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Regional climate dynamical downscaling over the Tibetan Plateau —From quarter-degree to kilometer-scale

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Abstract The Tibetan Plateau (TP) possesses the largest cryosphere in the world outside of the Arctic and Antarctic, and is the source of nine major rivers in Asia. The surface environment of the TP has undergone significant changes against the background of global warming. It is projected that the continuation of climate change in the future will result in most of the glaciers and frozen soil disappearing by the end of this century, and freshwater resources will be greatly reduced, on which 22% of the world's population depends. These environmental changes are of great concern to global society given the influences of the TP on the climate at the global scale. However, great uncertainties exist in global climate simulations over the TP, which affects our ability to properly understand the associated water security crisis. Based on atmospheric dynamics and physical processes, dynamical downscaling can characterize surface conditions more accurately than global simulations, and better simulate and predict regional or local weather and climate situations. With advances in supercomputing, the grid spacing of dynamical downscaling simulations has been continuously increasing, marching the technique into the kilometer-scale era. In this paper, the origin and development of dynamical downscaling in the TP region from the quarter-degree to kilometer scale is firstly introduced, including an assessment of the advantages and disadvantages of dynamical downscaling at the kilometer scale over the TP. Then, the main land surface factors affecting the performance of dynamical downscaling over the TP are described, as well as a brief introduction to a land surface model with specific plateau characteristics. Specifically, it has emerged that perfecting the land surface model and improving the performance of land-atmosphere interaction are the most effective ways to advance the performance of dynamic downscaling in this region. Finally, the challenges and some recommended future research directions are discussed and proposed.

Keywords Tibetan Plateau, Climate dynamical downscaling, Land surface processes

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1. Introduction

The Tibetan Plateau (TP) is characterized by numerous mountains, steep terrain, and harsh natural conditions. As such, the spatial representation of in-situ observation sites on the TP is poor, and it is difficult to obtain regional information based on these limited in-situ observations. Remote sensing can obtain spatial distribution information, but is limited to the ground surface. The simulation of land surface processes or earth surface ecological and hydrological processes is important for studying the surface conditions of the TP; however, the performance of land surface models strongly depends on the quality of the driving meteorological data—especially the accuracy of precipitation,

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which has an important impact on land surface processes and simulating the water cycle (Raleigh et al., 2016; Zhang et al., 2016; Gao et al., 2017). The uncertainty of the precipitation data covering the TP seriously hinders the accuracy of simulations and recognition of the interactions among Earth's different spheres. Therefore, the accuracy of precipitation datasets has become a bottleneck problem in the study of the response of the TP terrestrial environment to global warming.

Due to the TP's harsh natural conditions, large uncertainties remain in our understanding of its regional climate, and especially its precipitation. Firstly, observation sites are sparsely and unevenly distributed. Specifically, the majority of conventional meteorological observation stations are mainly distributed in the valleys of the central and eastern TP, rather than on hillslopes or summits; the density of stations in the high-altitude western TP is much lower than that in the central and eastern TP; and the altitude of the highest conventional meteorological station is no more than 4800 m. In the southeastern TP, the spatial representation of observation stations is particularly poor—more so than in other areas—due to its strongly varying topography. Therefore, it is difficult to elucidate the characteristics of the weather and climate of the whole TP based solely on the limited observation data of meteorological stations. Secondly, whilst atmospheric and ground-level remote sensing can obtain information on the regional-scale surface conditions, the accuracy of these data is limited by the quality of the inversion algorithms used to generate them and the ground-based observation data employed to verify them. Therefore, climate models have become an important complementary approach to obtaining regional-scale climate information over the TP (Giorgi and Gutowski, 2015; Papalexiou et al., 2020).

However, numerous studies have shown large biases in global climate model (GCM) simulations over the TP (Jiang et al., 2009; Su et al., 2013; Li Y et al., 2021). In addition, the TP is one of the regions with the largest inconsistencies among GCMs in historical simulations (IPCC, 2014; Li et al., 2016). Based on GCMs, reanalysis data can generate more accurate gridded information on meteorological variables by assimilating atmospheric sounding and satellite observation data. Since the turn of the 21st century, improvements in observation technology and capabilities have resulted in an increasing amount of observation information having been obtained, and the quality of the latest generation of reanalysis data has been greatly improved. For example, the second-generation NCEP-DOE and ERA-Interim reanalysis datasets perform better than their first-generation counterparts, NCEP-NCAR and ERA40; and the third-generation dataset, ERA5, is even better—superior to ERA-Interim. Therefore, reanalysis data are often used as observational data in many climate analyses. However, many studies have shown that reanalysis data also carry great uncertainties in the TP region (Wang and Zeng, 2012; Broxton et al., 2016; Dawson et al., 2016). For example, the magnitudes of warming, wetting, and stilling observed over the TP in recent decades are not reflected in the available reanalysis data (Gao et al., 2015a; Li X et al., 2018; Gao et al., 2018b). In fact, some of them even show the opposite signal of change (Gao et al., 2014). The second-generation reanalysis data perform better than the first generation, but are still not able to accurately describe the spatial differences in the drying and wetting changes over the TP. Even ERA5, the latest-generation reanalysis dataset produced by the European Centre for Medium-Range Weather Forecasts (ECMWF), which has been widely praised, still shows cold and wet biases over the TP (Liu et al., 2022), and even a significant snow-cover bias (Orsolini et al., 2019). All these biases have seriously hindered the study of regional climate and environmental changes over the TP against the background of global warming.

2. Quarter-degree (25–30 km) dynamical downscaling over the TP

Downscaling is an important way to obtain high-resolution climate information in the target region, and can be broadly categorized into two types: statistical downscaling and dynamical downscaling (Castro et al., 2005). Statistical downscaling is popular for its simplicity and efficiency; however, its accuracy is highly dependent on the richness of observations. Therefore, the applicability of statistical downscaling is very limited in the TP region, where observation data are scarce (Chen et al., 2006; Benestad et al., 2015; Poschlod et al., 2018). Based on regional climate models, dynamical downscaling (Figure 1) has become an effective way to provide gridded high-resolution meteorological data (Giorgi and Gutowski, 2015), but is highly demanding in terms of computing resources. Dynamical downscaling was quickly and widely adopted in North America and Europe (Mearns and Team, 2009; Giorgi et al., 2012); and early on in China, the research team of Gao Xuejie used RegCM to conduct dynamical downscaling research in the monsoon region of eastern China (Gao et al., 2006, 2012a, 2012b). Since then, a series of research teams have used other regional climate models to simulate the climate and extreme weather/climate in the monsoon region of eastern China (Ji and Kang, 2015; Yu et al., 2015; Xu et al., 2019). Essentially, up to and throughout the 2010s, domestic and international research teams carried out important dynamical downscaling research over the TP that opened a new chapter for such studies in the region.

German scientists carried out dynamical downscaling simulations over the TP using the WRF mesoscale climate

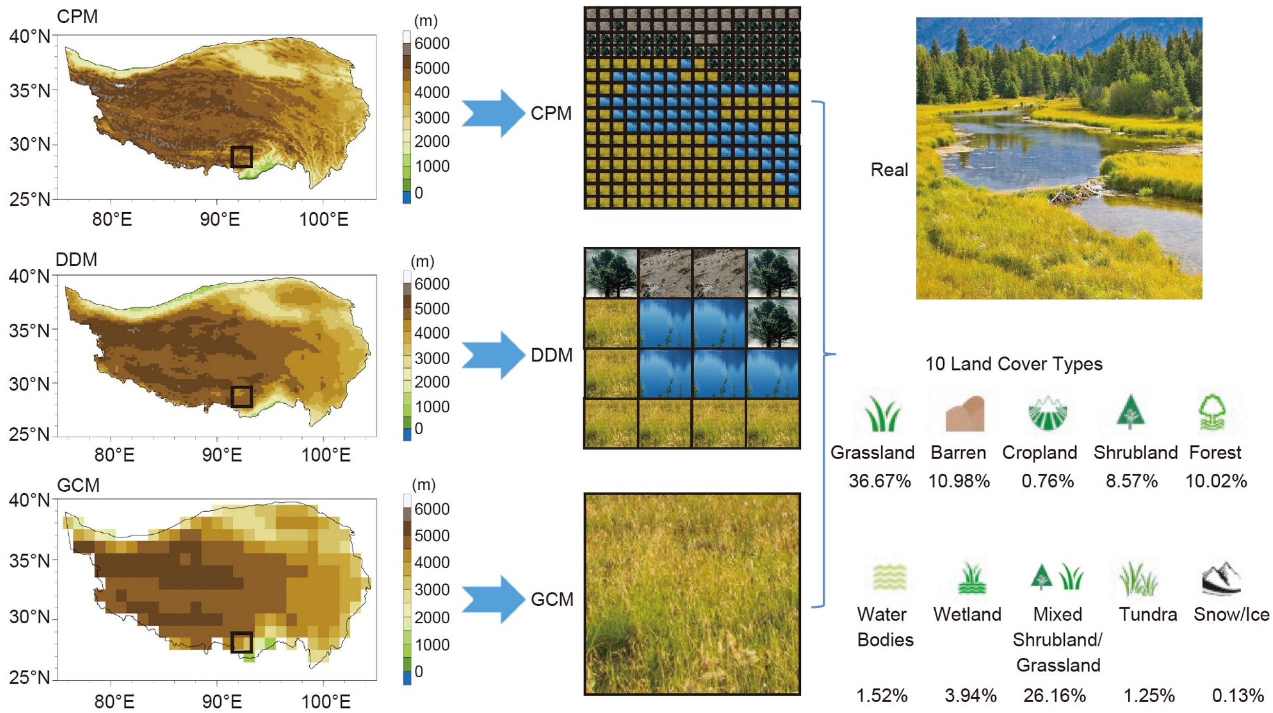

Figure 1 Schematic diagram of dynamical downscaling over the TP.

model with daily restarts and NCEP FNL as the large-scale driving data (Maussion et al., 2011, 2014). Simulations of the heavy precipitation (snowfall) process in October 2008 were carried out using ground-based rain gauge observations and Tropical Rainfall Measuring Mission (TRMM) satellite data as references, and the results showed that the simulations could not only reproduce the observed quantities, spatial patterns and seasonal characteristics of precipitation, but were also superior to the driving data in the simulations of snowfall frequency and orographic precipitation. Subsequently, the High Asia Refined analysis, with resolutions of 30, 10, and 2 km, was released. Their study focused on the precipitation type and the seasonal and interannual variability of precipitation in the High Asia glacial region, as well as the effects of the WRF model settings, nesting method, and parameterization schemes on the simulation results, in an attempt to provide an accurate precipitation simulation scheme over the TP. It was found that, although orographic precipitation can be simulated more accurately using dynamical downscaling rather than 100-km simulations, there are still many unsolved problems, such as its formation mechanism in high-altitude areas, due to the lack of observational data.

Meanwhile, the Chinese research team led by professor Yanhong Gao has also conducted dynamical downscaling simulations (at a 30-km spatial resolution) over the TP using the WRF model (Gao et al., 2015a, 2015b). There were three differences from the German team in terms of (1) the simulation period, (2) the driving data, and (3) the land surface parameterization scheme. Firstly, the study was aimed at simulating the changes to the climate and environment over the TP in recent decades, and therefore a continuous simulation was used to carry out long-term climate simulations for a period of 33 years from 1979 to 2011. Secondly, given the biases of reanalysis data and GCMs in the TP region, the large-scale driving data (reanalysis data (Gao et al., 2014) as well as GCMs (Xu et al., 2017)) were selected based on whether the observed climate change characteristics of warming, wetting and wind speed reduction could be accurately described. After ranking, ERA-Interim and CCSM4 were selected as the driving data. Furthermore, considering that the accuracy and persistence of surface conditions are important lower-boundary conditions for long-term climate simulations, the research team refined and optimized the land surface process model, providing more accurate lower-boundary conditions for regional climate simulations over the TP. The study showed that the 30-km dynamical downscaling simulated the observed elevation-dependent warming characteristics more accurately, and better reproduced the different *P-E* (precipitation minus evaporation) variability over the western hinterland and southeastern margin of the TP (Gao et al., 2015a, 2015b). The simulations of evapotranspiration and wind speed were also improved to some extent (Li X et al., 2018; Dan et al., 2021). However, there was still a failure to simulate the decreasing trend of wind speed observed over the TP in recent decades (Li X et al., 2018).

To study the possible future changes in water resources over the TP, the Chinese research team used the same model configuration as the reanalysis data-driven simulation described above. Using a GCM for the driving data to carry out climate simulations from 1980 to 2005, projections were then made of the changes in water resources (*P-E*) for the period 2006–2100 under two emission scenarios, RCM4.5 and RCP8.5 (Gao et al., 2018a). First, GCMs were evaluated, and the best-performing and available one was selected. Specifically, Xu et al. (2017) compared the upper-atmospheric and ground-level meteorological variables from the GCM outputs that were used to drive the regional climate model and selected CCSM4 as the best candidate for supplying the driving data for the historical-period and future-scenario projections. Comparison between the historical-period simulations and the reanalysis data-driven results showed that, although the systematic errors in the CCSM4-simulated temperature and precipitation over the TP were much larger than those of the reanalysis data, the deviations and spatial distributions of the two dynamical downscaling climate simulations differed little, while the trends of climate variables were significantly influenced by the driving data (Gao et al., 2017). The future climate change projection results indicated that CCSM4 is able to project the overall warming and wetting trend of the TP, and that the magnitude of the warming and wetting trend depends on the future time period and emission scenario. Unlike CCSM4, the dynamical downscaling projected the warming and wetting trend in the northern TP, while the southern TP was projected to get warmer and dryer (Gao et al., 2018a). Mechanistic analysis showed that CCSM4 basically follows the Clausius-Clapeyron equation, in which the increase in water vapor content in the atmosphere due to global warming is the dominant factor for changes in *P-E*. Meanwhile, in the projections of the dynamical downscaling, the warming mechanism was consistent with that of the historical-period *P-E* changes, and the dominant factor was the dynamical factor, reflecting the regional circulation changes (Zhang et al., 2019). Also, changes in regional circulation are closely related to finer-scale aspects such as the vegetation type and amount, meaning more accurate simulation of evapotranspiration and internal circulation processes are required in dynamical downscaling simulations (Gao et al., 2015a; Zhang and Gao, 2021).

3. Kilometer-scale dynamical downscaling

In recent years, with the improvements in supercomputing, several research teams have carried out kilometer-scale dynamical downscaling, but the names are rather confusing, such as cloud-resolving modeling, convection-resolving modeling, convection-permitting modeling (CPM), kilometer-scale modeling, gray zone, etc. These simulations with a grid spacing of less than 10 km all belong to kilometer-scale simulations. Such an ultra-high resolution can improve the simulation performance of the model; however, it will consume a huge amount of computational resource, so it is also of great significance to find a balance between model performance improvement and computational demand. An NCAR study indicated that deep convection processes can be resolved explicitly by simulations at scales of 4 km and below, while a higher resolution will lead to exponential growth in computational effort and limited room for further improvement in simulation performance, thus suggesting that 4 km is a more appropriate scale for convection-permitting climate simulations.

Compared with quarter-degree simulations, CPM not only has the advantage of improved grid spacing, but more importantly, it can also explicitly resolve certain sub-grid convective processes and more accurately describe the influence of the lower boundary. For example, the horizontal scale of convective clouds usually ranges from a few kilometers to 10 kilometers, and when the model grid spacing is refined to the kilometer scale, deep convective processes can be resolved explicitly, eliminating the need for a deep-convection parameterization scheme and thus avoiding the associated uncertainties. Therefore, regional climate simulations at the convection-permitting scale are believed to greatly improve the ability to simulate precipitation (Prein et al., 2016; Kendon et al., 2021; Liu et al., 2022).

Several research institutions in the United States and Europe have been carrying out kilometer-scale dynamical downscaling studies since the early 21st century. For example, the Coordinated Regional Downscaling Experiments-Europe (CORDEX), a European regional climate modeling team led by Professor Giorgi Filippo, has conducted a series of CPM studies examining convective processes in the European region and water resources in the Alps (Torma et al., 2015; Clark et al., 2016; Vionnet et al., 2016; Chan et al., 2018; Berthou et al., 2020; Knist et al., 2020). NCAR scientists have carried out long-term kilometer-scale regional climate simulations focusing on water resource changes in the Rocky Mountains, and found that kilometer-scale simulations can more accurately reproduce the spatial distribution characteristics of snowfall, annual runoff, evapotranspiration and in the Rocky Mountains. Researchers at the NCAR have also projected changes in winter and summer precipitation, snowmelt and runoff in the Rocky Mountains under climate warming scenarios based on kilometer-scale simulations (Prein et al., 2016; Liu et al., 2017; Feng et al., 2018; Wang et al., 2018).

A few studies have focused on kilometer-scale simulations over the Asian region. For instance, Li et al. (2019) analyzed a heavy rainfall event in the middle and lower reaches of the Yangtze River in China between June 30 and July 6, 2016, based on the ECMWF limited regional climate model, and found that CPM better simulated the small-scale characteristics and diurnal cycle of precipitation, but the simulated precipitation intensity was too strong. Yun et al. (2020) conducted a simulation at 3-km grid spacing, and the results showed that CPM reproduced the spatial distribution and diurnal cycle of seasonal and sub-seasonal precipitation in eastern China reasonably well, and better simulated the summer monsoon activity and the eastward propagation of convection over the TP, but overestimated the precipitation amount. Recently, although the simulation period was only a few months, researchers have achieved a global climate simulation at 1-km grid spacing (Wedi et al., 2020), marking a new era of numerical weather and climate simulation at ultra-high resolution.

Over the TP, although quarter-degree dynamical downscaling simulations have to some extent reduced the cold and wet biases in reanalysis data and global climate simulations, there are still non-negligible biases that hinder the study of the TP's climate and its environmental effects. Professor Yanhong Gao's group continues to explore new ways and methods to reduce the errors of precipitation simulations over the TP based on quarter-degree dynamical downscaling, and lead the way in conducting 4-km grid spacing simulations over the TP. They have thus far found that 4-km-scale simulations differ little from quarter-degree simulations at altitudinal ranges where observations are available. However, in high-altitude areas over 5000 m, there are significant differences between the two simulation scales. This work was communicated at the GEWEX CONVECTION-PERMITTING CLIMATE MODELING WORKSHOP II, held at the NCAR, September 4–6, 2018, and was the only CPM work over the TP reported at that meeting.

In view of the scarcity of rain gauge observations at high altitudes, Professor Gao's group used remotely sensed snow data to evaluate the precipitation simulated at 4-km and quarter-degree grid spacing in high-altitudes areas. Jiang et al. (2020), based on quarter-degree and 4-km dynamical downscaling and three widely acclaimed precipitation fusion datasets (CMFD, CMORPH, TRMM) to drive the High Resolution Land Surface Data Assimilation System (HRLDAS), simulated the snow cover of the TP and compared it with the cloud-removal products of MODIS and the FY satellite, developed by Professor Gao's group. Results showed that the observation-driven HRLDAS simulations underestimated the snow cover of the TP and overestimated the snow-free period. In contrast, both the quarter-degree and 4-km precipitation-driven snow-cover simulations had smaller errors, reproduced the distribution characteristics of snow cover with altitude more accurately, and resulted in a probability density distribution function that was closer to the MODIS snow product, with the 4-km simulation outperforming the quarter-degree simulation (Gao et al., 2020a). This study demonstrates that CPM can provide more accurate ultra-high-resolution precipitation data for high-altitude mountain areas, providing a new approach to studying precipitation in areas lacking observations.

In recent years, several kilometer-scale simulations have been conducted in the TP region (Norris et al., 2017; Lin et al., 2018; Ou et al., 2020; Wang Y et al., 2020; Li P X et al., 2021; Wang et al., 2021), most of which have pointed out that the closure of the convection parameterization scheme at this scale is an important way to further reduce the cold and wet biases of quarter-degree simulations. Due to the computational constraints involved, most studies have only conducted high-resolution simulations over certain small areas, such as the southern TP or the Himalayan region, and there have been few climate simulation studies covering the whole of the TP. These studies indicate that, because of the finely resolved topography, the kilometer scale can better describe the blocking of water vapor transport processes, thereby reducing the wet bias in precipitation simulations (Lin et al., 2018; Jiang et al., 2020; Wang Y et al., 2020; Li P X et al., 2021; Yun et al., 2021; Zhao et al., 2021; Ma et al., 2022).

Recent studies have indicated that kilometer-scale simulations are able to simulate the diurnal cycle characteristics of precipitation more accurately than previous quarter-degree dynamical downscaling studies (Ou et al., 2020; Li P X et al., 2021; Liu et al., 2022; Ma et al., 2022). For instance, Liu et al. (2022) revealed that the differences between the precipitation simulated by 4-km dynamical downscaling and other precipitation products were mainly caused by the precipitation frequency, and that reanalysis data (ERA-Interim and ERA5) severely overestimate the precipitation over the TP. In ERA5, the earlier and stronger diurnal peak of precipitation was found to be related to its stronger water vapor transport and the earlier and stronger peak of convective available potential energy. The 4-km and quarter-degree dynamical downscaling simulations performed better than the reanalysis data in reproducing the characteristics of precipitation; in particular, the 4-km simulation reproduced the peak time of summer precipitation more accurately at most sites on the TP (Figure 2), while the precipitation simulated in the quarter-degree run peaked earlier. Most studies explain the mechanism behind the alleviation of the biases in precipitation simulation at the kilometer scale from the perspective of water vapor transport and energy balance, but this does not explain the improvement in the representation of the diurnal cycle of precipitation. Recently, Liu et al. (2022) addressed this knowledge gap by explaining that the positive bias of wet convective instability in kilometer-scale simulations is less than that in quarter-degree simulations, which makes the timing of the triggering of convection, and its intensity, more consistent with observations, thus producing a more accurate peak timing of precipitation.

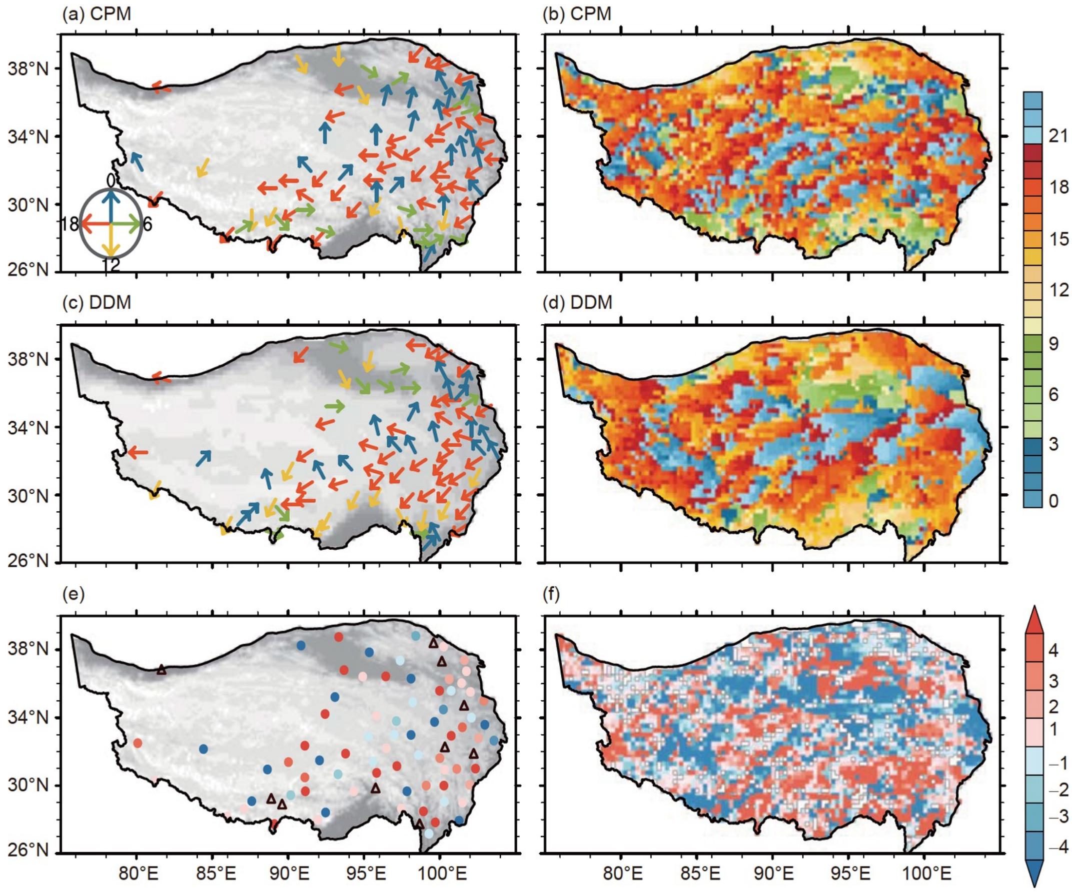

Figure 2 Distribution of the precipitation diurnal peak time at 83 stations (left) and the 0.25° grid points (right) in 4-km ((a), (b)) and quarter-degree ((c), (d)) simulations over the TP in June 2014. Panels (e) and (f) show the differences in peak times between the two simulations. Red dots in (e) and (f) denote that the precipitation diurnal peak of the 4-km simulation at this station or grid point is later than that of the quarter-degree simulation, while blue dots denote that the 4-km simulation has an earlier precipitation peak than the quarter-degree simulation. Stations/grid points with the same time are indicated by black triangles/blank cells. The gray background represents the elevation. Figure originally published in Liu et al. (2022) and reproduced here with permission.

To summarize, there are two main views regarding kilometer-scale simulations. One is that they reduce the uncertainty of the convection parameterization scheme and significantly improve the simulation of precipitation (Prein et al., 2016; Liu et al., 2017; Prein et al., 2020, 2021); while the other is that they can improve the simulation performance to some extent, but mainly in terms of the diurnal cycle of precipitation, i.e., whether the output is worthy of the input in terms of the computational effect remains open to question (Kendon et al., 2021). At present, the results of most studies are still in the evaluation stage of individual cases, with few studies having focused on the physical mechanisms involved, and the robustness of short-term findings in long-term simulations needs to be further verified. In order to obtain long-term simulation data, some studies have adopted repeated-start methods (Maussion et al., 2011; Norris et al., 2015, 2017), restarting the simulation every 1–2 days and bridging the individual simulations to form long-term series. Although this approach is capable of generating long-term series of meteorological data, it blocks the memory function of the climate system and, thus strictly speaking, should be regarded as weather simulation splicing rather than climate simulation.

4. Lower-boundary influences on dynamical downscaling over the TP

Modern climate model systems contain increasingly physical processes and interactions produced by coupling atmospheric, oceanic, glacial, and terrestrial biogeophysical and biogeochemical spheres processes, and have thus been widely used for simulating and projecting climate at the global or regional scales. However, there are still two major problems in the high-resolution simulations of climate models over the TP. (1) The surface features of the TP are varied, and the processes of land-atmosphere interaction are complex, which cannot be fully portrayed in current climate system models. The TP is one of the regions on Earth where there are strong multi-layer interactions. Not only does it have the same multi-layer interaction processes at lower altitudes, but also its unique topography, glaciers, snow, deserts, wetlands and other land types make the interactions between the land surface and weather/climate in this region more complex and diverse in space and time. With the increase in the horizontal resolution of models and the explicit resolution of deep convection processes, the strongly heterogeneous distribution of surface heat sources becomes an important influence on the simulation of convective processes, and the complexity and diversity of land-atmosphere interactions is expected to be more fully reflected (Gao et al., 2017, 2020a, 2020b; Liu W C et al., 2021). (2) The parameterization schemes and parameters of some processes in current land surface models may not be applicable to the TP. For instance, most of the physical processes and surface parameters in the moden land surface model were developed and obtained based on experiments conducted on plains, which have poor applicability over the TP and thus seriously affect the simulation and perception of the climate and its impacts in this region (Gao et al., 2015b; Li Z G et al., 2018; Yue et al., 2021). Therefore, multi-timescale, multi-physical process weather and climate studies over the TP require more suitable land surface process models to provide more accurate and finer-scale information on surface energy and moisture exchange for Earth system climate models.

In recent decades, a number of research groups have been working on improving land surface process schemes over the TP, as well as the accuracy of land-atmosphere interaction and climate simulations. For example, land surface process models have improved or added new soil texture type datasets (Li et al., 2020), soil organic matter schemes (Gao et al., 2015b; Chen et al., 2016), gravel parameterization schemes (Pan et al., 2017), terrain drag parameterization schemes (Zhou et al., 2018), an alpine vegetation root system parameterization scheme (Gayler et al., 2014; Gao et al., 2015b), permafrost parameterization scheme (Yang and Wang, 2019), lake ice albedo revision (Li Z G et al., 2018), lake salinity parameterization (Wen et al., 2016; Huang et al., 2019), hydrological process parameterization (Rummler et al., 2019), and so on. For brevity, the value added by land surface process model improvements in climate simulations over the TP is presented here from the following three perspectives: the snowpack, lakes, and soil.

The effect of the snowpack on the surface energy balance has always been an important topic in the study of the climate system and its changes. Recent studies on snow over the TP have indicated that it is thinner, with a short maintenance time and rapid melting, compared to higher latitudes (Li W K et al., 2018; Jiang et al., 2019). However, most snow parameterization schemes in land surface models are based on the characteristics of deep snow at high latitudes, and these schemes tend to severely overestimate the snow cover over the TP. Jiang et al. (2020) modified the snow cover parameterization scheme in a land surface model to address the snow cover characteristics of the TP, and significantly reduced not only the positive simulation bias of the snow volume, but also that of the cold bias of temperature. In addition, some other studies have achieved similar simulation results by reducing the snow albedo (Wang W L et al., 2020; Liu L et al., 2021).

There are many lakes on the TP, and these have important impacts on weather and climate through lake-atmosphere interactions. Traditional regional weather and climate models, such as WRF, use the nearest sea surface temperature as the lake surface temperature; however, Gao et al. (2020b) revealed that, due to the sea surface temperature being much higher than the lake surface temperature on the TP, it is easier for strong convection to occur over the lakes, thereby triggering excessive water vapor convergence and a severe overestimation of the precipitation downwind of the lakes. The use of a revised lake temperature observation significantly reduced the wet bias around the lakes, and further reduced the wet bias of precipitation averaged over the TP from 148% to 58%.

Some researchers have found that the soil type of the southern mountainous region of the TP is mostly bare bedrock and unsuitable for vegetation growth; while in the WRF model, the surface soil type in this region is loamy and ideal for vegetation growth. This surface-type identification error will affect the surface energy balance and water exchange, which in turn has an impact on the local climate. Using satellite data to identify bare bedrock in the southern TP and correct the soil type in the WRF model can effectively reduce the wet and cold bias in simulations in this region (Yue et al., 2021).

5. Challenges and prospects for dynamical downscaling research over the TP

Dynamical downscaling achieves more accurate simulations of regional climate by finely delineating the non-uniform distribution of the ground surface. However, there is no uniform answer to whether a higher resolution is better for downscaling. Many studies suggest that increasing the resolution can further improve the simulation performance. For instance, typhoon simulations with a resolution of less than 1 km can more finely characterize the vertical structure of typhoons (Gao et al., 2022); whereas, some other studies suggest that improvement in simulation performance is nonlinearly related to the resolution, with the largest improvement ranging from 12 to 4 km, and limited improvement, or even increased error, below 4 km (Prein et al., 2016, 2021). A study of surface flux scale effects over the TP by a research team from the Chinese Academy of Sciences concluded that 4 km is the inflection point of the surface flux variation curve with scale, and that the surface flux varies drastically with spatial scale if less than this threshold, while the regional average surface flux variation tends to be smooth if above this threshold (Sun et al., 2016). Since these studies require a large amount of ultra-high-resolution data, existing studies mostly carry out simulations in smaller areas for shorter periods of time, and so the question of the optimal scaling for dynamical downscaling is yet to be supported by more high spatial and temporal resolution data.

Validation of kilometer-scale dynamical downscaling simulations requires ultra-high-resolution observations, but the distribution of site observations over the TP is sparse, so there are large uncertainties in gridded data based on site observations and remote sensing observations (Ye et al., 2004; Lundquist et al., 2019; Gao et al., 2020a). Radar observations can provide quantitative precipitation data with ultra-high spatial and temporal resolution; however, the complex topography of the TP limits the erection and coverage of radar. How to set representative observation sites, develop data fusion algorithms, and improve the accuracy of gridded data has become the primary prerequisite for correctly evaluating the results of dynamical downscaling precipitation simulations. Some studies have suggested that the results from high-resolution simulations based on regional climate models are better than those from observations in areas with complex topography, especially at high altitudes (Lundquist et al., 2019). Results in the southeastern TP also support this view. However, the applicability of this finding to other regions needs to be further tested.

The discontinuation of the convective parameterization scheme in kilometer-scale dynamical downscaling can improve the simulation performance to some extent. However, other parameterization schemes (radiative, microphysical, boundary layer, and land surface process parameterizations) are mostly derived from global models, and the lack of suitable parameterization schemes for small and medium scales still limits the accurate representation of sub-grid processes. For example, studies of land surface processes have shown that a medium groundwater scenario significantly alters the surface hydrothermal conditions, which in turn affects the persistent warm bias of CPM-scale seasonal forecasts for central North America (Barlage et al., 2021). Additionally, the soil texture distribution alters the distribution of wet/dry soils, which further affects the amount and spatial distribution of precipitation (Ács et al., 2010).

Finally, dynamical downscaling is based on regional climate models and is influenced by the initial and boundary-value conditions provided by the driving data. The smaller the simulation area, the more it is influenced by the boundary conditions. If the simulation area is large enough, the complex topographic conditions within the simulation area can generate local circulation on their own, so increasing the simulation area is one approach to reducing the influence of the driving data in areas with complex topography. However, due to the ultra-high resolution of kilometer-scale simulations, increasing the simulation area comes at the cost of a nonlinear increase in the simulation time (typically, doubling the grid will increase the run time by a factor of about ten) (Kendon et al., 2021). Therefore, balancing buffering and driving effects becomes an important factor to be considered.

Despite these difficulties mentioned above, as computing capabilities strengthen, it is likely that kilometer-scale simulations can be carried out at larger scales, with longer and higher-resolution climate simulations over larger simulation areas that are expected to advance our knowledge of the Earth climate system. Data storage and sharing will become the biggest technical challenge. The vast outputs will require extremely large storage space and, more importantly, as ensemble forecasting is considered the most effective way to improve the forecast accuracy, which involves sharing simulation results for analysis, achieving rapid sharing of massive data will be needed to help advance the study of high-resolution climate and environmental changes over the TP.

In conclusion, dynamical downscaling is an effective way to obtain high-resolution gridded climate information. It can provide a solid support for the study of climate and environmental changes over the TP and its response to global changes. Improvements in high-performance supercomputing drive the development of dynamical downscaling from the traditional quarter-degree resolution to the ultra-high resolution. Along with improvement in the grid spacing and the explicit resolving of deep convective processes, kilometer-scale simulations show certain value-added effects in the triggering time of convection and water vapor transport, heralding a new stage in the evolution of this approach, but at the same time exposing some new problems and challenges. Progress is expected to made in the following two aspects: (1) based on the kilometer scale, how the non-uniform land surface affects the boundary layer and, further, the physical mechanism of precipitation, which is particularly important over the TP; and (2) how to use high-resolution research results to improve the convective parameterization scheme in large-scale simulations, so as to ensure the simulation performance, improve the computing efficiency, and provide scientific and technical support for operational applications.

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