Convection-permitting regional climate simulations over Tibetan Plateau: re-initialization versus spectral nudging

Mengnan Ma1,2 · Pinhong Hui3 · Dongqing Liu4 · Peifeng Zhou1,2 · Jianping Tang1,2

Received: 11 May 2021 / Accepted: 26 September 2021 / Published online: 9 October 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2021

Abstract
Two regional climate simulation experiments (spectral nudging and re-initialization) at convection-permitting scale are conducted using the WRF model driven by the 4th generation Global Reanalysis data (ERA5) from European Centre for Medium-Range Weather Forecasts over the Tibetan Plateau (TP). The surface air temperature (T2m) and the precipitation in summer during 2016–2018 are evaluated against the in-situ station observations and the Global Satellite Mapping of Precipitation (GSMaP) dataset. The results show that both experiments as well as ERA5 can successfully capture the spatial distribution and the daily variation of T2m and precipitation, with reasonable cold bias for temperature and dry bias for precipitation when compared with the station observations. In addition, the diurnal cycle of precipitation is investigated, indicating that both experiments tend to simulate the afternoon precipitation peak in advance and postpone the night precipitation peak. The precipitation bias is reduced by using the spectral nudging technique, especially at night and early morning. Both WRF experiments outperform ERA5 in reproducing the diurnal cycle of precipitation amount. Possible causes for the differences between the two experiments are also analyzed. In the re-initialization experiment, the daytime net shortwave radiation contributes a lot to the cold biases of Tmax, and the stronger vertically integrated moisture flux convergence leads to more precipitation compared with the spectral nudging experiment over the central and southeastern TP. These results can provide valuable guidance for further fine-scale simulation studies over the TP.

Keywords Tibetan Plateau · Spectral nudging · Re-initialization · Summer precipitation · Surface air temperature · Convection-permitting

1 Introduction
The Tibetan Plateau (TP), often known as the third pole of the Earth, is the highest and most extensive highland in the world, with an average altitude of 3000–5000 m and the maximum altitude above 8000 m (Kang et al. 2010). Due to its unique topography and geographical location, the TP exerts important influences on regional weather and climate, even spreading to the whole Asia and all around the world through both thermal and mechanical forcing (Duan and Wu 2005; Ye and Gao 1979). It has been called as ‘the driving force’ and ‘the amplifier’ for the global climate change (Pan et al. 1996). In addition, it is also the source of many Asian river systems and serves as ‘the Asian water tower’ (You et al. 2012). The regional climate change over the TP has important impacts on the regional hydrological cycle and even the river discharge of Asia (Su et al. 2013). More and more attention has been paid to the regional climate change over the TP, and it is very essential to obtain the detailed regional climate characteristics to accurately evaluate the sustainability of water resources and the impact of climate change over the TP.

Regional climate models (RCMs), which can well describe the regional characteristics such as local topography and land-use distribution, have been widely used to conduct the regional climate research and project the future climate change over the TP (Wang et al. 2013; Gao et al. 2015).
Using the Weather Research and Forecasting (WRF) model driven by the global reanalysis dataset, Gao et al. (2015) conducted a 33-year regional climate simulation over the TP with the resolution at 30 km and the results presented that the RCM could improve the simulation of annual cycles of precipitation and surface air temperature in the wet season. With long-term regional climate simulations with different horizontal resolutions, Gu et al. (2020) also showed that RCMs could improve the regional climate simulations over the TP with higher resolution. Although RCMs have been proven to be useful tools to provide detailed regional climate information over the TP, they retain great deficiencies due to the complex terrain and the relatively coarse resolution (grid spacing > 10 km) used. The cumulus parameterization, which is used to resolve the deep convection process at coarse resolution, has been identified as one of the major sources of errors and uncertainties in the regional climate simulations over the TP (Gu et al. 2020). A promising remedy to the error-prone climate simulations using convective parameterizations is the use of convection-permitting model (CPM; horizontal grid spacing < 4 km). It operates on the kilometer scale and no longer relies on convection parameterization schemes, which provides more reliable climate information on regional to local scales (Prein et al. 2015; Zhou et al. 2021). By resolving deep convection explicitly and improving the representation of orography and other surface forcing, the CPM climate simulations are able to improve the climatological mean temperature especially in mountainous regions during summer (Hohenegger et al. 2008; Prein et al. 2013) and the diurnal cycle of summer precipitation. Using the WRF model, Gao et al. (2020) simulated the precipitation over the TP without reliable in-situ observations and found that the high-resolution CPM has the added value in reproducing the precipitation. Li et al. (2020) showed that the CPM could significantly reduce the wet bias in the coarse resolution simulations and better depict the precipitation frequency and intensity over the TP. Several CPM experiments have also been conducted over the TP to assess the effect of physical options on the CPM performance (Ou et al. 2020; Lv et al. 2020), and to study the impact of resolution on the simulation of water vapor transport (Lin et al. 2018).

However, due to the deficiency in the RCM structure and physics, the large-scale flow in the RCM simulation may depart from the driving fields, leading to the systematic model biases growth in long-term integrations. To prevent the RCMs from drifting away from the large-scale forcing and ensure the model results consistent with the driving fields, several dynamical downscaling methods have been developed. In GCM-driven models, variants of the relaxation technique (Davies and Turner 1977) which essentially consists of adding a relaxation term to each prognostic equation (Giorgi et al. 2019) have been used with the aim to drive the model solution toward the imposed lateral boundary conditions in the buffer area. In addition to this standard relaxation technique, the spectral nudging approach applies the relaxation forcing throughout the entire domain on the long wave components of the large-scale fields, which is mostly used in models driven by global reanalysis (von Storch et al. 2000; Tang et al. 2010, 2017). As a fake data assimilation technique, spectral nudging introduces bias corrections of large-scale circulation throughout the whole RCM domain rather than just on the initial and lateral boundary conditions, thus minimizing climate drift. Using the SN approach, Song et al. (2011) conducted a series of experiments in East Asia and revealed that the SN approach could improve the simulation of precipitation due to the reduced bias of large-scale circulation field. Similarly, the re-initialization approach (RI) (Lo et al. 2008) is also widely used in the RCMs driven by global reanalysis, which alleviates the noise and wave reflection caused by mismatches between the model-generated solution and the imposed lateral boundary condition. The RI approach aims to mitigate the systematic error accumulation in the continuous long-term simulations through the consecutive or periodically reinitialized short-term runs (Qian et al. 2003). Usually, this approach can be carried out at different frequencies (e.g., daily, weekly or monthly). Lo et al. (2008) demonstrated that a run with more frequent re-initialization outperforms that with less frequent re-initialization. Over the TP, the daily re-initialization approach was used to generate the High Asia Reanalysis (HAR) (Maussion et al. 2014; Wang et al. 2021), which showed added value in reproducing the spatial pattern and seasonality of precipitation. Although both RI and SN approaches have been widely used in regional climate simulations, few works have been done to compare these two methods in convection-permitting (CP) scale simulations, especially over the TP regions with complex topography.

In this study, using the CP WRF model, we perform two experiments with different dynamical downscaling methods (RI and SN) over the TP in summer from 2016 to 2018. The simulated surface variables are compared with both the station observations and the satellite-derived dataset. The purpose of this study is to: (1) evaluate the CPM’s performance in reproducing the spatiotemporal characteristics of surface variables over the TP; (2) identify the strengths and weaknesses of the two dynamical downscaling approaches in simulating the regional climate over the TP at CP scale. The paper is organized as follows. Section 2 briefly describes the model, data and methodology. Section 3 compares the models’ simulations with the observations. Discussion and major conclusions are presented in Sects. 4 and 5.
2 Data, model and experimental design

2.1 Model and experimental design

The WRF model version 4.1.1 (Skamarock et al. 2019), which is a nonhydrostatic mesoscale numerical weather prediction system designed to serve both operational forecasting and atmospheric research needs, is used in this study. The WRF model has been widely used in regional climate simulations around the world (Tang et al. 2016, 2017; Glisan et al. 2013; Huang et al. 2021; Xu and Yang 2015). The model domain in this work is centered at 33° N and 88.5° E, with 1081 × 721 grid points in east-west and north-south directions, covering the whole TP and the surrounding area (Fig. 1). Fifty hybrid-sigma levels are defined from surface to model top at 50 hPa. The horizontal resolution is set to 3 km for the convection-permitting scale simulation over the TP. To evaluate the skill of WRF in reproducing the regional climate over the TP in detail, four sub-regions are chosen from the whole study area based on the topography and climate features: the northwest region (TP-NW, 32.5°–37° N, 75°–91° E), the southwest region (TP-SW, 28°–32.5° N, 82°–91° E), the northeast region (TP-NE, 32.5°–39° N, 91°–102° E) and the southwest region (TP-SE, 28°–32.5° N, 91°–102° E).

The physical parameterization schemes employed in this research include the Thompson microphysics scheme (Thompson et al. 2008), the Mellor-Yamada Nakanishi Niino 2.5 level TKE scheme (MYNN) planetary boundary layer (PBL) parameterization (Nakanishi and Niino 2006), the RRTMG shortwave and longwave radiation schemes (Iacono et al. 2008), and the Noah-MP land surface model (Niu et al. 2011). With the horizontal resolution at CP scale (3 km), the cumulus convection parameterization scheme is switched off.

Two sets of regional climate simulations are carried out, employing the spectral nudging scheme (hereinafter Exp-SN) and the re-initialization approach (hereinafter Exp-RI), respectively. In the SN approach, it is supposed that the regional climate model is forced to satisfy not only the boundary conditions, possibly in a boundary sponge region, but also the large-scale flow conditions inside the integration area (von Storch et al. 2000). The time-varying large-scale information with the wavenumber less than a preset value is nudged on the interior model domain in the SN experiment. In this study, the simulation domain is about 3200 and 2200 km in zonal and meridional directions, respectively. The wavenumber of 4 is employed in both directions with the corresponding wave lengths about 800 and 500 km, which means the forcing circulation information with the scale larger than the wave lengths can be nudged, and the nudging coefficient is $3 \times 10^{-3}$. Previous studies indicated that applying the SN to the horizontal winds showed good performance in reproducing the regional climate characteristics (Alexandru et al. 2009; Tang et al. 2010, 2016). In the Exp-SN simulation, SN is only applied to the wind fields above the PBL to allow the development of the mesoscale circulation. The Exp-RI consists of multiple consecutive reinitialized model runs with a 36-hour time integration. Each run starts at 12:00 UTC with the first 12 h as the spin-up time, and the remaining 24 h of the model outputs are used. By subdividing the long-term continuous integration into short ones, re-initialization has been successful in weather forecasting to mitigate the problem of systematic error growth in long integrations (Lo et al. 2008). Many studies had pointed out that the re-initialization approach could be beneficial to RCM simulations (Druyan et al. 2001; Qian et al. 2003). All the experiments are driven by the 4th generation Global Reanalysis data (ERAS) from European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach et al. 2020), and simulate the summer climate.

![Fig. 1](image-url) The simulation domain (yellow shading) with the TP framed with red lines and four sub-regions framed with black lines (a), and the locations of the meteorological stations over the TP (b)
(June, July and August, JJA) from 2016 to 2018. In the Exp-SN, the simulation starts from May 16 and integrates continuously to September 1 with the first 16 days (May 16–31) as the spin-up time.

2.2 Observation data and method

Several datasets are used to evaluate the performance of the WRF model in simulating the surface climate over the TP at CP scale. One is the daily in-situ observation provided by the data service center at China Meteorology Administration (CMA, http://data.cma.cn/en). Only 144 stations over the TP are applied in this study (Fig. 1b), which have comparatively applicable observations of daily surface air temperature (T2m), maximum/minimum surface air temperature (Tmax and Tmin) and precipitation. Most of the meteorological stations are located in the central and eastern part of the TP and few over the western TP. Therefore, the data from the meteorological stations cannot fully represent the TP, especially the western TP and the region above 4,800 m ASL (Qin et al. 2009). Thus, to validate the WRF-simulated precipitation and temperature over the TP in detail, the satellite precipitation and skin temperature products are also used to carry out a more objective evaluation.

The Global Satellite Mapping of Precipitation version 6 (GSMaP) products, operated by the Japan Aerospace Exploration Agency (JAXA), are used for the precipitation evaluation. The spatiotemporal resolution of the GSMaP products are 0.1° × 0.1°and 1-h, respectively. The gauge-adjusted GSMaP data (GSMaP-Gauge) is adopted to evaluate the WRF simulations, which is obtained by adjusting the GSMaP estimate using the National Oceanic and Atmospheric Administration (NOAA)/Climate Prediction Center (CPC) gauge-based analysis of global daily precipitation. Lu and Yong (2018) demonstrated that the GSMaP-Gauge data showed comparable performance with the gauge reference data, suggesting that it can be selected for hydrological application over the TP.

A new long-term spatially and temporally continuous Moderate Resolution Imaging Spectroradiometer (MODIS) land surface temperature (LST) dataset for China from 2003 to 2017 (Zhao et al. 2020) is used to validate the WRF simulations. The temporal and spatial resolutions are monthly and 5600 m, respectively. It takes full advantages of the MODIS data and the meteorological station data by combining them to reconstruct real LST with the help of a regression analysis model. Thus, it makes up for the deficiency of sparse observation stations and effectively overcomes the limitations in reconstructing the real LST under cloudy conditions. The high-precision monthly LST dataset constructed for China is convinced to be highly consistent with the in-situ observation and provides detailed spatiotemporal patterns of LST. Therefore, it is suitable for analyzing the regional characteristics of LST at the annual, seasonal and monthly scales.

In addition, the ERA5 reanalysis dataset is also included in the evaluation of WRF experiments in this study. ERA5 combines vast amounts of historical observations into global estimates using advanced modelling and data assimilation systems and is the latest climate reanalysis produced by ECMWF. It provides hourly data of various atmospheric, land-surface and oceanic climate variables, and includes information about uncertainties for all the variables at reduced spatial and temporal resolutions. The data covers the Earth on a 30 km grid spacing and resolves the atmosphere using 137 levels from the surface up to a height of 80 km. Chen and Ji (2019) evaluated the performance of ERA5 over the TP during the period of 1979–2012 and found that ERA5 well reproduces the temporal and spatial variations of surface air temperature and demonstrates overestimation of precipitation in wet season with an average bias of 1.0 mm/day.

Several statistics are calculated to quantify the accuracy of the WRF simulations, including the correlation coefficient, the uncentered root-mean-square error (RMSE) and the relative bias (RB). The correlation coefficient is used to describe the temporal and spatial similarity between the observation and the simulation. The RMSE can measure the average magnitude of the deviation of a model simulation from the observation (Hu et al. 2016), with mean error, correlation coefficient, and standard deviation taken into account (Taylor et al. 2001; Xu and Han 2019).

3 Results from the re-initialization and spectral nudging experiments

The WRF experiments using two regional climate simulation approaches (Exp-SN and Exp-RI) are evaluated through statistical verifications of mean and daily T2m and precipitation, as well as the diurnal variation of precipitation over the TP region. All the simulation results are interpolated to the station sites or the grid cells with the inverse distance weight interpolation method to be compared with the in-situ observations and the satellite precipitation products. Moreover, bias-corrections are carried out for the surface air temperature based on the lapse rate (LR) when the results are interpolated from the WRF experiments and ERA5 to the station sites. According to the spatiotemporal variability of LR proposed by Wang et al. (2018), the mean LRs over the western TP, northeastern TP and southeastern TP in summer are − 4.90, − 4.53 and − 4.03 K/km, respectively, which are consistently lower than the commonly used global mean LR (− 6.5 K/km). In addition, considering the diurnal cycle of lapse rate over the TP, another trial has been made to apply different lapse rates to Tmax and Tmin, deriving very similar results to that presented below.
3.1 Summer mean surface air temperature and precipitation

Figure 2 shows the 3-year averaged (2016–2018) summer mean daily T2m, Tmax and Tmin from the in-situ observations, and the differences between the WRF simulations as well as ERA5 and the observation. The observed T2m decreases from the southeast TP to the northwest, with the maximum T2m about 24 °C over the eastern TP while the minimum T2m below 10 °C over the central TP. All the WRF experiments can well produce the spatial pattern of T2m with the spatial correlation coefficients (SCCs) larger than 0.95, but tend to underestimate the T2m over the regions south of 35° N, especially in the Exp-RI with slightly greater cold bias. The simulated distributions of Tmax and Tmin also agree well with the observations with the SCCs above 0.9 and the RMSE below 2.6 °C. Compared to the Exp-RI, the Exp-SN has lower RMSEs for the spatial

Fig. 2 The 3-year averaged (2016–2018) summer mean T2m, Tmax and Tmin from the in-situ observations (a–c), and the biases in the Exp-SN (d–f), the Exp-RI (g–i) and ERA5 (j–l)
patterns of T2m and Tmax. ERA5 shows comparable performance with the WRF experiments in reproducing the spatial pattern of the 3-year summer mean surface air temperature with SCCs above 0.90. However, the WRF experiments outperform ERA5 in simulating the Tmax with reduced RMSEs, especially in the Exp-SN over the regions south of 35° N. The daily temperature range (DTR) is higher over the regions north of 30° N according to the station observations (figure not shown), which is above 12 °C, while the minimum DTR below 10 °C is found over the southeastern TP. All the WRF experiments can well capture the spatial pattern of DTR with the SCCs higher than 0.73 and the RMSEs less than 2.31 °C, and the Exp-SN shows a higher SCC of 0.78 and lower RMSE of 1.24 °C. However, they both show obvious underestimation over the central and northern TP, which is approximately 1 °C in the Exp-SN and up to 3 °C in the Exp-RI. The spatial pattern of DTR in ERA5 is similar to that of Exp-RI in which colder bias are found compared with Exp-SN. Therefore, ERA5 and the WRF experiments all show satisfying ability in reproducing the spatial pattern of surface air temperature, and the Exp-SN shows added value in simulating the characteristics of DTR, which is probably attributed to its better depict of Tmax with the RMSE reduced by about 1 °C.

The summer mean LST is also evaluated against the satellite data. Figure 3 shows the summer mean LST from the MODIS dataset and the WRF experiments in 2016 and 2017, and the difference between the two years. According to the MODIS data, the warmer LST is located over the northeastern TP, with the maximum value above 24 °C in the Qaidam Basin. The colder LST is located over the central TP and along the southern slope of TP with the minimum value below 4 °C. All the WRF experiments can reproduce the spatial pattern of LST with the SCCs above 0.75 and the RMSEs below 4.6 °C. The Exp-SN experiment generates warm biases of LST especially over the western and southern TP, with the RMSE larger than that in the Exp-RI when compared with the MODIS data. In addition, both WRF experiments underestimate the difference of summer LST between 2016 and 2017, especially over the northern and eastern TP, and the underestimation is improved over the southwestern TP in Exp-RI.

Fig. 3 The summer mean LST in 2016 and 2017 and the difference between the two years in the MODIS dataset (a, d, g), the Exp-SN (b, e, h) and the Exp-RI (c, f, i)
Figure 4 depicts the 3-year averaged summer precipitation from the station observations and the GSMaP satellite dataset, and the biases in the WRF simulations. The observed precipitation decreases from the southeast TP to the northwest, with the maximum precipitation above 6 mm/day located at the southeastern corner of TP and along the southern slope of TP, while the minimum precipitation below 1 mm/day extending along the northwest of TP. All the WRF experiments can well capture the spatial pattern of summer precipitation with the SCCs above 0.7 and the RMSEs below 1.16 mm/day when compared with the station observations, but they tend to underestimate the precipitation in most regions of TP with greater bias over the regions south of 35°N. Unlike the sparse station observations over the TP especially the western TP, the GSMaP dataset has a whole coverage over the TP with a high resolution. When compared with the GSMaP precipitation dataset, the WRF experiments show higher SCCs (> 0.64) and comparable RMSEs. The Exp-SN has slight biases ranging from −2 to 2 mm/day over most regions of TP. However, obvious wet biases (above 4 mm/day) exist over the central TP in the Exp-RI, which may account for the larger RMSEs and the lower SCCs than those in the Exp-SN. For ERA5, higher SCCs are found especially when compared with the GSMaP dataset, indicating its competitive ability in capturing the spatial pattern of summer precipitation over the TP. However, wetter biases exist especially over the central and southeastern TP. Overall, the WRF experiments have similar performance with ERA5 in reproducing the spatial pattern of precipitation, and the Exp-SN exhibits added value with the wet bias reduced by about 1 mm/day especially over the central TP when compared with the GSMaP dataset.

The Taylor diagrams are presented to evaluate the two WRF experiments and ERA5 in simulating the spatial distributions of summer temperature and precipitation over the TP in each year (2016–2018) (Fig. 5). When compared with the station observations, the WRF experiments and ERA5 have similar performances in simulating the distributions of T2m, Tmax and Tmin with the SCCs of about 0.95. For the precipitation, the two WRF experiments also show comparable performances and outperform ERA5 with reduced RMSEs when compared with the station observations. However, the Exp-SN outperforms the Exp-RI when the GSMaP precipitation dataset is used as a reference, with obviously higher SCC and lower RMSE in each year. In ERA5, higher SCCs and larger RMSEs co-exist with both the station observation and the GSMaP dataset as references, and the difference between the WRF experiments and ERA5 is reduced when compared with the GSMaP dataset. To conclude, although there exist subtle differences in the simulation of precipitation between the two experiments when different datasets are selected as references, they still show similar spatial patterns in most regions of TP and reduce the wet biases in ERA5, which promotes our understanding of summer precipitation over the TP.

3.2 Daily surface temperature and precipitation

The 3-year averaged (2016–2018) daily variations of regional mean (over the TP) T2m, Tmax, Tmin and DTR from the in-situ observations, the Exp-SN, the Exp-RI and ERA5 are shown in Fig. 6. The observed T2m ranges from 10 to 16 °C throughout summertime, with the maximum T2m in late July and early August. All the WRF experiments and ERA5 can well simulate the daily variation of T2m with the temporal correlation coefficients (TCCs) higher than 0.95 and the RMSEs less than 0.7 °C (Table 1). The Tmax ranges from 18 to 24 °C in the observation, and Exp-SN outperforms Exp-RI and ERA5 with the cold bias reduced by more than 1 °C. For the Tmin and DTR, ERA5
shows slightly higher TCCs than WRF experiments. The observed DTR varies between 9 and 18 °C, with the maximum DTR exceeding 16 °C in early June and the minimum below 10 °C in early July. The DTR in the Exp-SN is closer to the observation, with lower RMSE at about 1.0 °C, which probably benefits from its better simulation of Tmax. Obviously, ERA5 can better catch the characteristics of the daily variation of surface air temperature over the TP, especially for Tmin and DTR, but the Exp-SN simulates the Tmax and the DTR closer to the observation.

Regarding the daily variation of regional averaged precipitation over the TP (Fig. 7), both Exp-SN and Exp-RI can catch its main characteristics with the TCCs all above 0.80. The two experiments have comparable performance when compared with the station observations. While with the GSMaP as the observation, the two experiments clearly overestimate the daily precipitation, and the Exp-SN can improve the simulation with lower RMSE. Wetter bias exists in ERA5 regardless of the selection of reference dataset which is about 1mm/day larger than that in the WRF.

Fig. 5 Taylor diagrams for the spatial distributions of temperature (a) and the precipitation (b) from 2016 to 2018

Fig. 6 3-Year averaged daily variations of regional mean T2m (a), Tmax (b), Tmin (c) and DTR (d) from the in-situ observations, the simulations of Exp-SN and Exp-RI as well as ERA5. Units: °C
Convection-permitting regional climate simulations over Tibetan Plateau: re-initialization…

Overall, the WRF experiments outperform ERA5 with significantly reduced RMSEs.

The spatial distributions of TCCs and RBs of T2m, Tmax and Tmin are presented in Figs. 8 and 9, respectively. For temperature, RB is calculated by bias for WRF experiments and ERA5 divided by observations from stations in degree Celsius which are consistently positive values, which is probably because stations are mostly located at low altitude regions and only observation data in summer is analyzed here. The TCCs of T2m and Tmax demonstrate similar patterns in both experiments, decreasing from northeast to southwest, with the TCCs above 0.9 mostly occurring over the northeast TP and those below 0.7 along the south slope of TP. The TCC of Tmin is lower than that of T2m and Tmax, ranging from 0.6 to 0.8 with less spatial variation. ERA5 demonstrates similar TCC patterns for T2m and Tmax to those in the WRF experiments, while it produces larger TCCs for Tmin at almost all the stations over the TP. The RBs of Tmax range from –10 to 10% in the WRF experiments and ERA5 (Fig. 9), and the RMSEs range from 1 to 1.5 °C over most regions (figure not shown). Cold bias of Tmin predominates over the TP especially in the Exp-RI and ERA5 with the RBs ranging from –20 to –10%, while they are reduced in the Exp-SN. Accordingly, larger RMSEs of Tmax above 4 °C are found in the Exp-RI and ERA5 especially over the southeastern TP. However, the two WRF experiments and ERA5 show similar RMSEs for Tmin over the southeastern TP, and the RB indicates that the WRF experiments tend to underestimate Tmin and ERA5 tends to overestimate it.

Figure 10 shows the spatial distributions of TCC and RB for the simulated daily precipitation. The two WRF experiments demonstrate quite similar spatial pattern of TCCs with the TCCs above 0.5 mainly located over the eastern TP. In the Exp-RI, there exists obvious wet bias with RBs of about 30–50% over the central TP while dry bias predominates in the Exp-SN. Higher TCCs and larger RBs above 50% co-exist in ERA5, indicating its advantage in capturing the daily variation of precipitation and disadvantage in qualitatively presenting the summer precipitation over the TP.

Therefore, the TCCs and the RBs give more objective evaluations of the WRF experiments and ERA5 over different regions of TP, revealing that the added value of Exp-SN for the Tmax lies over the southeastern TP and the main difference of precipitation simulation between the two WRF experiments lies over the central TP.

3.3 Diurnal cycle of precipitation

To evaluate the performance of WRF in simulating the diurnal variation of precipitation over the TP, the GSMaP satellite precipitation dataset with the temporal resolution...
of 1-hour is used as the observation. Figure 11 shows the 3-year averaged (2016–2018) occurrence time of maximum precipitation from the observation and the Exp-SN and Exp-RI experiments as well as ERA5. The observed maximum precipitation mostly occurs after 18:00 Local Standard Time (LT) over the TP, and even after 22:00 LT over the southeastern TP, while it mainly occurs in early morning in the Qaidam Basin. The WRF experiments can well produce the spatial pattern of the occurrence time of maximum precipitation over the eastern TP with 1–2 h in advance. However, they both tend to simulate a much more advanced occurrence time of maximum precipitation over the southeastern TP and along the south slope of TP. The greatest difference between the Exp-SN and the Exp-RI lies over the western and central TP. The maximum precipitation in the Exp-SN occurs before 06:00 LT over most regions of central TP, while the simulation of Exp-RI agrees more with the observation. ERA5 shows less spatial variation than the WRF experiments, with the precipitation peak at afternoon and night in most regions over the TP.

Figure 12 shows the 3-year averaged regional mean diurnal cycle of precipitation amount (PA) over the whole TP, TP-NW, TP-SW, TP-NE and TP-SE. It can be found that the observed PA ranges from 0.05 to 0.2 mm/h over the TP, with the two peaks occurring at 17:00 LT and 22:00 LT. Both Exp-SN and Exp-RI can well capture the bimodal structure of the diurnal variation of precipitation over the TP with the correlation coefficient above 0.7 which passes the 0.01 significance test (Table 2), but they both tend to simulate the 17:00 LT precipitation peak in advance by 1 h and postpone the 22:00 LT peak by 3 h. The Exp-SN can reduce the wet bias in the Exp-RI, especially at night and in early morning. In general, the characteristics of PA diurnal cycle vary with regions, with the magnitude greater over the southern TP than the northern TP. In addition, the observed diurnal variations of PA are quite similar over TP-SE and TP-SW, with two peaks in the afternoon (about 16:00 LT) and at night (about 22:00 LT), respectively. Both Exp-SN and Exp-RI can generally reproduce the diurnal cycle, but they all simulate the afternoon peak about 3 h earlier than the observation. The Exp-SN can catch the bimodal structure of the diurnal cycle over TP-SE and well simulate the PA peak at night, while the Exp-RI only simulates a unimodal structure and miss the PA peak at night. The two experiments can reproduce the diurnal cycle of PA over TP-NE with the peak in the afternoon, while the Exp-RI clearly overestimates the
daytime PA. Over TP-NW, PA is weaker than that in the other sub-regions. Although the WRF experiments can simulate the diurnal variation of PA over TP-NW, they both significantly overestimate the PA especially in the afternoon and at night, with the RB larger than 100% in the Exp-SN and 200% in the Exp-RI. ERA5 tends to present a similar
unimodal structure of PA diurnal cycle over the whole TP with the precipitation peak occurring at about 17:00 LT, which indicates its limited ability in reproducing the PA diurnal cycle of over the TP.

The diurnal variations of precipitation frequency (PF) and precipitation intensity (PI) are quite similar to those of PA (figure not shown), and both Exp-SN and Exp-RI can reproduce the diurnal cycles with obvious nocturnal precipitation. The WRF experiments tend to overestimate PI and underestimate PF over the TP except for TP-NW where exists consistent overestimation of PA, PF and PI, indicating that the overestimation of PA over the TP may be induced by the overestimation of PI. On the contrary, the overestimation of PA in ERA5 may be attributed to the overestimation of PF.

In general, both WRF experiments can well reproduce the spatial pattern of the occurrence time of maximum precipitation and the diurnal cycle of precipitation over the TP, especially over the eastern TP. The WRF model tends to overestimate the PI over the TP, which leads to the overestimation of PA. However, ERA5 shows limited ability in reproducing the diurnal cycle of PA and produces great overestimation for PA and PF.

4 Discussion

To investigate into the causes of the differences between the Exp-SN and Exp-RI in simulating the temperature over the TP, the 3-year averaged surface energy balance is studied. According to Xu et al. (2015), the surface energy balance equation is as follows:

$$\sigma T_s^4 = SW \downarrow + SW \uparrow + LW \downarrow + SH + LH + GHF,$$

where $\sigma$, $T_s$, $SW \downarrow$, $SW \uparrow$, $LW \downarrow$, $SH$, $LH$ and GHF represent the Stefan-Boltzmann constant, skin temperature, downward solar radiation, upward solar radiation, downward longwave radiation, sensible heat flux, latent heat flux and ground heat flux, respectively. The sum of the right-hand terms at 06:00 and 18:00 UTC from the WRF experiments are plotted (Fig. 13) to reflect the spatial pattern of skin temperature, which is correlated with surface air temperature.

At 06:00 UTC, the sum of the right-hand terms is greater in the Exp-SN than that in the Exp-RI, which is above 420 W/m$^2$ in most regions over TP in the Exp-SN. The surplus energy in the Exp-SN mainly comes from the net shortwave radiation which is about 50 W/m$^2$ greater than that in the Exp-RI and the insufficient upward sensible and latent heat flux which is about 40 W/m$^2$ less than that in the Exp-RI over most regions (figure not shown). Therefore, more downward solar radiation as well as less upward sensible and latent heat flux makes up for the GHF which transports heat from land surface to deeper soil layers in the Exp-SN, and leads to more energy conserved at surface which further warms the near surface air.

At nighttime (18:00 UTC), the Exp-RI produces greater downward longwave radiation which contributes a lot to the net radiation and more upward GHF which represents the
transport of heat from deeper soil to surface over the southeastern TP. As a result, it simulates higher skin temperature and further leads to higher surface air temperature at night (Tmin) over the southeastern TP. However, over the central and northern TP, the Exp-SN simulates stronger upward heat flux transport from the deeper soil to surface which makes up for the insufficient downward longwave radiation, as well as surplus upward sensible and latent heat flux. Therefore, the Tmin is higher in the Exp-SN over the central and northern TP.

Atmospheric water vapor is very important for precipitation. Figure 14 shows the 3-year averaged column moisture flux divergence in the two experiments and the difference between them. In both Exp-SN and Exp-RI, vigorous moisture convergence and divergence occur over the southeastern TP and along the south slope of TP, which is stronger in the Exp-RI. Over the central TP where more precipitation occurs in the Exp-RI, stronger moisture flux convergence can be found in the Exp-RI. Furthermore, the greater upward latent heat flux in the Exp-RI indicates more water vapor transported from surface over the central and eastern TP. To carry out a more specific comparison between Exp-SN and Exp-RI, three regions with significant difference between the two experiments are selected (framed with black lines

Fig. 12 3-Year averaged regional mean diurnal cycle of precipitation amount (PA) over the whole TP (a), TP-NW (b), TP-SW (c), TP-NE (d) and TP-SE (e)
They are located at the central and eastern TP (Region 1, 32°–36° N, 86°–102° E), the southeastern TP (Region 2, 26°–32° N, 96°–102° E) and along the south slope of TP (Region 3, 26°–30° N, 84°–92° E). In Region 1, more precipitation and stronger moisture convergence of about $-3.46 \times 10^{-8}$ kg/(m² s) co-exist in the Exp-RI. The column moisture flux divergence in Region 2 is similar to that in Region 1, with stronger moisture convergence of about $-3.42 \times 10^{-8}$ kg/(m² s) in the Exp-RI, which results in more precipitation. However, in Region 3, dry biases are demonstrated in both experiments, which is more significant in the Exp-RI. A regional mean column moisture flux divergence of about $1.27 \times 10^{-7}$ kg/(m² s) is produced in the Exp-RI, which indicates a dominant divergence and contributes to the great dry bias. Meanwhile, the Region 3 averaged column moisture flux divergence is about $-4.12 \times 10^{-9}$ kg/(m² s) in the Exp-SN, which indicates a much weaker moisture convergence than that in Region 1 and Region 2 and results in less precipitation. Thus, the stronger moisture flux convergence and the more water vapor lead to more precipitation in the Exp-RI over the central and southeastern TP than in the Exp-SN, and the dominant divergence along the south slope of TP contributes to the greater dry bias in the Exp-RI.

### 5 Conclusions

Two WRF experiments with the regional climate simulation schemes of spectral nudging and re-initialization are performed over the TP. The surface air temperature and the precipitation are evaluated based on the in-situ station observations and the GSMaP dataset.

Both WRF experiments successfully capture the spatial patterns and the daily variations of T2m and Tmx, with the SCCs and the TCCs over 0.9, and the Exp-SN outperforms...
the Exp-RI and ERA5 in simulating the spatiotemporal characteristics of Tmax especially over the southeastern TP. In addition, the spatiotemporal characteristics of Tmin are also reasonably reproduced. The DTR is underestimated over southern TP in summer in both experiments, with the biases smaller and the SCCs higher in the Exp-SN. Warm biases are produced for the LST, especially in the Exp-SN over western and southern TP. However, the difference of summer LST between 2016 and 2017 is better simulated in the Exp-RI over the southwestern TP based on comparison against MODIS. ERA5 shows comparable ability in reproducing the spatial pattern of surface air temperature but has an advantage over the WRF experiments in capturing the daily variation of Tmin over the whole TP. The surface energy budget is further analyzed, indicating that the surplus net shortwave radiation and the insufficient upward heat fluxes at daytime result in the higher surface air temperature in the Exp-SN. At nighttime, more downward longwave radiation and upward GHF over the southeastern TP in the Exp-RI lead to higher skin temperature and surface air temperature over the southeastern TP. Over the central and northern TP, the Exp-SN generates more upward ground heat flux that makes up for the insufficient downward longwave radiation and surplus upward sensible and latent heat flux, which jointly lead to the higher Tmin.

The spatial pattern and the daily variation of summer precipitation are also reasonably reproduced in both WRF experiments, with the SCCs and the TCCs above 0.7 and 0.86, respectively. However, dry bias exists in the regions south of 35° N in summer when compared with station observations, which are reduced in the Exp-RI especially over the central and southeastern TP. Based on the GSMaP dataset, dominant wet biases are found in both experiments, which is smaller in the Exp-SN over the central TP and southeastern TP. The opposite bias reminds us that validations of model simulation against observational data should be considered with care, especially when the datasets come from different sources. The further investigation into the column moisture flux divergence indicates that the stronger moisture flux convergence together with the more water vapor transported from surface leads to more precipitation in the Exp-RI experiment over the central and southeastern TP.

The diurnal cycle of precipitation over the TP is explored to better understand its temporal variation. Both WRF experiments can well produce the spatial pattern of the occurrence time of maximum precipitation over eastern TP, despite an advance of 1–2 h in the simulations. Over the central TP, the Exp-RI performs better than the Exp-SN. In addition, the diurnal cycles of PA and PF are reasonably simulated in both experiments, with the obvious nocturnal precipitation well captured. However, the precipitation peak at 17:00 LT is produced in advance and that at 22:00 LT is postponed. The WRF experiments tend to overestimate PI and underestimate PF over the TP except for TP-NW, indicating that the overestimation of PA over the TP may be induced by the overestimation of PI. However, ERA5 shows limited ability in reproducing the diurnal cycle of PA with a similar unimodal structure over the whole TP and greatly overestimates PA and PF.

The re-initialization scheme has been proved to be a favorable approach for RCM simulations (Druyan et al. 2001; Qian et al. 2003). This study reveals that the spectral nudging scheme is also a competitive approach, since the Exp-SN and the Exp-RI demonstrate comparable performances in the simulations of temperature and precipitation over the TP. The results in this research can provide a better understanding of the climate in recent years over the TP.

Acknowledgements We would like to thank the reviewers and the associate editors for their constructive suggestions and comments that substantially improved the paper. The research is supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP, Grant No.2019QZKK0206) and National Key Research and Development Program of China (2018YFA0606003), as well as the National Natural Science Foundation of China (41875124).
Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by MM, PZ and JT. PH, DL and JT helped perform the analysis with constructive discussions. The first draft of the manuscript was written by MM and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Funding This work was supported by the Second Tibetan Plateau Scientific Expedition and Research Program (STEP, Grant No.2019QZKK206) and National Key Research and Development Program of China (2018YFA0606003), as well as the National Natural Science Foundation of China (41875124).

Availability of data and material The station observations used in this work are available at: http://data.cma.cn/en. The GSMaP satellite dataset is available at: https://sharaku.eorc.jaxa.jp/GSMaP/. The combined Terra and Aqua MODIS land surface temperature and meteorological station product for China is available at: https://data.tpdc.ac.cn/en/data/055dfa65-e097-4000-9bda-992def329697/?q=. The hourly ERA5 reanalysis dataset is available at: https://cds.climate.copernicus.eu/#/search?text=ERA5&type=dataset.

Code availability The analysis code is available on request from the corresponding author.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Consent to participate Written informed consent was obtained from all participants.

Consent for publication Written informed consent for publication was obtained from all participants.

References

Alexandrino A, de Elia R, Laprise R, Separovic L, Biner S (2009) Sensitivity study of regional climate model simulations to large-scale nudging parameters. Mon Weather Rev 137(5):1666–1686. https://doi.org/10.1175/2008mwr2620.1

Chen Y, Ji D (2019) Evaluation of ERA5 atmospheric reanalysis datasets for surface climatology over the Tibetan Plateau. In: AGU fall meeting abstracts

Davies H, Turner R (1977) Updating prediction models by dynamical relaxation: an examination of the technique. Q J R Meteorol Soc 103(436):225–245

Druyan LM, Fulakeza M, Lonergan P, Saloun M (2001) A regional model study of synoptic features over West Africa. Mon Weather Rev 129(6):1564–1577. https://doi.org/10.1175/1520-0493(2001)129<1564:ARMSOS>2.0.CO;2

Duan AM, Wu GX (2005) Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. Clim Dyn 24(7–8):793–807. https://doi.org/10.1007/s00382-004-0488-8

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

Gao Y, Chen F, Jiang Y (2020) Evaluation of a convection-permitting modeling of precipitation over the Tibetan Plateau and its influences on the simulation of snow-cover fraction. J Hydrometeor 21(7):1531–1548. https://doi.org/10.1175/jhm-d-19-0277.1

Giorgi F (2019) Thirty years of regional climate modeling: where are we and where are we going next? J Geophys Res Atmos. https://doi.org/10.1029/2018jd030094

Glisan JM, Gutzowki WJ, Cassano JJ, Higgins ME (2013) Effects of spectral nudging in WRF on Arctic temperature and precipitation simulations. J Clim 26(12):3985–3999. https://doi.org/10.1175/jcli-d-12-00318.1

Gu H, Yu Z, Peltier WR, Wang X (2020) Sensitivity studies and comprehensive evaluation of RegCM4.6.1 high-resolution climate simulations over the Tibetan Plateau. Clim Dyn 54(7–8):3781–3801. https://doi.org/10.1007/s00382-020-05205-6

Hersbach H, Bell B, Berrisford P, Hirahara S, Horányi A, Muñoz-Sabater J, Nicolas J, Peubey C, Radu R, Schepers D, Simmons A, Soci C, Abdalla S, Balsamo G, Bechtold P, Biavati G, Bidlot J, Bonavita M, Chiara G, Dahlgren P, Dee D, Diamantakis M, Dragani R, Flemming J, Forbes R, Fuentes M, Geer A, Haimberger L, Healy S, Hogan RJ, Hólm E, Janisková M, Keeley S, Laloyaux P, Lopez P, Lupu C, Radnoti G, Rosnay P, Rozum I, Vamborg F, Villaume S, Thépaut JN (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146(730):1999–2049. https://doi.org/10.1002/qj.3803

Hohenegger C, Brockhaus P, Schär C (2008) Towards climate simulations at cloud-resolving scales. Meteorol. Z 17(4):383–394. https://doi.org/10.1002/1600-0870/200803303

Hu G, Zhao L, Wu X, Li R, Wu T, Xie C, Qiao Y, Shi J, Cheng G (2016) An analytical model for estimating soil temperature profiles on the Qinghai-Tibet Plateau of China. J Arid Land 8(2):232–240. https://doi.org/10.1007/s00333-015-0558-4

Huang Z, Zhong L, Ma Y, Fu Y (2021) Development and evaluation of spectral nudging strategy for the simulation of summer precipitation over the Tibetan Plateau using WRF (v4.0). Geosci Model Dev 14(5):2827–2841. https://doi.org/10.5194/gmd-14-2827-2021

Iacono MJ, Delamere JS, Mlawer EJ, Shephard MW, Clough SA, Collins WD (2008) Radiative forcing by long-lived greenhouse gases: calculations with the AER radiative transfer models. J Geophys Res. https://doi.org/10.1029/2008jd009944

Kang S, Xu Y, You Q, Flügel W-A, Pepin N, Yao T (2010) Review of climate and cryospheric change in the Tibetan Plateau. Environ Res Lett 5:152. https://doi.org/10.1088/1748-9326/5/1/015101

Li P, Furtado K, Zhou T, Chen H, Li J (2020) Convection-permitting modelling improves simulated precipitation over the central and eastern Tibetan Plateau. Q J R Meteorol Soc 147(734):341–362. https://doi.org/10.1002/qj.3921

Lin C, Chen D, Yang K, 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. Clim Dyn 51(9–10):3195–3207. https://doi.org/10.1007/s00382-018-4074-x

Lo JC-F, Yang Z-L, Pielke RA (2008) Assessment of three dynamical climate downscaling methods using the Weather Research and Forecasting (WRF) model. J Geophys Res. https://doi.org/10.1029/2007jd009216

Lu D, Yong B (2018) Evaluation and hydrological utility of the latest GPM IMERG V5 and GSMaP V7 precipitation products over the Tibetan Plateau. Remote Sens. https://doi.org/10.3390/rs10112202

Lv M, Xu Z, Yang ZL (2020) Cloud resolving WRF simulations of precipitation and soil moisture over the Central Tibetan Plateau: an assessment of various physics options. Earth Space Sci. https://doi.org/10.1002/2019ea000865

Maussion F, Scherer D, Mölg T, Collier E, Curio J, Finkelnburg I, Vamborg F, Villaume S, Thépaut JN (2020) The ERA5 global reanalysis. Q J R Meteorol Soc 146(730):1999–2049. https://doi.org/10.1002/qj.3803

R (2014) Precipitation seasonality and variability over the Tibetan Plateau as resolved by the High Asia Reanalysis. J Clim 27(5):1910–1927. https://doi.org/10.1175/JCLI-D-13-00282.1

Nakanishi M, Ninni H (2006) An improved Mellor–Yamada level-3 model: its numerical stability and application to a regional...
Convection-permitting regional climate simulations over Tibetan Plateau: re-initialization…

Taylor KE (2001) Summarizing multiple aspects of model performance in a single diagram. J Geophys Res Atmos 106(D7):7183–7192. https://doi.org/10.1029/2000jd000719

Thompson G, Field PR, Rasmussen RM, Hall WD (2008) Explicit forecasts of winter precipitation using an improved bulk microphysics scheme. Part II: implementation of a new snow parameterization. Mon Weather Rev 136(12):5095–5115. https://doi.org/10.1175/2008MWR2387.1

von Storch H, Langenbergh H, Feser F (2000) A spectral nudging technique for dynamical downscaling purposes. Mon Weather Rev 128(10):3664–3673. https://doi.org/10.1175/1520-0493(2000)128<3664:ASNDT2.0.CO;2

Wang X, Yang M, Wan G, Chen X, Pang G (2013) Qinghai-Xizang (Tibetan) Plateau climate simulation using the regional climate model RegCM3. Clim Res 57(3):173–186. https://doi.org/10.3354/cr01167

Wang Y, Wang L, Li X, Chen D (2018) Temporal and spatial changes in estimated near-surface air temperature lapse rates on Tibetan Plateau. Int J Climatol 38(7):2907–2921. https://doi.org/10.1002/joc.5471

Wang X, Tolksdorf V, Otto M, Scherer D (2021) WRF-based dynamical downscaling of ERA5 reanalysis data for High Mountain Asia: towards a new version of the High Asia Refined analysis. Int J Climatol 41(1):743–762. https://doi.org/10.1002/joc.6686

Xu Z, Han Y (2019) Short communication comments on ‘DISO: A rethink of Taylor diagram’. Int J Climatol 40(4):2506–2510. https://doi.org/10.1002/joc.6359

Xu Z, Yang ZL (2015) A new dynamical downscaling approach with GCM bias corrections and spectral nudging. J Geophys Res Atmos 120(8):3063–3084. https://doi.org/10.1002/2014jd022958

Xu Z, Mahmood R, Yang ZL, Fu C, Su H (2015) Investigating diurnal and seasonal climatic response to land use and land cover change over monsoon Asia with the Community Earth System Model. J Geophys Res Atmos 120(3):1137–1152. https://doi.org/10.1002/2014jd022479

Ye D, Gao Y (1979) Meteorology of the Tibetan Plateau (in Chinese). Science Press, Beijing, pp 30–55

You Q, Fraedrich K, Ren G, Ye B, Meng X, Kang S (2012) Inconsistencies of precipitation in the eastern and central Tibetan Plateau between surface adjusted data and reanalysis. Theoret Appl Climatol 109(3–4):485–496. https://doi.org/10.1007/s00382-012-0594-1

Zhao B, Mao K, Cai Y, Shi J, Li Z, Qin Z, Meng X, Shen X, Guo Z (2020) A combined Terra and Aqua MODIS land surface temperature and meteorological station data product for China from 2003 to 2017. Earth Syst Sci Data 12(4):2555–2577. https://doi.org/10.5194/essd-12-2555-2020

Zhou X, Yang K, Ouyang L, Wang Y, Jiang Y, Chen D, Prein A (2021) Added value of kilometer-scale modeling over the third pole region: a CORDEX-CPTP pilot study. Clim Dyn. https://doi.org/10.1007/s00382-021-05653-8

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.