https://doi.org/10.11898/1001-7313.20130504.

Yu, R., Li, J., Chen, H. and Yuan, W. (2014) Progress in studies of the precipitation diurnal variation over contiguous China (in Chinese with an English abstract). *Acta Meteorologica Sinica*, 72(5), 948–968. https://doi.org/10.11676/qxxb2014.047.

Yu, R., Li, J., Zhang, Y. and Chen, H. (2015) Improvement of rainfall simulation on the steep edge of the Tibetan Plateau by using a finite-difference transport scheme in CAM5. *Climate Dynamics*, 45(9–10), 2937–2948. https://doi.org/10.1007/s00382-015-2515-3.

Yun, Y., Liu, C., Luo, Y., Liang, X., Huang, L., Chen, F. and Rasmussen, R. (2020) Convection-permitting regional climate simulation of warm-season precipitation over eastern China. *Climate Dynamics*, 54(3–4), 1469–1489. https://doi.org/10.1007/s00382-019-05070-y.

Zhang, Q., Zhao, Y. and Fan, S. (2016) Development of hourly precipitation datasets for national meteorological stations in China (in Chinese with an English abstract). *Torrential Rain Disasters,*
Zhang, Y. and Chen, H. (2016) Comparing CAM5 and superparameterized CAM5 simulations of summer precipitation characteristics over continental East Asia: mean state, frequency–intensity relationship, diurnal cycle, and influencing factors. *Journal of Climate*, 29(3), 1067–1089. https://doi.org/10.1175/JCLI-D-15-0342.1.

Zhang, Y. and Li, J. (2016) Impact of moisture divergence on systematic errors in precipitation around the Tibetan Plateau in a general circulation model. *Climate Dynamics*, 47(9–10), 2923–2934. https://doi.org/10.1007/s00382-016-3005-y.

Zheng, Y., Alapaty, K., Herwehe, J.A., Genio, A.D. and Niyogi, D. (2016) Improving high-resolution weather forecasts using the Weather Research and Forecasting (WRF) model with an updated Kain–Fritsch scheme. *Monthly Weather Review*, 144(3), 833–860. https://doi.org/10.1175/MWR-D-15-0005.1.

Zhou, T., Wu, B., Guo, Z., He, C., Zou, L., Chen, X., Zhang, L., Man, W., Li, P., Li, D., Yao, J., Huang, X., Zhang, W., Zuo, M., Lu, J. and Sun, N. (2018) A review of East Asian summer monsoon simulation and projection: achievements and problems, opportunities and challenges (in Chinese with an English abstract). *Chinese Journal of Atmospheric Sciences*, 42(4), 902–934. https://doi.org/10.3878/j.issn.1006-9895.1802.17306.

Zhu, K., Xue, M., Zhou, B., Zhao, K., Sun, Z., Fu, P., Zheng, Y., Zhang, X. and Meng, Q. (2018) Evaluation of real-time convection-permitting precipitation forecasts in China during the 2013–2014 summer season. *Journal of Geophysical Research: Atmospheres*, 123(2), 1037–1064. https://doi.org/10.1002/2017JD027445.

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