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Qinghai-Xizang (Tibetan) Plateau climate simulation using the regional climate model RegCM3

Xuejia Wang[1,3], Meixue Yang[1,*], Guoning Wan[1,3], Xiaolei Chen[1,3], Guojin Pang[2,3]

[1]State Key Laboratory of Cryospheric Sciences, and [2]Key Laboratory of Desert and Desertification, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou Gansu 730000, China

[3]University of Chinese Academy of Sciences, Beijing 100049, China

ABSTRACT: Regional climate models are widely used because of their high resolution. They are especially useful for regions with complex topography and with sparse observations such as the Qinghai-Xizang (Tibetan) Plateau (QTP). We examined the effectiveness of a regional model for simulating climate along the route of the Qinghai-Xizang (Tibetan) Railway (QTR) for use as a practical tool to guide maintenance and long-term management of the railway. We present a 20 yr (1982–2001) climate simulation using a regional climate model (RegCM3) over the QTP with 45 km spatial resolution, and compare the simulated results with the CRU TS3.1 climate data set and with meteorological station data. We investigated the distribution and variation of temperature and precipitation over the QTP and along the QTR. The results show that RegCM3 is able to reproduce the broad characteristics and spatial distribution of temperature over the QTP, including significant regional differences and interannual variability, compared with the CRU dataset. The annual cycle of simulated temperature is close to the observed, although simulated temperatures are slightly higher than observed in winter. RegCM3 also reproduces the broad spatial distribution of summer precipitation (when most precipitation occurs on the QTP) and in more spatial detail than the limited observational data. More precipitation is simulated than observed in the southern QTP, and less in the northern QTP. Although RegCM3 does reproduce annual variations of precipitation at the QTR stations reasonably well, there are some flaws. The simulated interannual variations of precipitation are not as good as those for temperature. Further improvements to the land-surface parameterization scheme for local conditions are required in future work on the QTP.

KEY WORDS: Qinghai-Xizang (Tibetan) Plateau · Qinghai-Xizang (Tibetan) Railway · Regional climate model · Temperature · Precipitation

1. INTRODUCTION

The Qinghai-Xizang (Tibetan) Plateau (QTP) has an extremely important influence on regional and even global climate because of its unique and complicated topography, and underlying surfaces. As it is vulnerable to climate change, the QTP has become a focal point of scientific research. In China, the cryosphere (snow, lake ice, glaciers, frozen ground, etc.) is mainly distributed over the QTP. During the 20th century, and especially since the 1950s, the QTP experienced pronounced warming, which resulted in glacier retreat, permafrost degradation and a series of environmental and ecological issues (Yang et al. 2004, 2010, Tian et al. 2006, Yao et al. 2007, Xiao et al. 2007, Wu & Zhang 2008). Extensive concerns about these issues have been raised in both academic and social domains.

However, due to the sparse and unevenly distributed observational network over the QTP and the limited observational database, station data cannot always meet the requirements of climate research

*Corresponding author: Email: mxyang@lzb.ac.cn

(Yang et al. 2010). Moreover, it is unlikely that this situation will improve within a short time. Thus, high resolution regional climate models, which can describe climate variations due to mesoscale and smaller topography, underlying surface characters and other factors, have become a powerful tool to investigate climate mechanisms and to predict regional climate. Some researchers have used RegCM2 to analyze the climate effect of abnormal snow cover over the QTP. Results from these studies suggest that snow depth anomaly, especially in winter, was one of the factors influencing precipitation in China. Heavier snow cover over the western part of QTP had a more obvious effect on the regional atmospheric circulation in the later period (Qian et al. 2003, Liu et al. 2005). Li & Xue (2010) used NCEP GCM/SSiB and satellite derived vegetation data to evaluate major QTP climate features in summer. It showed that land cover change from vegetated land to bare ground results in lower net radiation and weaker surface thermal effects, which leads to lower atmospheric temperature, as well as weaker vertical ascending motion, low-layer cyclonic, upper level anticyclonic, and summer monsoon circulation. These changes in circulation cause a decrease in the precipitation in the southeastern TP. A remarkable warming over the Yarlung Zangbo River Basin, East and South Asia, and an increase of annual precipitation over most of China north of 30° N and a decrease or little change in the rest of China, India and Indochina in the 21st century are predicted by a high resolution regional climate model under the IPCC SRES A1B future scenario (Shi et al. 2011, Gu et al. 2012).

The regional climate model RegCM3 is based on previous versions (National Center for Atmospheric Research, NCAR RegCMs) and was updated and improved by the International Centre for Theoretical Physics (ICTP). It has been widely used, including for climate simulation over the QTP (e.g. Gao et al. 2003, Qian et al. 2003, Liu et al. 2005, Zhang et al 2005, Pal et al. 2007, Qu et al. 2009, Shi et al. 2011). Gao et al. (2003) simulated the distribution of temperature and precipitation over the QTP for 5 yr using both RegCM2 and a general circulation model (GCM). Their results indicated that RegCM2 could represent the temperature and precipitation features of the QTP in detail. Its capability to simulate precipitation intensity and location was considerably improved over the GCM. Zhang et al. (2005) conducted a numerical simulation experiment over the QTP for 15 yr employing RegCM3. The basic character of the spatial distribution of precipitation and temperature over the QTP was reproduced by the model. A recent RegCM3 numerical simulation study for 10 yr of summer (JJA) air temperature and precipitation showed that simulated results could rectify some disadvantages of the sparse observational network (Qu et al. 2009). However, until now little long-term regional climate model validation work has been done over the QTP, due to the limitation of computing resources. In general, model simulation time scales for the QTP have been just from months to a few years.

In this study we used the regional climate model RegCM3 to conduct a numerical experiment at 45 km resolution for 20 yr (1982 to 2001), to investigate the model's ability to simulate interannual climate variability of the QTP. A brief introduction of RegCM3 and the data used for this experiment is given in Section 2. The simulated 20 yr averaged large-scale features, including temperature and precipitation over the QTP, are presented in Section 3. In Section 4, we interpolate the simulation results onto stations along the Qinghai-Xizang (Tibetan) Railway (QTR), and compare these with both individual meteorological data and Climate Research Unit (CRU) data. The performance of RegCM3 for simulating annual and interannual variability of the QTR stations, and a comparison between RegCM3 and RegCM4, is presented in Section 5. Section 6 is the Discussion.

2. MODEL AND VALIDATION DATA

RegCM3 is a version of the NCAR RegCM2 model (Giorgi et al. 1993a,b, Pal et al. 2007), which includes an updated land surface scheme, the Biosphere-Atmosphere Transfer Scheme (BATS 1e) (Dickinson et al. 1993), the radiative transfer scheme of the Community Climate Model version 3 (CCM3) (Kiehl et al. 1996), a large-scale cloud and precipitation scheme which accounts for the subgrid-scale variability of clouds (Pal et al. 2000), new parameterizations for ocean surface fluxes (Zeng et al. 1998), and a cumulus convection scheme (Emanuel 1991, Emanuel & Živkovic-Rothman 1999). Also, improvements to the user-friendliness of the model were made. A new version, RegCM4 (Giorgi et al. 2012) is coupled with a more advanced land surface process model, CLM 3.5, described in Oleson et al. (2004, 2008) and Dickinson et al. (2006).

In our simulation, the RegCM3 center point is 33° N, 89° E. The horizontal grid consists of 56 and 94 points in the latitudinal and longitudinal directions, respectively, with 45 km resolution, and 23 vertical layers with the model top at 10 hPa. The simulation

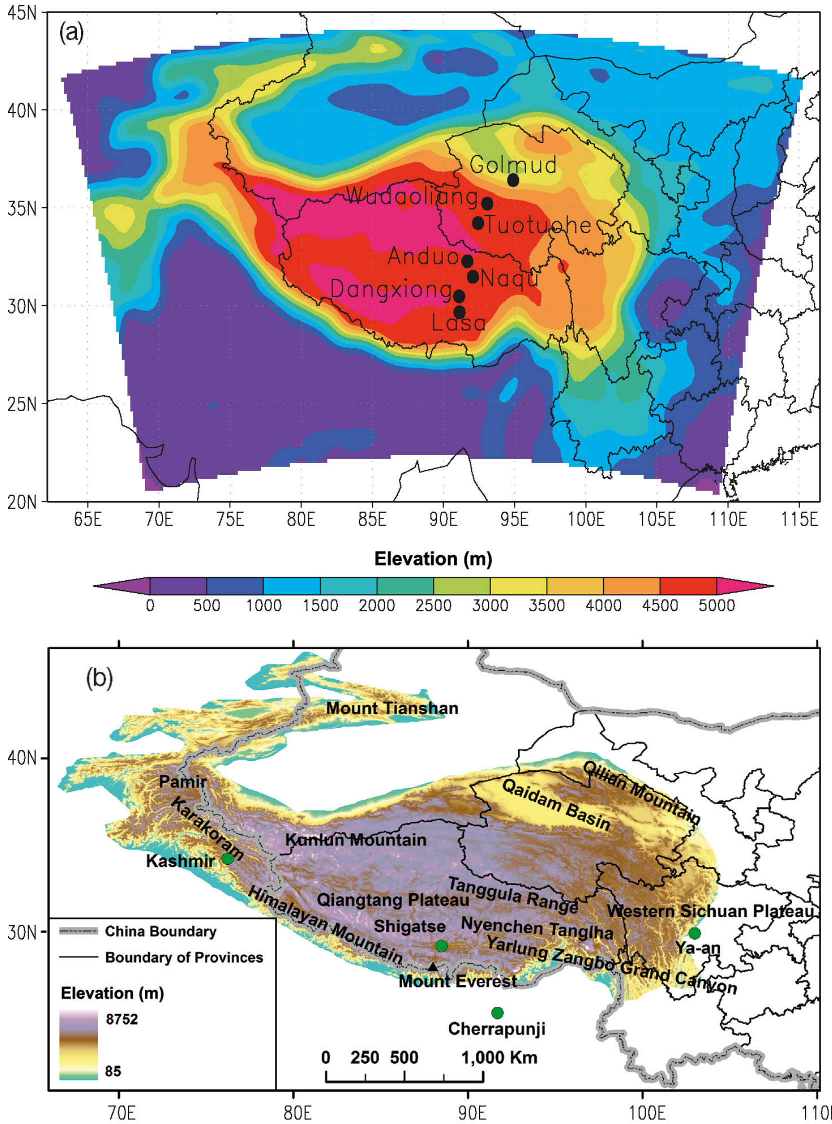

Fig. 1. (a) Elevation (m) of experimental domain. The Qinghai-Xizang (Tibetan) Plateau (QTP) is the broad area over ~3000 m elevation, and the Qinghai-Xizang (Tibetan) Railway (QTR) follows the line of stations shown in Table 1. (b) Place names discussed in text

domain, and the QTP and its peripheral regions, are shown in Fig. 1. Buffer zones are located across 12 grid points along all 4 domain edges. In order to maintain model computational stability, which can be a problem due to high wind speeds in some winter months and complicated topography over the QTP, we set 75 s as the time step.

The initial and lateral atmospheric boundary data used in this simulation are the ECMWF/ERA40 reanalysis data. Lateral boundary conditions are provided every 6 h. Sea surface temperature (SST) data with a 1 × 1° spatial resolution and 7 d temporal period generated by the Integrated Global Ocean Service System are spatially and temporally interpolated as the initial and boundary conditions of SST. We chose 10 × 10′ terrain data and United States Geological Survey (USGS) Global Land Cover Characterization (GLCC) data based on satellite observations as the topography and vegetation inputs, respectively. Table 2 shows the major parameterization schemes used in this experiment. The cumulus clouds convective parameterization scheme is Grell, because it is better than Anther-Kuo when simulating the spatial pattern of climate over the QTP (Yang & Yang 2008). In this study, the integral time of the simulation is from 1 November 1981 to 31 August 2002, a total of 20 yr and 10 mo. 1 November to 31 December 1981 is the spin-up period for initializing the atmosphere and other longer memory variables such as soil moisture, and we selected the interval of 1 January 1982 to 31 December 2001 (20 yr) to analyze the simulated results. We also

Table 1. Details of the 7 meteorological stations along the Qinghai-Xizang (Tibetan) Railway (QTR): Chinese and local name (where applicable)

Name	Latitude (°N)	Longitude (°E)	Elevation (m)
Geermu/Golmud	36.42	94.90	2807.6
Wudaoliang	35.22	93.08	4612.2
Tuotuohe	34.22	92.43	4533.1
Anduo/Amdo	32.27	91.68	4800
Naqu/Nagchu	31.48	92.07	4507
Dangxiong/Damxung	30.48	91.10	4200
Lasa/Lhasa	29.07	91.13	3648.9

Table 2. Parameterizations used in this experiment

Physics	Scheme
Physical frame	MM5 Hydrostatic
Map projection	Lambert
Cumulus clouds	Grell with Frisch-Chappell
Radiation	CCM3
Large-scale precipitation	SUBEX
Land-surface	BATS
Planetary boundary layer	Non Local
Ocean surface fluxes	Zeng Scheme
Lateral boundary	Relaxation (exponential)
Pressure gradient	Hydrostatic deduction

included a 27 mo (1 October 1998 to 31 December 2000) RegCM4.1 simulation experiment for the same domain and initial and lateral atmospheric boundary data, and compared this with RegCM3 to see whether some aspects of the simulation might improve. In the RegCM4.1 simulation, in order to eliminate the effect of initial land surface conditions, the first 15 mo (i.e. 1 October 1998 to 31 December 1999) were used for model spin-up and were not included in the analysis.

The monthly CRU TS3.1 dataset was used for the evaluation of regional scale features and interannual variation of the simulated results. The CRU TS3.1 dataset, which was developed by the CRU of East Anglia University (New et al. 1999), is a long time series (1901 to 2009) monthly averaged climate parameter dataset with a high spatial resolution (0.5 × 0.5°). We interpolate the simulated results onto the QTR stations by bilinear interpolation. The annual and interannual variations of temperature and precipitation along the QTR stations are derived from the CRU TS3.1 data set and from meteorological observation data provided by Data and Information Center, China Meteorological Administration.

The bilinear interpolation method is an extension of linear interpolation for interpolating functions of 2 variables (e.g. *x* and *y*) on a regular 2D grid. The key idea is to perform linear interpolation first in one direction, and then again in the other direction. Although each step is linear in the sampled values and in position, the interpolation as a whole is not linear but rather quadratic at the sample location (http://en.wikipedia.org/wiki/Bilinear_interpolation). All station data of the QTR were processed using the same method.

Since there are only scarce observations in the western and northern parts of the QTP, the temperature and precipitation of CRU TS3.1 were selected as validation data to test the simulated results on a large regional scale. The CRU data contain 160 climate base stations in the China area, which are released internationally by National Climate Center, as well as some non-base observation stations derived from personal contacts (New et al. 1999). Previous studies (Wen et al. 2006) suggest that CRU data reflect the interannual temperature variations of a reconstructed proxy series from tree rings, ice cores, and lake sediments for China. The correlation coefficient is 0.84 between CRU data and the reconstructed proxy series. The CRU annual total precipitation was also consistent with the 160 Chinese stations for 1951–2000 with a correlation coefficient of 0.93. Xu et al. (2007) used the CRU TS2.0 as validation data for IPCC AR4 models over East Asia, and Chen et al. (2011) analyzed spatiotemporal precipitation variations, and spatial differences in the context of global warming, in arid Central Asia based on CRU TS3.1.

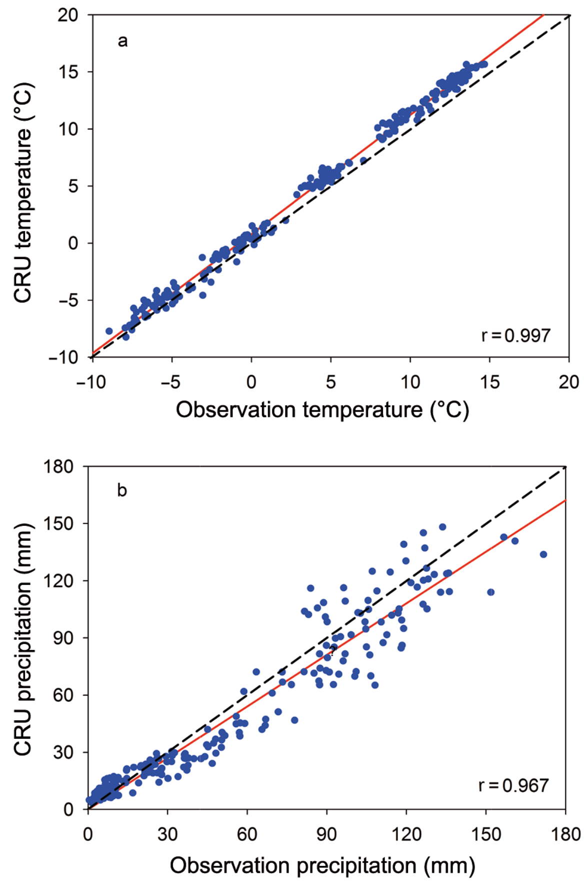

Fig. 2. Scatter diagrams comparing Climate Research Unit (CRU) data with meteorological observations of (a) temperature and (b) precipitation for 1982-2001. Dashed line = 1:1, full line = regression

To test whether the CRU TS3.1 data are applicable over the QTP, we selected the monthly mean CRU data averaged over QTP (25–42° N, 70–105° E) and compared that with monthly mean data from 111 Chinese standard meteorological stations with elevation ≥2000 m over the QTP for the period 1982–2001. Regional average values for various variables over the QTP were derived from the simple arithmetic mean of all the 111 meteorological stations. High correlation (0.997) was found between the CRU and meteorological station temperature data (Fig. 2a). However, the CRU temperature was 0.98°C higher, mostly due to high temperatures in summer. The pattern of variation of precipitation of the CRU and meteorological observations are mostly consistent (Fig. 2b). However, the CRU value was lower in summer, and ~4.12 mm lower for the annual average than the observational data. In summary, the relatively high consistency between the CRU data and the meteorological stations demonstrates that the CRU TS3.1 data reflect the climate variability over the QTP. Although the CRU data set is interpolated from observations, it provides good reference values to validate the model simulation.

3. TEMPERATURE AND PRECIPITATION OVER THE TIBETAN PLATEAU

3.1. Temperature

RegCM3 reproduces the basic characteristics of the spatial distribution of temperature over the QTP. Isotherms are nearly coincident with topographic contours (Fig. 3a,b), and the temperature in the middle of QTP is lower than in the surrounding regions. Temperature in the eastern QTP is higher than in the western QTP, in the southern section it is higher than in the northern, and there is a low temperature center in the Qilian Mountains of the northeastern QTP. Overall, the spatial correlation coefficient between the simulated results and CRU is 0.78 ($p > 95\%$) over most parts of the QTP except for the areas within the dotted lines in Fig. 3c. This indicates that the model can also well reflect interannual variability of temperature over the QTP during the 20 yr. This result is similar to that in the study of Zhang et al. (2005). However, regional differences are apparent. For the Plateau hinterland, the average simulation results are 2.5°C higher than CRU data, and in the Qilian Mountains they are 6°C higher. In southeastern and western areas of the QTP, the simulation results are lower, while in the northwestern QTP there is a maximum cold bias of ~9°C (Fig. 3d). The simulated results are notably worst in areas with high topographic relief. Observation sites are sparsely distributed in these areas. It should also be

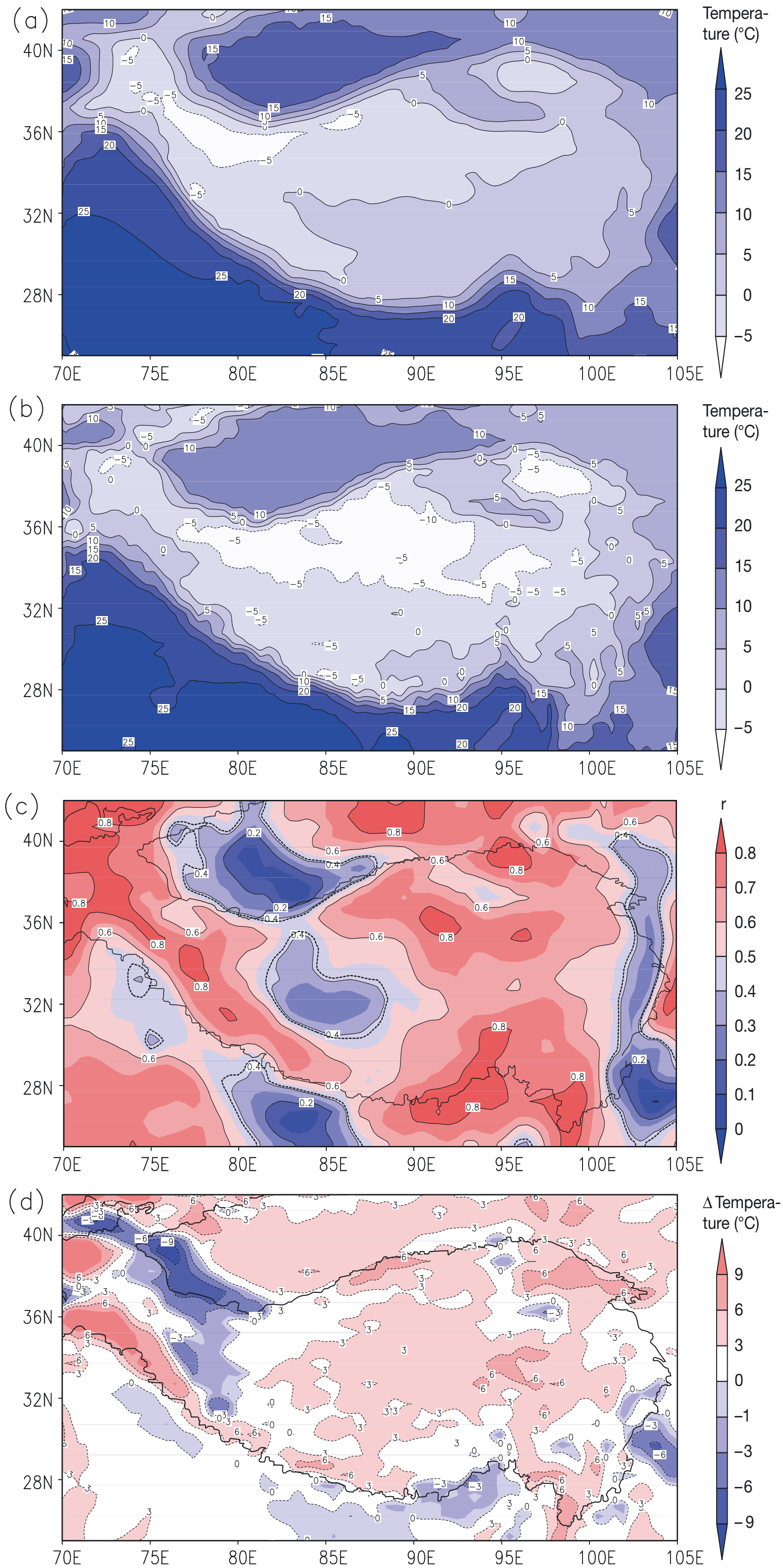

Fig. 3. Qinghai-Xizang (Tibetan) Plateau (QTP) 20 yr average temperature (°C) distribution from (a) model simulation; (b) Climate Research Unit (CRU) data set; (c) annual mean correlation between (a) and (b); and (d) difference (a) minus (c)

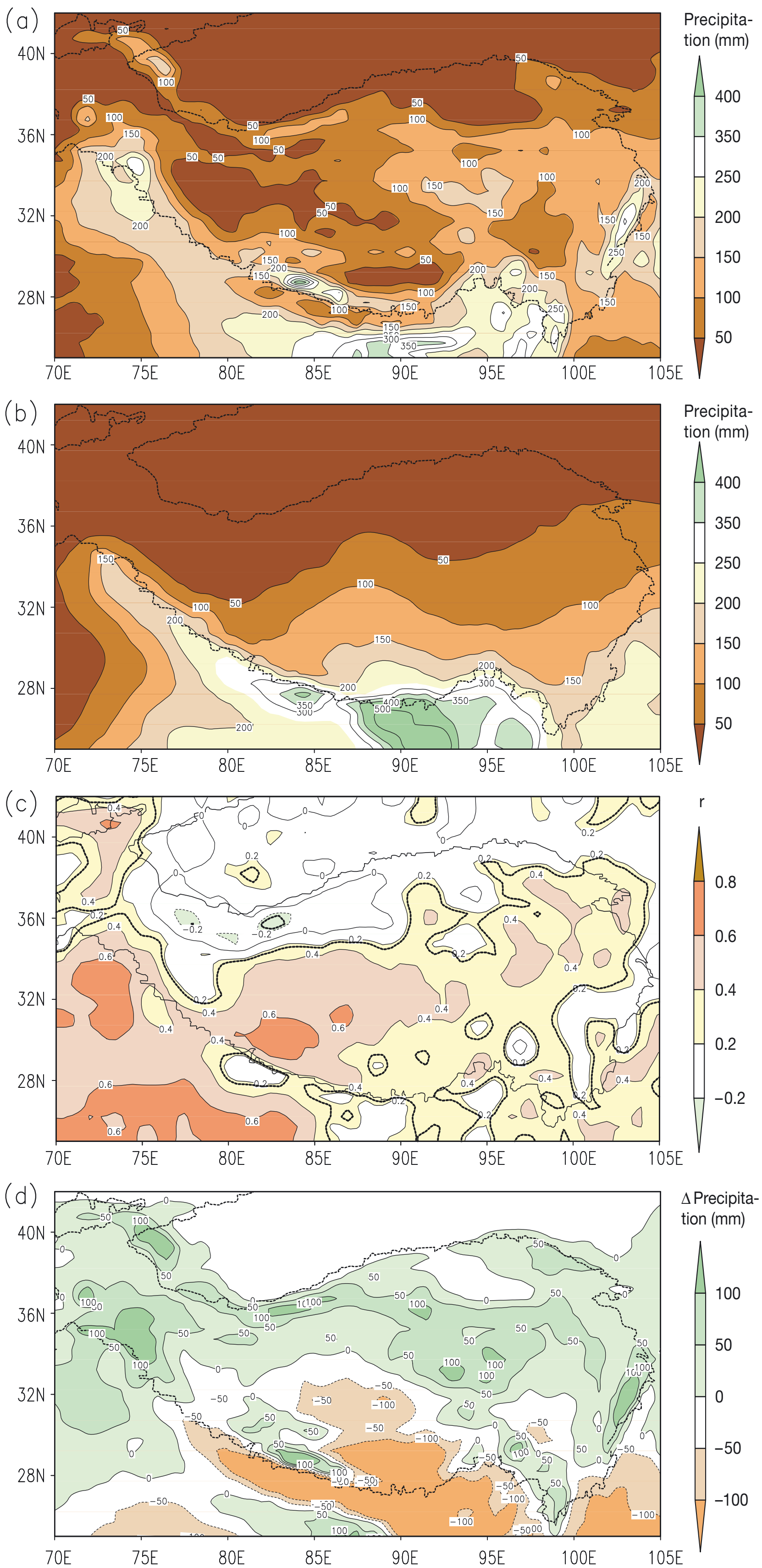

Fig. 4. QTP 20 yr summer mean precipitation distribution (mm) from (a) model simulation; (b) CRU data set; (c) annual mean correlation between (a) and (b); and (d) difference (a) minus (c). See Fig. 3 for definitions

noted that this would also produce errors when interpolating the ECMWF/ERA40 forcing field and CRU data to the model grid.

3.2. Summer precipitation

Most parts of the QTP are arid or semi-arid. Summer precipitation accounts for ~60 to 70% of the annual total (Lu et al. 2007). In addition, interannual variations of precipitation are large (Duan et al. 2008). The spatio-temporal distribution of precipitation over the QTP is more complex than temperature. Rainfall in the peripheral QTP is low and there is a heavier rain belt adjacent to the periphery along the edge of the QTP. This belt lies along the southern slopes of the Himalayan Mountains from west Pamir to Mount Tianshan, turns southeast to the Qilian Mountains, then extends southward between 100 and 103° E. This belt is along the steepest slope where ascending motion is the highest. The terrain inside the Plateau is relatively flat, and the rainfall variation is also slight, decreasing from Western Sichuan Plateau to west Qiangtang Plateau. The southeast region, where southerly winds with abundant water vapor prevail in summer, is moist, whereas the northwest, where northerly winds with dry air prevail, is arid (Ye & Gao 1979).

The dominant spatial pattern of interannual variability of summer precipitation is a seesaw between the southern and northern parts of the QTP. Generally, precipitation varies greatly north and south of Tanggula Range, which is the natural boundary of Qinghai province and Xizang (Tibet). These variations almost show opposite trends (Liu & Yin 2001, Yang et al. 2007, Duan et al. 2008). The QTP precipitation based on meteorological data decreases from southeast to northwest during the summer half year (Wang et al. 2011), and the CRU data show a decrease in the main distribution of summer precipitation from south to north (Fig. 4b). These features of the spatial distribution are captured approximately by RegCM3 (Fig. 4a). The areas with less rain are the Qaidam Basin, and the northern and northwestern QTP. The areas with more rain are Yarlung Zangbo Grand Canyon, western Sichuan Plateau, and Mount Everest, with rainy centers located in Cherrapunji, Ya-an, and Kashmir. The spatial distribution of precipitation is depicted better by RegCM3 than by CRU. For example, Fu et al. (2008), using the Tropical Rainfall Measuring Mission (TRMM) satellite data, found that there was more rain in the northern Nyainqentanglha Range in summer. The model shows this, but not CRU.

The correlation coefficients between simulation and observations are high in most regions of the QTP (dotted line in Fig. 4c represents the 95% confidence level), but some small areas show negative correlation. Simulated interannual variations of summer precipitation over the 20 yr are not as good as for temperature. Fig. 4d shows that the differences are small in the Qaidam Basin and on the margin of the QTP. Simulated values are larger north of the zero isoline, but smaller south of it. Larger positive deviations exist in the Karakoram Mountains, Kunlun Mountains, Himalayan Mountains, Tanggula Mountains and the southern QTP. Negative deviations exist in the Shigatse area and on the north and south slopes of the east Himalayan Mountains. Generally, the simulated precipitation is not correct on high, large, and complex mountains. Simulated precipitation there depends on imperfect description of the σ coordinate system and inadequate cumulus cloud parameterization for this kind of terrain. Scarce observational data may be a reason for the difference.

4. TEMPERATURE AND PRECIPITATION ALONG THE TIBETAN RAILWAY

The QTR extends for 1118 km, from Golmud to Lasa (Lhasa). More than half (632 km) of the railway is in permafrost terrain, including 275 km of warm permafrost (mean annual ground temperature between 0 and –1°C) and 221 km of ice-rich permafrost (ice content >20% by volume). The section underlain by permafrost that is both warm and ice-rich is 134 km in length (Cheng et al. 2008). About 550 km of the Railway's roadbed is in terrain underlain continuously by permafrost, with ~82 km underlain by discontinuous permafrost. The effect of permafrost degradation on the railway maintenance is an issue requiring further examination (Yang et al. 2010). If the model can well simulate the climate of the QTR it will provide an important foundation for railway construction and maintenance in the future. Therefore, we interpolated the simulated results to the QTR observation stations, including Golmud, Wudaoliang, Tuotuohe, Anduo, Naqu, Dangxiong, and Lasa, by bilinear interpolation (Fig. 1 & Table 1). To further as-

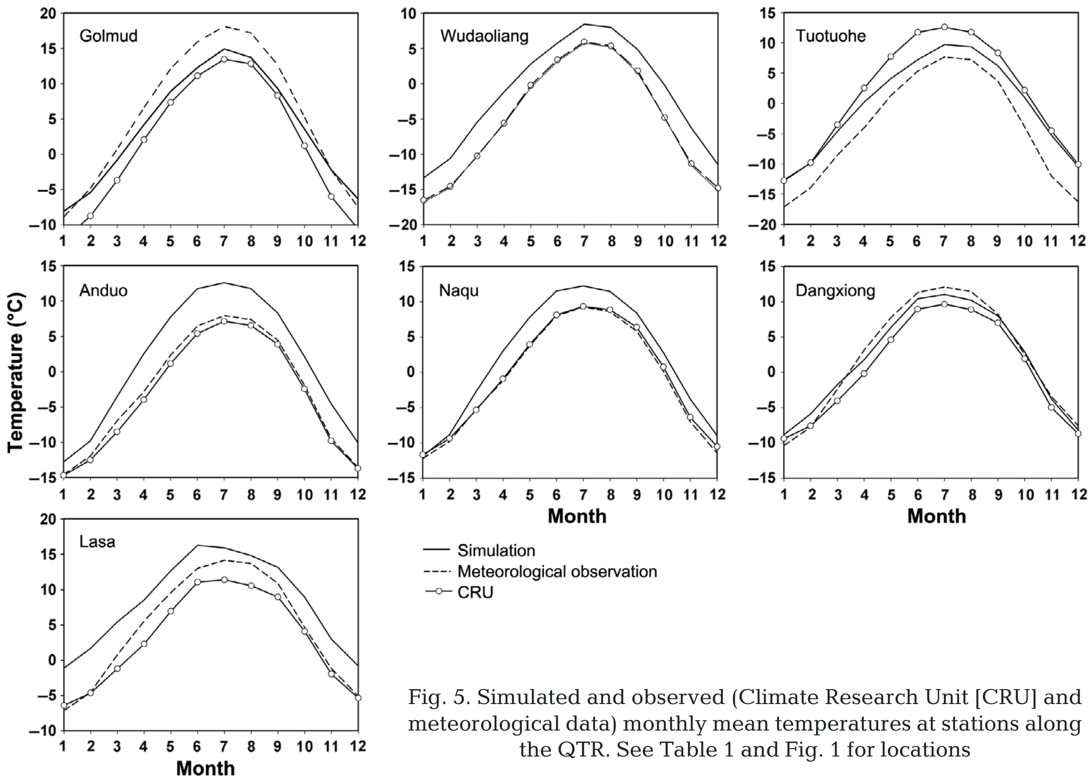

Fig. 5. Simulated and observed (Climate Research Unit [CRU] and meteorological data) monthly mean temperatures at stations along the QTR. See Table 1 and Fig. 1 for locations

sess the model's capability, we compare the simulated results after interpolation with both CRU gridded data and meteorological observations along the QTR.

4.1. Temperature

Fig. 5 shows that the simulated annual temperature cycle is consistent with observations (meteorological and CRU data) for each station. The maximum monthly average temperature is in July, and the minimum occurs in January. The correlation coefficients between observed and simulated monthly means are all >0.99 (significant at >99% level). In winter, the simulated values at all 7 stations are higher than both the meteorological and CRU data by 0.47 to 5.51°C, and 0.69 to 5.39°C, respectively. In summer, the simulated results are higher than the meteorological data (by 2.04 to 4.78°C) at all stations except Golmud and Dangxiong. However the agreement with meteorological data is better than with CRU as the simulated results at all stations are 1.19 to 5.67°C higher. This is likely due to relatively dry soils in the land surface scheme (BATS) of RegCM3. In winter the warmer temperatures would lead to reduced snow cover, enhancing solar radiation absorption at the surface. In summer they could lead to drier soils, which lead to lower surface evaporation rates and latent heat fluxes, causing higher temperatures in the model (Steiner et al. 2009, Mearns et al. 2012).

Fig. 6 shows the simulated and observed curves of interannual temperature anomaly at the stations along the QTR. Clearly, the simulation trends in most years coincide with observations. RegCM3 is capable of simulating major temperature fluctuations such as the relative peaks in 1988, 1991, 1998 and 1999 as well as the lows in 1983, 1992, 1997 and 2000. The simulated peaks and lows are, however, smaller than observations. In Table 3, the correlation coefficients with the meteorological data (RSM) have p >95% in Tuotuohe and Dangxiong, and p >99% at other stations. The standard deviation between the simulated results and meteorological data (ESM) of all stations except Tuotuohe are small. In the case of the correlation coefficient between the simulated results and CRU (RSC), all stations except Dangxiong (which does not pass the

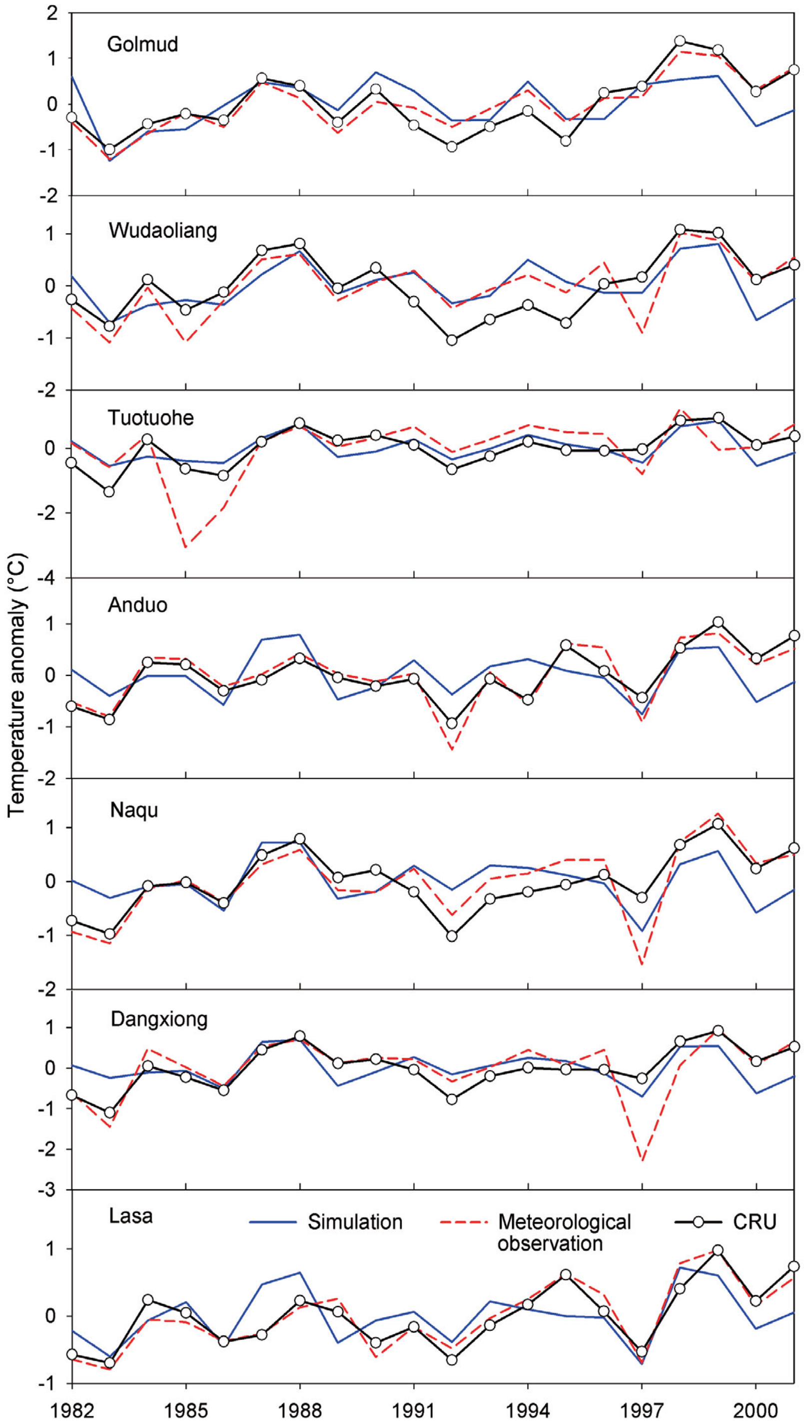

Fig. 6. Simulated and observed interannual anomaly curves of annual mean temperature at stations along the Qinghai-Xizang (Tibetan) Railway (QTR). CRU: Climate Research Unit

Table 3. Correlation coefficient between simulated and observed temperature and multi-year SD (°C) along the Qinghai-Xizang (Tibetan) Railway (QTR). Correlation coefficients and SDs between simulated results and (1) meteorological data (RSM and ESM, respectively), and (2) Climate Research Unit data (RSC and ESC, respectively). **99% and *95% confidence levels

	Golmud	Wudaoliang	Tuotuohe	Anduo	Naqu	Dangxiong	Lasa
RSM	0.61**	0.67**	0.55*	0.58**	0.67**	0.50*	0.64**
RSC	0.60**	0.59**	0.70**	0.54**	0.48*	0.42	0.61**
ESM	0.48	0.43	0.80	0.60	0.49	0.52	0.39
ESC	0.53	0.48	0.40	0.44	0.50	0.51	0.38

confidence level) are good and the standard deviations between simulated results and CRU data at all 7 stations are low. In general the simulated results are better correlated with meteorological data than with CRU. Overall the model simulates interannual temperature variations reasonably well.

4.2. Precipitation

The annual variation of precipitation simulated by RegCM3 shows a single summer peak at each station (Fig. 7). However, this peak sometimes occurs one month earlier or later than in the observations. The simulations for Anduo, Naqu and Dangxiong are best. But the simulated results for Golmud, Wudaoliang and Tuotuohe show a larger summer peak than observations and the model underestimates the monthly mean precipitation of Lasa by ~50 to 100 mm. This may relate to the fact that as much as 65% of the rainfall in Lasa occurs at night, from 20:00 to 08:00 h Local Sidereal Time (LST) (Liu 1992). The meteorological station data record this phenomenon, but the model fails to do so. Winter precipitation is controlled more by the large-scale flow, such as the planetary westerlies (Ye & Gao 1979). Simulated values are close to observations in winter. The correlation coefficients between simulated results and observation are all >0.83 ($p > 99\%$). Golmud and Anduo have small average deviations, but the average deviations between the simulated results and the meteorological data are smaller than with CRU at all other stations. The average deviations between meteorological data and simulated results of the 7 stations are different. This may relate to the local terrain, which affects precipitation at meteorological stations. Many meteorological stations on the QTP, for example Lasa, are situated in valleys. During the day, the sun heats the valley air and then at night the hillside air cools rapidly and rolls downslope, causing the warm, wet air of the valley to lift. Clouds formed by the con-

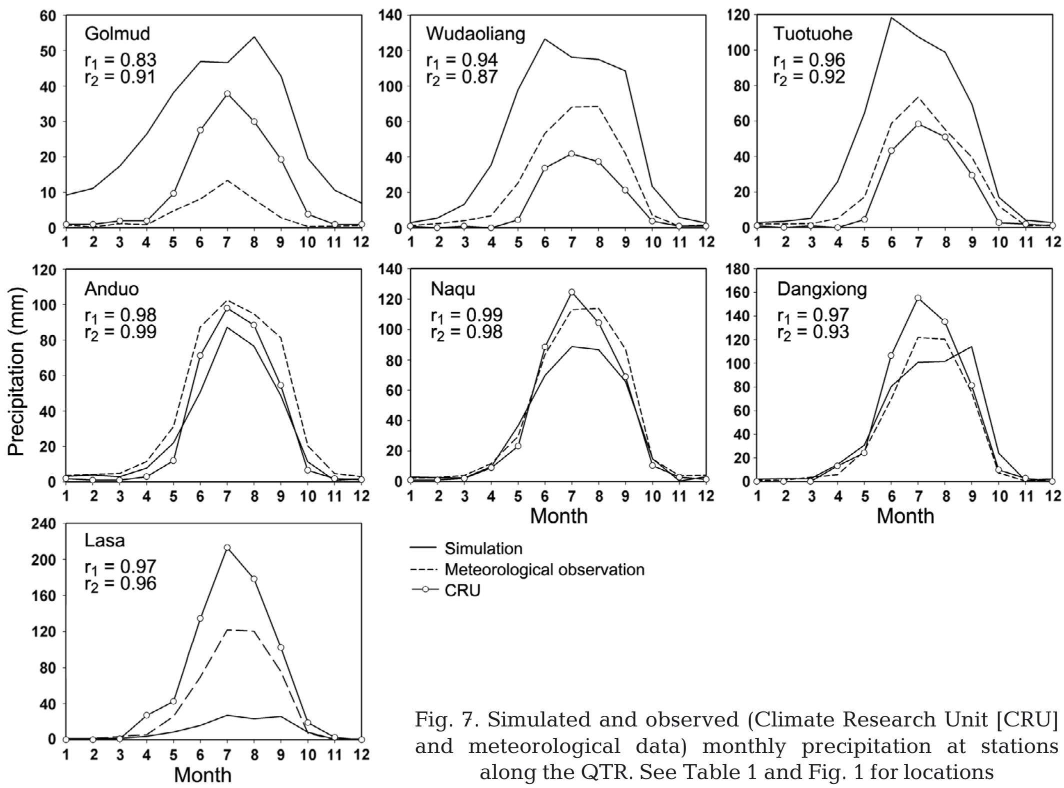

Fig. 7. Simulated and observed (Climate Research Unit [CRU] and meteorological data) monthly precipitation at stations along the QTR. See Table 1 and Fig. 1 for locations

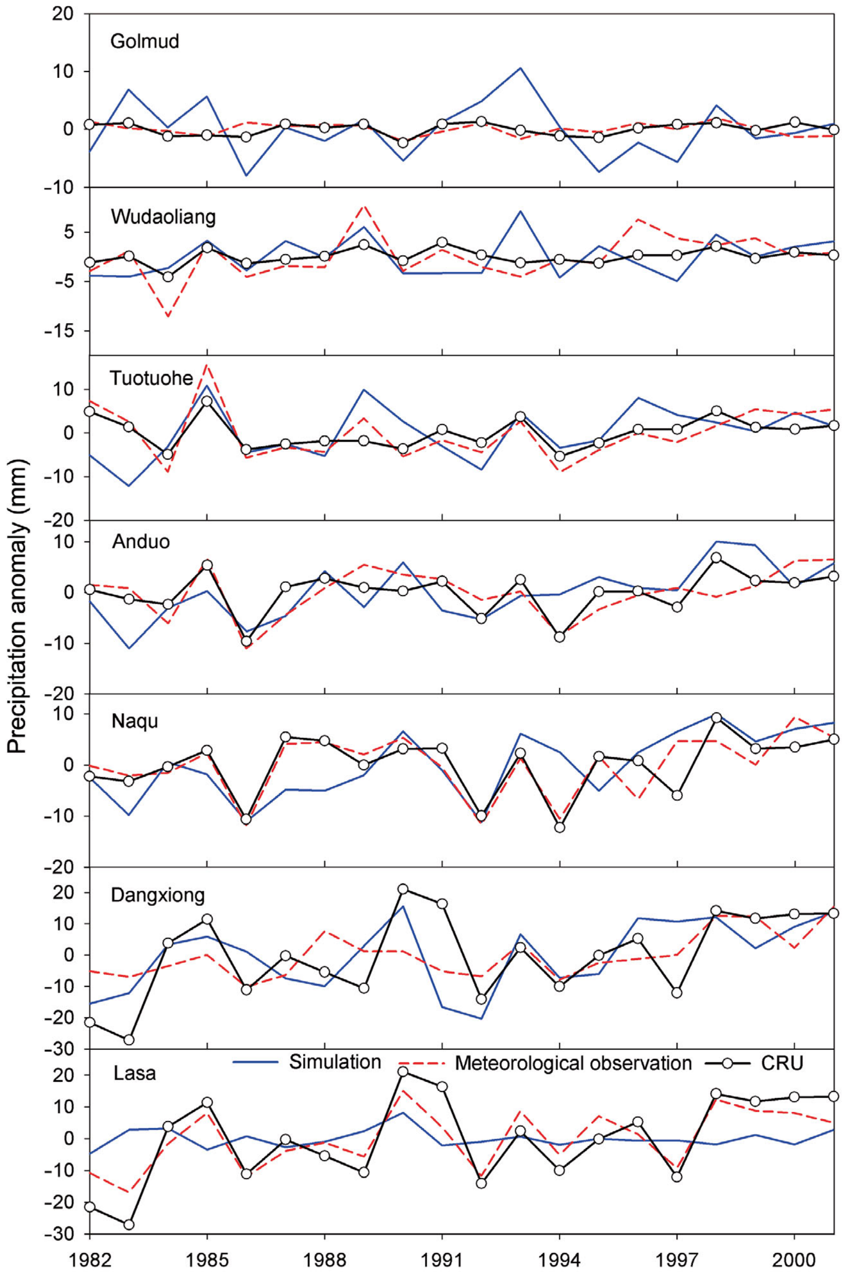

Fig. 8. As for Fig. 6, but for precipitation

Table 4. Correlation coefficient between simulated and observed precipitation and multi-year SD (mm) along the QTR. Correlation coefficients and SDs between simulated results and (1) meteorological data (RSM and ESM) and (2) Climate Research Unit data (RSC and ESC). **98% and *95% confidence levels. See Table 3 for definitions

	Golmud	Wudaoliang	Tuotuohe	Anduo	Naqu	Dangxiong	Lasa
RSM	−0.14	0.20	0.47*	0.33	0.56**	0.56**	0.19
RSC	0.37	0.22	0.36	0.55**	0.47*	0.57**	0.20
ESM	4.98	5.40	6.08	5.79	5.73	9.04	8.87
ESC	4.43	3.84	5.60	4.52	6.17	11.36	12.96

densation of this warm, wet air produce the night rain. Model resolution is insufficient to capture this process. As mentioned in Section 3, the Plateau precipitation is dominated by the prevailing southerly and northerly winds in summer. Thus, the overestimation of precipitation by RegCM3 may arise from their failure in reproducing the progression and intensity of the southerly and northerly air flows. Further investigation of large-scale atmospheric circulation and local convective processes is needed.

RegCM3 has limited ability to simulate the interannual precipitation anomalies at each station (Fig. 8). The simulated annual precipitation anomalies are opposite to observations in some years (e.g. at Golmud). Comparison with observations exceed the 98% significance level only at Naqu and Dangxiong, the 95% level at Tuotuohe, while other stations do not pass the confidence level at all (Table 4). The multi-year standard deviations of precipitation are large at all stations except Tuotuohe and Naqu.

5. COMPARISONS BETWEEN RegCM3 AND RegCM4

RegCM3 and RegCM4 employ different land surface models. The new land surface scheme, Community Land Model (CLM3.5), provides a more detailed representation than BATS, although CLM3 does incorporate some of the advantages of BATS (Dickinson et al. 2006). This improves the RegCM4 simulation of surface energy and water budgets as well as the surface hydrological cycle (Steiner et al. 2009). Fig. 9 compares the annual mean temperature over the QTP for RegCM3 and RegCM4. The RegCM4 simulated spatial distribution of annual mean temperature is largely consistent with RegCM3, albeit with slightly lower values. Compared with CRU data (Fig. 9b), there is a warm bias in RegCM3 (Fig. 9c) and a cold bias in RegCM4 (Fig. 9e). The western QTP exhibits the biggest cold bias in both models.

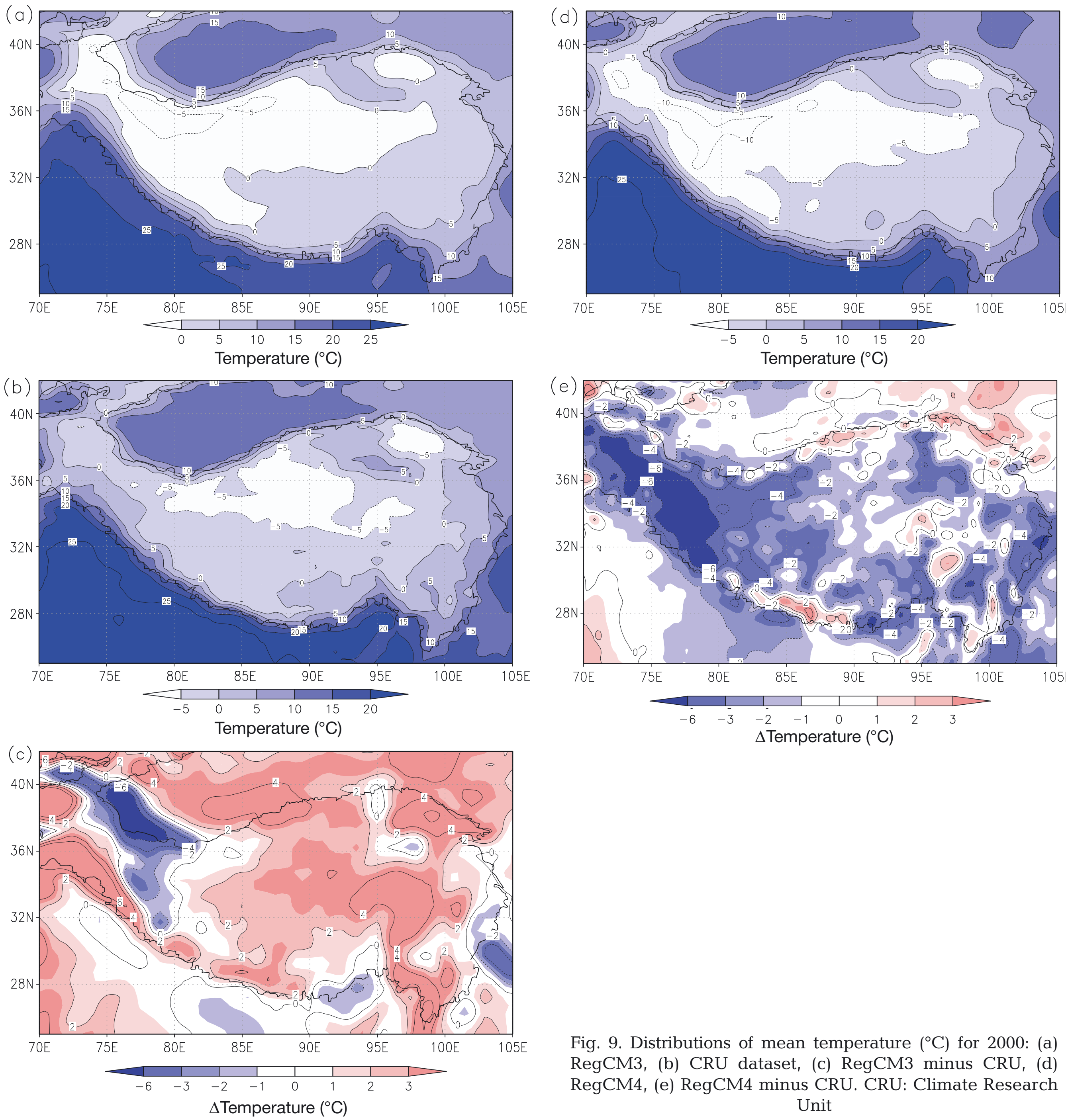

Fig. 9. Distributions of mean temperature (°C) for 2000: (a) RegCM3, (b) CRU dataset, (c) RegCM3 minus CRU, (d) RegCM4, (e) RegCM4 minus CRU. CRU: Climate Research Unit

Fig. 10 shows the difference in annual mean precipitation over the QTP between RegCM3 and RegCM4 for the year 2000. The spatial pattern of the simulated precipitation in RegCM4 (Fig. 10d) is similar to that in RegCM3 (Fig. 10a). Overall, this shows that the model is sensitive to the land surface scheme and that further testing is needed to assess the performance of RegCM4.

6. DISCUSSION

RegCM3 has the ability to reproduce the basic spatial distribution of temperature over the QTP when compared with the CRU dataset. Regional differences are very apparent. In the QTP hinterland, the average simulation results are 2.5°C higher than CRU, and 6°C higher in the Qilian Mountains. How-

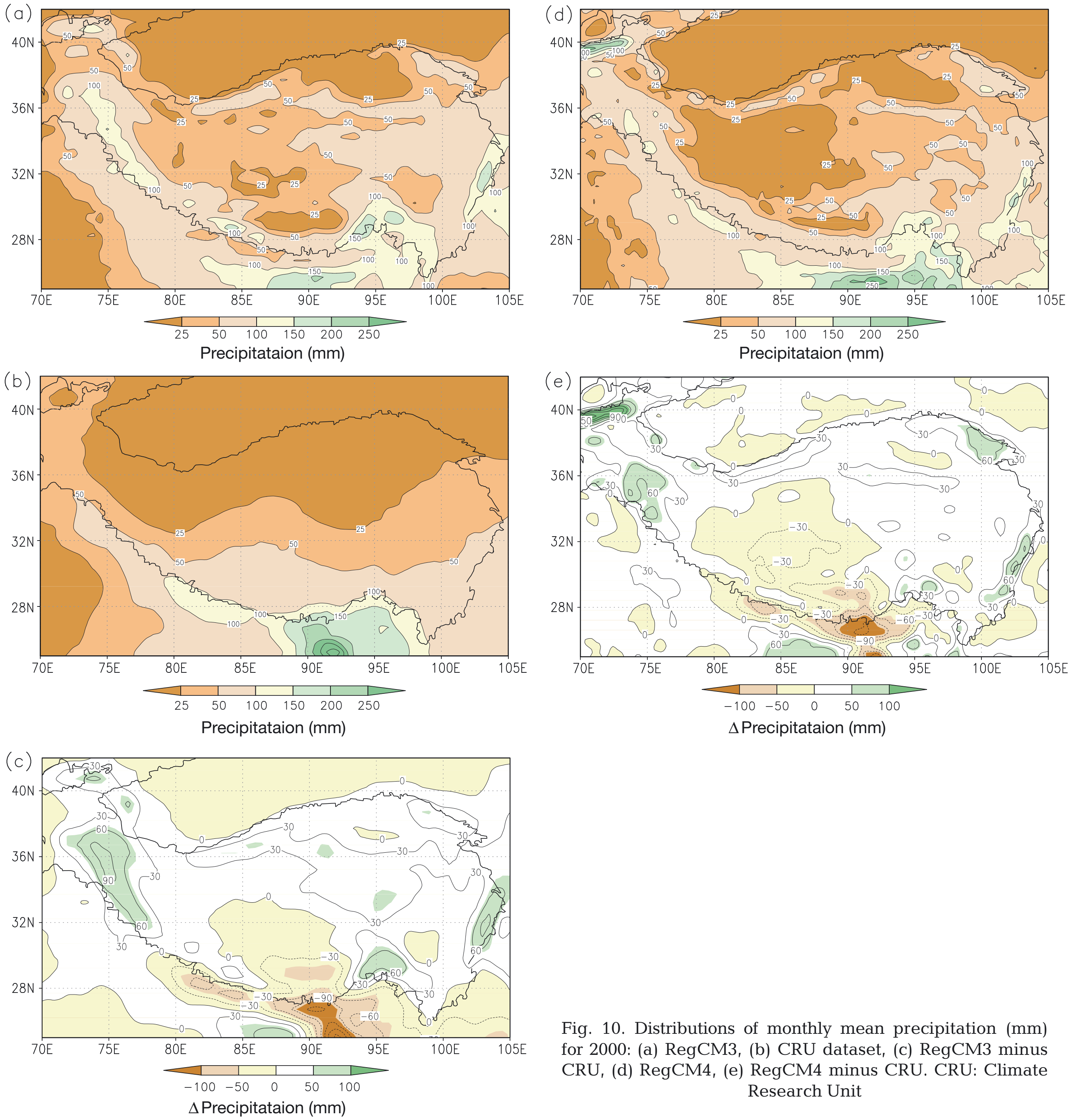

Fig. 10. Distributions of monthly mean precipitation (mm) for 2000: (a) RegCM3, (b) CRU dataset, (c) RegCM3 minus CRU, (d) RegCM4, (e) RegCM4 minus CRU. CRU: Climate Research Unit

ever, the simulation results are lower in southeastern and western areas of the QTP. The northwestern QTP has a maximum cold bias of ~9°C. These conclusions are similar to those of Qu et al. (2009). These cold biases are partly attributable to the simulation of excess precipitation in these regions (Lee & Suh 2000). The lack of high-elevation observation stations in the CRU data may also be partly responsible for the apparent cold bias of the model (Gu et al. 2012). The high correlation coefficient ($r = 0.78$, $p < 0.01$) between the simulation and CRU suggests that the model well reflects the interannual variability of temperature over the QTP. The simulated results are however not good in those areas with high topographic relief. This is partly because the σ coordinate system is inadequate in abrupt topography. In steep terrain, the gradient of σ is large, which amplifies changes to physical parameters linked to vertical change, and increases calculation errors. Limited observational data may also be an important reason for discrepancies in this kind of terrain.

RegCM3 can also reproduce the major spatial distribution of summer precipitation over the QTP, and it depicts it better than the CRU dataset. More precipitation is simulated in the southern QTP and less in the northern QTP. However, precipitation simulations are much less accurate than temperature simulations because of the complexity of precipitation over the QTP and limitation of the model, especially in complex terrain. Poor description of the σ coordinate system, inadequate cumulus clouds parameterization in this kind of terrain, and scarce observational data all contribute to the differences. Besides, precipitation is sensitive to model resolution (horizontal and vertical) (Giorgi & Marinucci 1996, Zhao & Luo 1998, Gao et al. 2006, Liu et al. 2011).

Annual variations of temperature at QTR stations simulated by RegCM3 are close to, but higher than observed data in winter. The annual variation of simulated precipitation has some flaws. The interannual variability of temperature and precipitation are also captured by RegCM3, although worse for precipitation than for temperature. Meteorological station data may be better for validation of a regional climate model than the CRU data set.

Although some biases exist between the model and observational data, the model is still an invaluable tool for understanding regional climate and for investigating climate change on the QTP. Daily average temperature data with a spatial resolution of 0.5 × 0.5° (CN05) (variables including maximum and minimum temperature) and precipitation data (GPCP) have already been used to examine climate models (Xie et al. 2007, Xu et al. 2009). These high quality data may be better for future regional climate model validation. A comparison between RegCM3 and RegCM4 shows that the land-surface process model in RegCM3, which was developed for non-cryospheric areas, is inadequate for the QTP. Therefore, improving the land-surface parameterization scheme and developing appropriate physical parameterization schemes are essential steps to enhance climate simulation over the QTP.

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