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Evaluation of CORDEX regional climate models in simulating temperature and precipitation over the Tibetan Plateau

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ABSTRACT
Using a regional climate model (RCM) is generally regarded as a promising approach in researching the climate of the Tibetan Plateau, due to the advantages provided by the high resolutions of these models. Whilst previous studies have focused mostly on individual RCM simulations, here, multiple RCMs from the Coordinated Regional Climate Downscaling Experiment are evaluated in simulating surface air temperature and precipitation changes over the Tibetan Plateau using station and gridded observations. The results show the following: (1) All RCMs consistently show similar spatial patterns, but a mean cold (wet) bias in the temperature (precipitation) climatology compared to station observations. The RCMs fail to reproduce the observed spatial patterns of temperature and precipitation trends, and on average produce greater trends in temperature and smaller trends in precipitation than observed results. The multi-model ensemble overall produces superior trends in both simulated temperature and precipitation relative to individual models. Meanwhile, RegCM4 presents the most reasonable simulated trends among the five RCMs. (2) Considerable dissimilarities are shown in the simulated quantitative results from the different RCMs, which indicates a large model dependency in the simulation of climate over the Tibetan Plateau. This implies that caution may be needed when an individual RCM is used to estimate the amplitude of climate change over the Tibetan Plateau. (3) The temperature (precipitation) in 2016–35, relative to 1986–2005, is projected by the multi-model ensemble to increase by 1.38 ± 0.09 °C (0.8% ± 4.0%) and 1.77 ± 0.28 °C (7.3% ± 2.5%) under the RCP4.5 and RCP8.5 scenario, respectively. The results of this study advance our understanding of the applicability of RCMs in studies of climate change over the Tibetan Plateau from a multiple-RCM perspective.

摘要
区域气候模式对研究地形复杂的青藏高原地区气候具有高分辨率的优势。以前的相关研究主要基于单个区域模式，我们评估了CORDEX多区域气候模式对青藏高原气候的模拟能力。结果显示：（1）5个区域气候模式一致模拟出了相似的气温、降水空间模态，但产生了冷偏差和湿偏差。所有区域气候模式未能再现观测的气温、降水趋势空间模态，并且平均高估了气温趋势、低估了降水趋势。综合考虑模拟的气温、降水趋势，多模式集合的结果最优。就单个模式而言，RegCM4所得趋势最为合理。（2）各区域气候模式结果之间的差异十分显著，表明青藏高原气候模拟具有很大的模式依赖性。这一结果建议当利用单个区域气候模式开展青藏高原气候变化研究时需要谨慎。（3）多区域模式集合预估显示，相对1986–2005年，到2016–2035年气温（降水）将增加1.38 ± 0.09 °C (0.8% ± 4.0%)（RCP4.5）和1.77 ± 0.28 °C (7.3% ± 2.5%)（RCP8.5）。这些结果从多模式角度提高了我们对运用区域气候模式研究青藏高原气候的认识。

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1. Introduction

One significant aspect of the Tibetan Plateau is its contribution to the global amount of water held on land. It features a glacial area of approximately 1.0×10^5 km^2 (Yao et al. 2012), a snow-water-equivalent rate of approximately 41.9×10^9 m^3 yr^{-1} (Li et al. 2008), and a permafrost area of approximately 1.5×10^6 km^2 (Li and Cheng 1996). These water resources feed the major rivers in East Asia, South Asia, and Southeast Asia, and provide water to more than 20% of the global population. The Tibetan Plateau is thus recognized as the 'Asian water tower'.

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Climate change affects the fate of solid-phase water resources on the Tibetan Plateau. Therefore, proper predictions of climate change in the Tibetan Plateau region are essential for accurately evaluating the sustainability of water resources. In recent years, the global climate models (GCMs) in the third and fifth phases of the Coupled Model Intercomparison Project (CMIP3 and CMIP5, respectively) have been used to simulate and project climate change in the Tibetan Plateau region (Hu, Jiang, and Fan 2015; Liu, Chen, and Zhang 2009; Su et al. 2013). The results project a warming and wetting climate under a warming climate scenario.

The varied topography of the Tibetan Plateau requires high-resolution simulations that can capture regional details. Consequently, regional climate models (RCMs) are promising tools for researching climate in the Tibetan Plateau region. Several RCM-based simulations have recently been carried out (Gao, Wang, and Giorgi 2013; Guo and Wang 2016; Ji and Kang 2013, 2015; Ji et al. 2016; Wang et al. 2013; Yu and Xiang 2015). For example, using RegCM4, Ji and Kang (2013) performed a 10-km dynamical downscaling simulation over the Tibetan Plateau for the twenty-first century and reported more spatial details in terms of climate dynamics, as compared to the GCM results. However, such studies have mostly been based on an individual RCM simulation. The extent of the differences among results from different RCMs and how these differences affect the projected results of climate change are not well understood.

The objective of this study is to (1) examine the inconsistencies among multiple RCMs in simulating climate over the Tibetan Plateau, and (2) assess the climate change in the near future (2016–35) over the Tibetan Plateau implied by the ensemble results from the various RCMs. The RCM simulations are derived from the Coordinated Regional Climate Downscaling Experiment (CORDEX) in East Asia. In-situ observations at 71 weather stations and a set of gridded observations are used to evaluate the models.

2. Data and methods

2.1. Data

Five regional simulations are obtained from CORDEX (Giorgi, Jones, and Asrar 2009). These simulations are run by: HadGEM3-RA (Hadley Centre Global Environment Model, version 3, with regional atmosphere configurations) (Martin et al. 2006); MM5 (Fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model) (Lee, Cha, and Kang 2004); RegCM4 (Regional Climate Model, version 4) (Oh et al. 2011); WRF (Weather Research and Forecasting model, version 3.2) (Skamarock et al. 2008), and RSM (Regional Spectral Model) (Hong et al. 2013). Each model is driven using the output of HadGEM2-AO (Hadley Centre Global Environment Model, version 2, with atmosphere, ocean and sea ice configurations) (Baek et al. 2013). These five simulations have the same spatial resolution and model domain, but slightly different simulation periods (Table 1). The physical schemes and more detail regarding each simulation can be seen at https://cordex-ea.climate.go.kr/main/mainPage.do. Common periods (historical: 1980–2005; future: 2006–49) and two representative concentration pathway (RCP) scenarios (RCP4.5 and RCP8.5) are used for the five simulations in this study. Notably, WRF-produced precipitation is questionable under the RCP4.5 scenario, and is therefore not used in the projections in this study. As a result, the precipitation from the WRF simulation under the RCP8.5 scenario is also not used, to ensure a homogeneous comparison between these two scenarios. These data have been widely used for research efforts on regional climate change and associated mechanisms (Guo, Yu, and Wang 2016; Yu and Xiang 2015).

In-situ observations, used to evaluate the models, are obtained from the China Meteorological Administration. Specifically, the yearly surface air temperature (temperature) and precipitation measured at 71 weather stations from 1980 to 2005 are employed. These weather stations are located mostly in the central and eastern Tibetan Plateau region (Figure 1(g)). A basic logic test and spatial consistency test are carried out for data quality control (Li et al. 2004). These data are reliable and have been used extensively to identify climate change and validate climate models (Guo and Wang 2012; Wang et al. 2012).

A set of gridded observations, CN05.1 (CN051) (Wu and Gao 2013), are used to evaluate the simulated area-averaged results over the entire Tibetan Plateau. These data are developed based on *in situ* observations at 2416

Table 1. Details of the six dynamical downscaling simulations and observed data.

Model name	Horizontal resolution	Model domain	Historical simulation period	Future simulation period	Scenario
HadGEM3-RA	50 km	CORDEX East Asia domain	1950–2005	2006–2100	RCP 4.5, RCP 8.5
MM5	50 km	CORDEX East Asia domain	1979–2005	2006–49	RCP 4.5, RCP 8.5
RegCM4	50 km	CORDEX East Asia domain	1979–2005	2006–50	RCP 4.5, RCP 8.5
WRF	50 km	CORDEX East Asia domain	1979–2005	2006–49	RCP 4.5, RCP 8.5
RSM	50 km	CORDEX East Asia domain	1979–2005	2006–50	RCP 4.5, RCP 8.5
CN051	0.25°	China	1980–2005		
In-situ observations		71 stations	1980–2005		

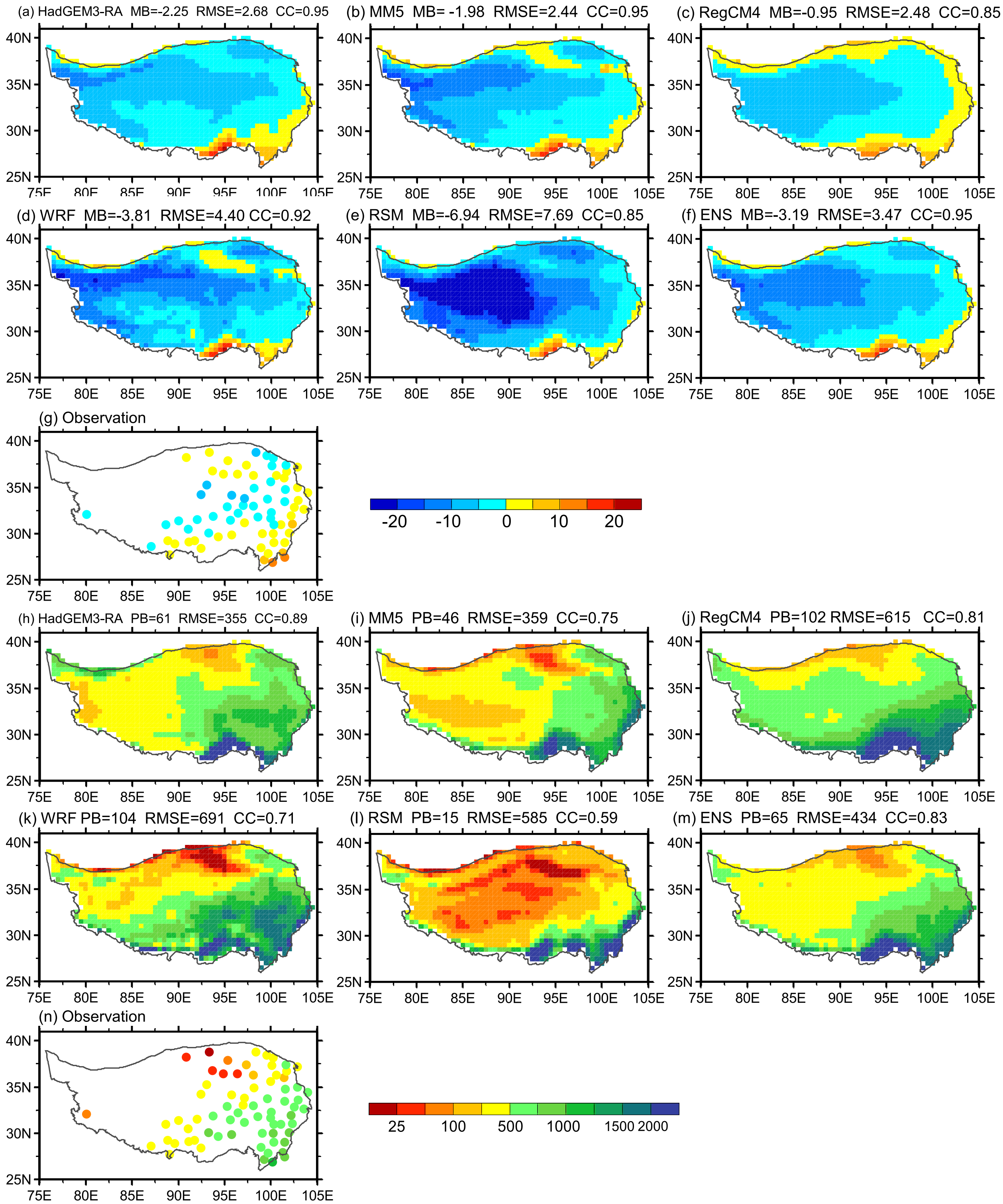

Figure 1. Comparison of simulated (a–g) temperature (units: °C) and (h–n) precipitation (mm yr^{-1}) climatology (1986–2005) with *in situ* observations at 71 stations.

Notes: The model name (ENS refers to the ensemble mean), mean bias (MB) (temperature: °C; precipitation: mm yr^{-1}), percentage bias (PB) (%), root-mean-square error (RMSE) (temperature: °C; precipitation: mm yr^{-1}), and spatial correlation coefficient (CC) between the 71 station observations and the corresponding gridded simulations are given at the top of each panel. For temperature, observed values are topographically corrected to simulated grids for spatial comparison (g). In contrast, simulated results are topographically corrected to observation stations when calculating the MB, RMSE, and CC.

weather stations in China. They have a spatial resolution of 0.25° × 0.25° and cover a period from 1961 to 2015. The data cover the entire land area of China, and the Tibetan Plateau region is extracted for analysis in this study. These data have been widely used as a reference for the validation of model results (Gao, Wang, and Giorgi 2013; Guo and Wang 2016).

2.2. Methods

When using station data to evaluate the gridded simulated results, the simulated results are first topographically corrected to observation stations, and then compared with the station observations. The mean bias (MB), percentage bias (PB), root-mean-square error (RMSE), correlation coefficient, and Taylor Diagram are used to assess the level of agreement between the simulated and observed results. The linear trend is the slope of the linear fit, which is calculated using the ordinary least-squares regression method. The Student's *t*-test is used to identify the statistical significance of the trend.

The MB, PB, and RMSE are calculated as follows:

$$\mathrm{MB} = \frac{1}{n}\sum_{i=1}^{n}(S_i - O_i);$$

$$\mathrm{PB} = \frac{\sum_{i=1}^{n}(S_i - O_i)}{\sum_{i=1}^{n} O_i} \times 100\%;$$

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{n}}.$$

Here, S_i represents the simulated value, O_i the observed value, and n the total sample number.

The standard deviation (SD) is used to assess the inter-model variance in the climatology and trend of air temperature and precipitation in this study, which is calculated as follows:

$$\mathrm{SD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2};$$

$$\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i.$$

Here, $\bar{x}$ represents the inter-model arithmetic mean, and x_i represents one of the samples.

The coefficient of variance (CV) is used to assess the inter-model variance in the precipitation climatology in this study, to consider the impact of mean precipitation on the variance, which is calculated as follows:

$$\mathrm{CV} = \frac{\mathrm{SD}}{\bar{x}} \times 100\%.$$

3. Results and discussion

3.1. Climatology (1986–2005)

The five models consistently show similar spatial patterns of temperature climatology to observations (Figure 1(a–g)). The spatial correlation coefficients range from 0.85 to 0.95 across the five models. However, all models produce a cold bias, with a range from −0.95 °C to −6.94 °C. For precipitation, the models also capture the observed spatial patterns, with spatial correlation coefficients ranging from 0.59 to 0.89, but they consistently produce 15%–104% more precipitation than observed (Figure 1(h–n)). Among the five models and the ensemble, MM5, HadGEM3-RA, and the ensemble show similar, reasonable performance in simulating temperature; whereas, HadGEM3-RA shows the most reasonable performance in simulating precipitation (Figure 2(a)).

The simulated quantitative results from the five models show large inter-model variances (Figure 3(a) and (b)). For temperature, much of the Tibetan Plateau has an SD ranging from 2 to 8 °C, with an evident center of higher values over the northwestern Tibetan Plateau. For precipitation, much of the Tibetan Plateau has an SD ranging from 100 to 400 mm yr^{-1}. The SDs are distinctly larger over the southeastern Tibetan Plateau than the northwestern Tibetan Plateau. However, CVs are low over the southeastern Tibetan as a result of more mean precipitation in that region (Figure S1). Because the five simulations use the same forcing data and have the same spatial resolution and model domain, the models themselves cause these variances—for instance, through their various physical parameterization schemes or surface and soil data. These variances indicate that different RCMs can cause considerable uncertainties, implying that large model dependence may exist in the results from individual RCM simulations. Caution is thus needed when an individual RCM is used to quantitatively estimate the climate over the Tibetan Plateau.

3.2. Trends (1980–2005)

All five models show statistically insignificant relationships between simulated and observed spatial patterns of temperature trends (Figure 4(a–g)). All of them also produce a larger temperature trend compared with observations (MB: 0.09–0.33 °C/decade), with the exception of HadGEM3-RA, which shows a 0.02 °C/decade temperature decline relative to observations. With the exception of RegCM4, all models also show statistically insignificant relationships between simulated and observed spatial patterns of precipitation trends (Figure 4(h–n)). All of the models except RegCM4 produce a mean trend that is 0.52–29.07 mm/decade smaller than that seen in observations. Among the five models and their ensemble, the ensemble overall produces superior simulated trends in both temperature and precipitation relative to the individual models (Figure 2(b)). Among individual models, RegCM4 shows superior simulated trends in both temperature and precipitation.

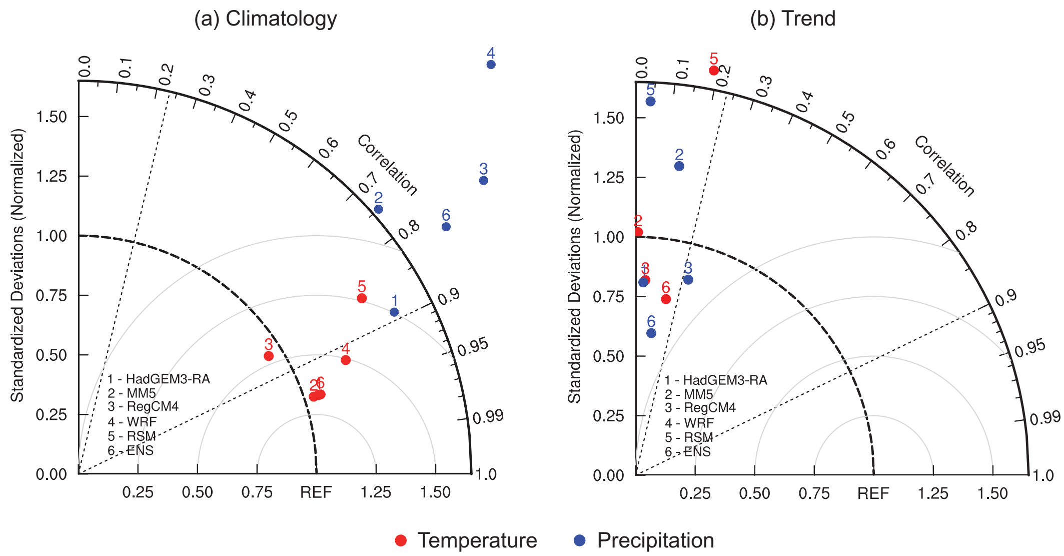

Figure 2. Taylor diagrams between simulated temperature and precipitation (a) climatology (1986–2005) and (b) trends (1980–2005) and *in situ* observations at 71 stations.

Notes: For (a), the RSM precipitation is not shown due to its high standard deviation. For panel (b), the HadGEM3-RA and WRF temperatures are not shown due to a high standard deviation and a negative correlation coefficient, respectively, and the WRF precipitation is not shown due to its negative correlation coefficient. The two dashed lines refer to correlation coefficients of 0.23 (95% confidence level) and 0.90.

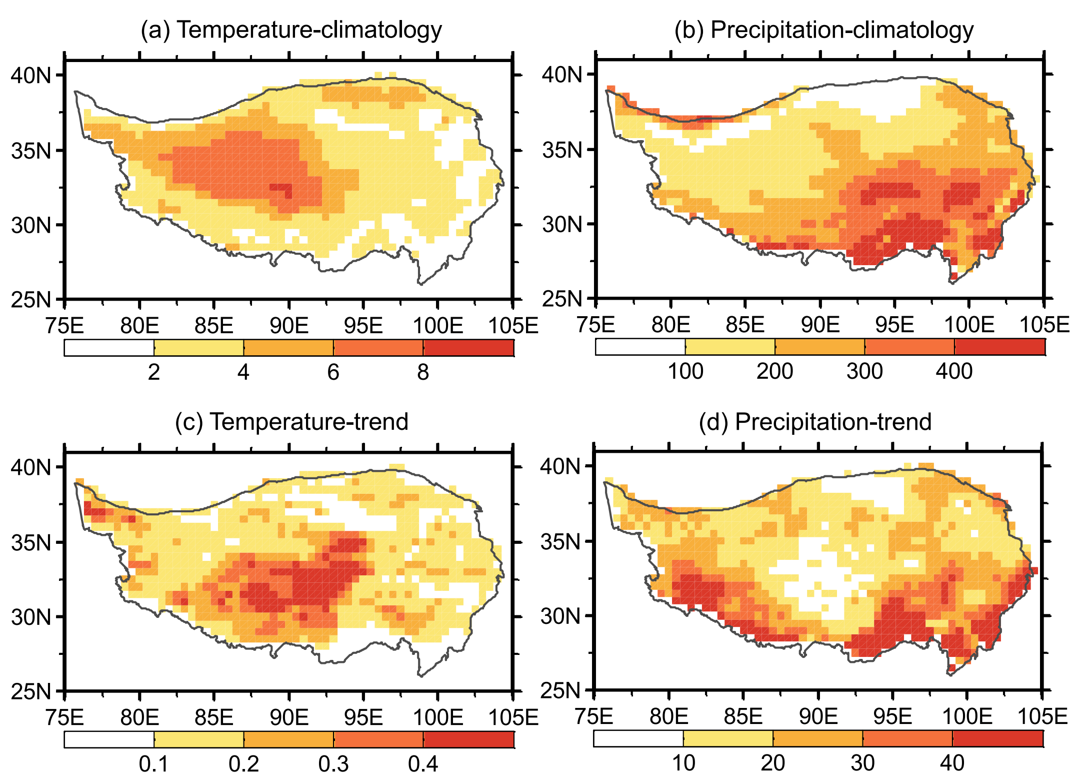

Figure 3. Standard deviation of the (a) air temperature climatology (units: °C) (1986–2005), (b) precipitation climatology (mm yr^{-1}) (1986–2005), (c) air temperature trend (units: °C/decade) (1980–2005), and (d) precipitation trend (units: mm/decade) (1980–2005) across the five regional climate models.

The simulated area-averaged trends are compared to the observed ones over the entire Tibetan Plateau (Figure S2). Most of the RCMs produce similar area-averaged trends in temperature to those from gridded observations. For precipitation, the biases between simulated and observed area-averaged trends are larger than the temperature biases. Overall, the multi-model ensemble shows the best agreement with the observed area-averaged trend in both temperature and precipitation. However, it should be mentioned that uncertainties exist. The gridded

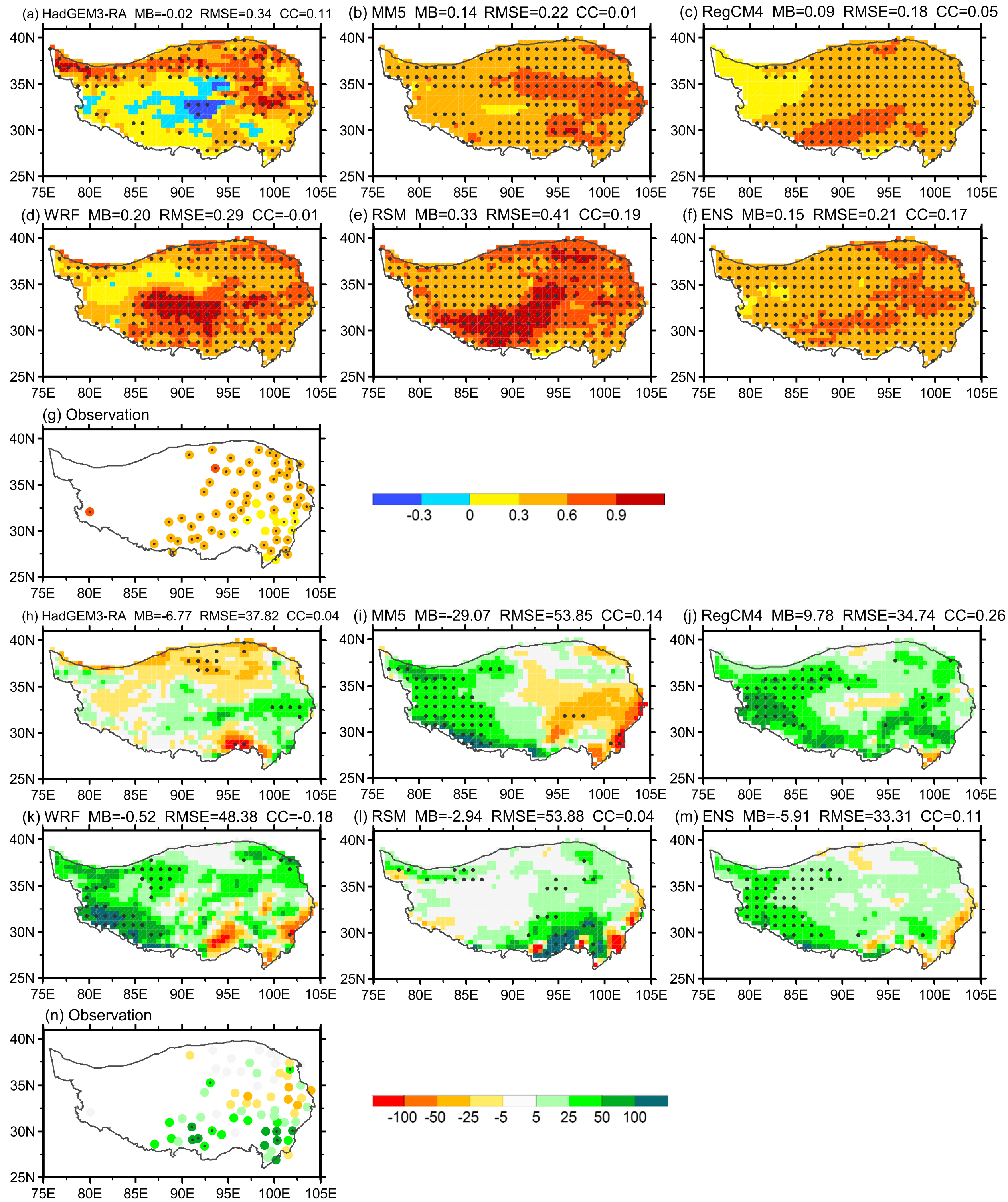

Figure 4. Comparison of simulated trends (1980–2005) in (a–g) temperature (units: °C/decade) and (h–n) precipitation (units: mm/decade) with *in situ* observations at 71 stations.

Notes: The model name (ENS refers to the ensemble mean), mean bias (MB) (temperature: °C/decade; precipitation: mm/decade), root-mean-square error (RMSE) (temperature: °C/decade; precipitation: mm/decade), and spatial correlation coefficient (CC) between the 71 station observations and the corresponding gridded simulations are given at the top of each panel.

observations used for comparison may have low accuracy over the Tibetan Plateau because of the sparse distribution of stations in the western Tibetan Plateau (Wu and Gao 2013).

Similar to the climatology, obvious inter-model variances can also be seen in the simulated trends in temperature and (especially) precipitation (Figure 3(c) and (d)). For temperature, most of the SDs range from 0.1 to 0.4 °C/

decade. There is a high-value center over the southwestern Tibetan Plateau, where some SD values exceed 0.4 °C/decade. For precipitation, the SDs are less than 10 mm/decade over the central Tibetan Plateau and the Qaidam Basin, but distinctly large over the southeastern Tibetan Plateau and the southwestern edge (the Himalaya) of the Tibetan Plateau, with SD values greater than 30 mm/decade. These results indicate considerable uncertainties caused by the different RCMs, meaning a multi-RCM ensemble is necessary to estimate the amplitude of climate change over the Tibetan Plateau.

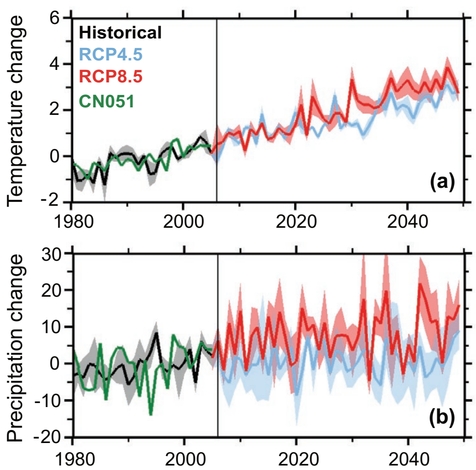

Figure 5. Area-averaged changes in (a) temperature and (b) precipitation during the historical period from 1980 to 2005 and future period from 2006 to 2049 under the RCP4.5 and RCP8.5 scenarios, relative to 1986–2005.

Note: Shaded areas represent one standard deviation across the five regional climate models.

3.3. Multi-RCM ensemble projection of climate in the near future

The simulated temporal changes in ensemble-mean temperature and precipitation are comparable to those in observations during the historical period of 1980–2005 (Figure 5). The simulated temperature trend is 0.51 °C/decade from 1980 to 2005, which is close to but larger than the observed trend of 0.44 °C/decade. The simulated precipitation trend is 2.2%/decade, which is close to but slightly smaller than the observed trend of 2.4%/decade.

For the future period, the RCP4.5 and RCP8.5 scenarios show a significant increasing temperature trend, with values of 1.38 ± 0.09 °C and 1.77 ± 0.28 °C, respectively, during the period 2016–35 relative to 1986–2005 (Figure 5). These results are close to but larger than previous multi-GCM ensemble results, which show temperature increasing by 1.1 °C during the same period under the RCP4.5 scenario (Hu, Jiang, and Fan 2015). In terms of spatial pattern, the entire Tibetan Plateau shows increasing temperatures during the period 2016–35 under the RCP4.5 scenario, with significant increases located over the central Tibetan Plateau, the Himalaya, the northwestern corner of the Tibetan Plateau, and the Qilian Mountains (Figure 6(a) and (b)). Under the RCP8.5 scenario, significant increases are shown over the central and western Tibetan Plateau. Previous results have also shown similar significant increases in the Himalaya, the northwestern corner of the Tibetan Plateau, and the Qilian Mountains (Hu, Jiang, and Fan 2015; Ji and Kang 2013). Hu, Jiang, and Fan (2015) also showed significant increases located over the central Tibetan Plateau, but at a location more towards

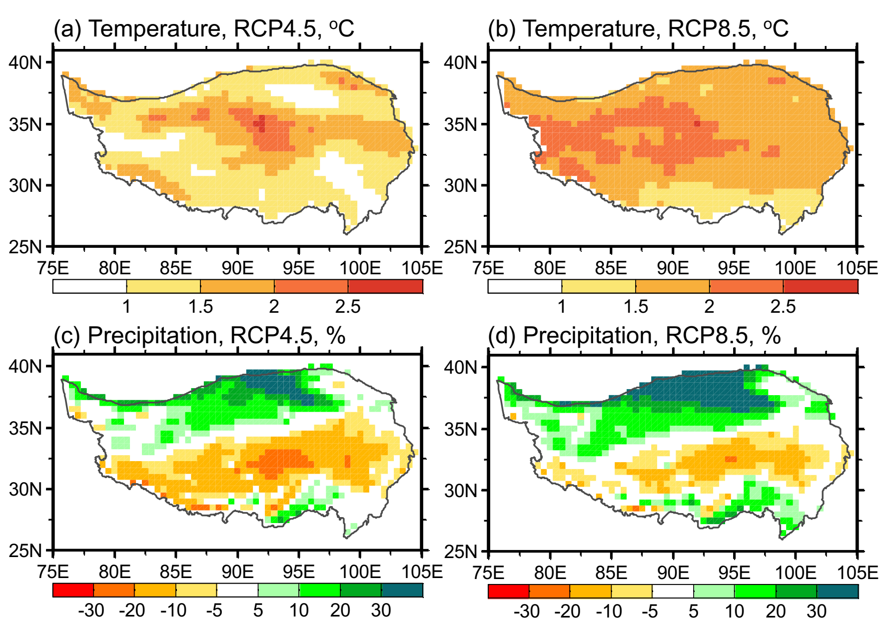

Figure 6. Spatial changes in ensemble-mean (a, b) temperature (units: °C) and (c, d) precipitation (units: %) during the period 2016–35 relative to 1986–2005 under the (a, c) RCP4.5 and (b, d) RCP8.5 scenario.

the southeast part of our locations in the central Tibetan Plateau that showed significant increases.

The precipitation is projected to increase by 0.8% ± 4.0% and 7.3% ± 2.5% in 2016–35 relative to 1986–2005 under the RCP4.5 and RCP8.5 scenarios, respectively (Figure 5). A larger increase of 4.4% was derived from a multi-GCM ensemble during the same period under the RCP4.5 scenario (Hu, Jiang, and Fan 2015). In terms of spatial pattern, a clear north–south-oriented pattern of positive–negative–positive change is projected in precipitation under both the RCP4.5 and RCP8.5 scenarios (Figure 6(c) and (d)). From RCP4.5 to RCP8.5, the positive changes over the northern and southern Tibetan Plateau strengthen, whereas the negative change over the central Tibetan Plateau weakens. This spatial pattern of change is similar to that of projected changes during the period 2090–99 (Ji and Kang 2013), but differs from multi-GCM ensemble results that show a gradually increasing change from the southeastern to northwestern Tibetan Plateau (Hu, Jiang, and Fan 2015).

4. Conclusions

Five CORDEX RCMs are evaluated in simulating temperature and precipitation over the Tibetan Plateau. All models reproduce the observed spatial patterns of the temperature and precipitation climatology reasonably well, but consistently produce a cold bias in temperature and wet bias in precipitation. All models fail to capture the spatial patterns of the temperature and precipitation trends, with an overestimation of the observed warming trend and an underestimation of the observed wetting trend on average (except for RegCM4). The multi-RCM ensemble overall shows superior performance in simulating both the temperature and precipitation trends relative to individual models. Among the five RCMs, RegCM4 presents the most reasonable simulated trends.

Considerable dissimilarities in the simulated temperature and precipitation changes between different RCMs are shown, which indicates a large model dependence related to RCM simulation over the Tibetan Plateau. This suggests that caution is needed when an individual RCM is used to quantitatively examine climate change over the Tibetan Plateau. The multi-RCM ensemble projection shows temperature increasing by 1.38 ± 0.09 °C (RCP4.5) and 1.77 ± 0.28 °C (RCP8.5), and precipitation by 0.8% ± 4.0% (RCP4.5) and 7.3% ± 2.5% (RCP8.5), in 2016–35 relative to 1986–2005.

The results of this study provide insight into the differences among different RCMs in simulating climate change over the Tibetan Plateau, which advances our understanding of the applicability of RCMs in assessing climate change in this region. The present projections are comparable with previous studies, but deviations exist between them in quantities. Historically, research on climate change projection over the Tibetan Plateau has moved, in terms of models, from individual GCMs (Xu, Xue, and Lin 2003), to multiple GCMs (Hu, Jiang, and Fan 2015; Su et al. 2013; Xu, Ding, and Li 2003), and then to individual RCMs (Gao, Wang, and Giorgi 2013; Ji and Kang 2013). The present study evaluates the ability of multiple RCMs and then uses them to perform a near-future ensemble projection of climate change over the Tibetan Plateau. In the future, more RCM simulations at higher resolution should be conducted and ensembled to examine the climate dynamics of the Tibetan Plateau.

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