INTERNATIONAL JOURNAL OF CLIMATOLOGY
Int. J. Climatol. **36**: 2660–2670 (2016)
Published online 2 October 2015 in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/joc.4520

Royal Meteorological Society

Rapid warming in the Tibetan Plateau from observations and CMIP5 models in recent decades

Qinglong You,[a]* Jinzhong Min[a] and Shichang Kang[b]
[a] *Earth System Modeling Center, Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University of Information Science and Technology, China*
[b] *State Key Laboratory of Cryospheric Science, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, China*

ABSTRACT: On the basis of mean temperature, maximum temperature and minimum temperature from the updated China Homogenized Historical Temperature Data Sets, the recent warming in the Tibetan Plateau (TP) during 1961–2005 and global warming hiatus period are examined. During 1961–2005, the mean temperature, maximum temperature and minimum temperature in the whole TP show a statistically increasing trend especially after the 1980s, with the annual rates of 0.27, 0.19 and 0.36 °C decade^{-1}, respectively. The performance of 26 general circulation models (GCMs) available in the fifth phase of the Coupled Model Intercomparison Project (CMIP5) is evaluated in the TP by comparison with the observations during 1961–2005. Most CMIP5 GCMs can capture the decadal variations of the observed mean temperature, maximum temperature and minimum temperature, and have significant positive correlations with observations ($R > 0.5$), with root mean squared error <1 °C. This suggests that CMIP5 GCMs can reproduce the recent temperature evolution in the TP, but with cold biases. However, most CMIP5 GCMs underestimate the observed warming rates, especially the CNRM-CM5, GISS-E2-H and MRI-CGCM3 models. There are significant positive correlations between the trend magnitudes and the anomaly of the mean temperature, maximum temperature and minimum temperature, with correlations of 0.85, 0.86 and 0.87, respectively. The warming from the observations and CMIP5 mean in the TP is significant during the global hiatus period, consistent with decreasing snow cover and albedo in the region. This study suggests that positive snow/ice-albedo feedback processes may account for ongoing surface warming in the TP despite the pause in global mean surface warming.

KEY WORDS Tibetan Plateau; CMIP5; climate warming; hiatus

Received 13 March 2015; Revised 22 August 2015; Accepted 1 September 2015

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) estimated global mean surface temperature warming of 0.85 °C since 1880 (IPCC, 2013), which is already having substantial ecological, economic and societal impacts. The warming rate, however, has not been homogeneous across the globe (IPCC, 2013). The fastest rate of warming has occurred in the coastal, mountain and high-latitude regions (such as the Arctic) (Screen, 2014). The global mean surface temperature during the first decade of the 21st century has been <0.05 °C, much less rapid rise than in the previous few decades. This slowdown in global mean surface warming has been termed the global warming hiatus (Fyfe and Gillett, 2014; Watanabe *et al.*, 2014). The causes and longer term implications of this global warming hiatus have been extensively debated in recent years (Kaufmann *et al.*, 2011; Kosaka and Xie, 2013; Meehl *et al.*, 2014; Watanabe *et al.*, 2014). The slowdown in the rate of global warming in the early 2000s is not evident in the multi-model ensemble average of traditional climate change projection simulations (Fyfe *et al.*, 2013; Fyfe and Gillett, 2014). Therefore, understanding the causes of the hiatus is important for assessing the fidelity of current climate models and their projections of the magnitude of future climate warming (Hawkins *et al.*, 2014).

The Tibetan Plateau (TP), with an average elevation of over 4000 m, is the highest and the largest highland in the world and exerts a great influence on regional and global climate through its thermal forcing mechanism (Duan *et al.*, 2012; Wu *et al.*, 2012; Yao *et al.*, 2012). The TP and its surroundings contain the largest number of glaciers outside the polar regions, which are at the headwaters of many prominent Asian rivers (Yao *et al.*, 2012). In the context of global warming, climate and cryospheric change in the TP are well evident, including glacier shrinkage, expansion of glacier-fed lakes, permafrost degradation, shortened soil frozen period and thickening of the active layer (Kang *et al.*, 2010; You *et al.*, 2010; Yang *et al.*, 2011, 2014; Yao *et al.*, 2012). Moreover, more than 1.4 billion people depend on water from the Indus, Ganges, Brahmaputra, Yangtze and Yellow Rivers, and the warming in the TP

* Correspondence to: Q. You, Earth System Modeling Center, Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China. E-mail: yqingl@126.com

© 2015 Royal Meteorological Society

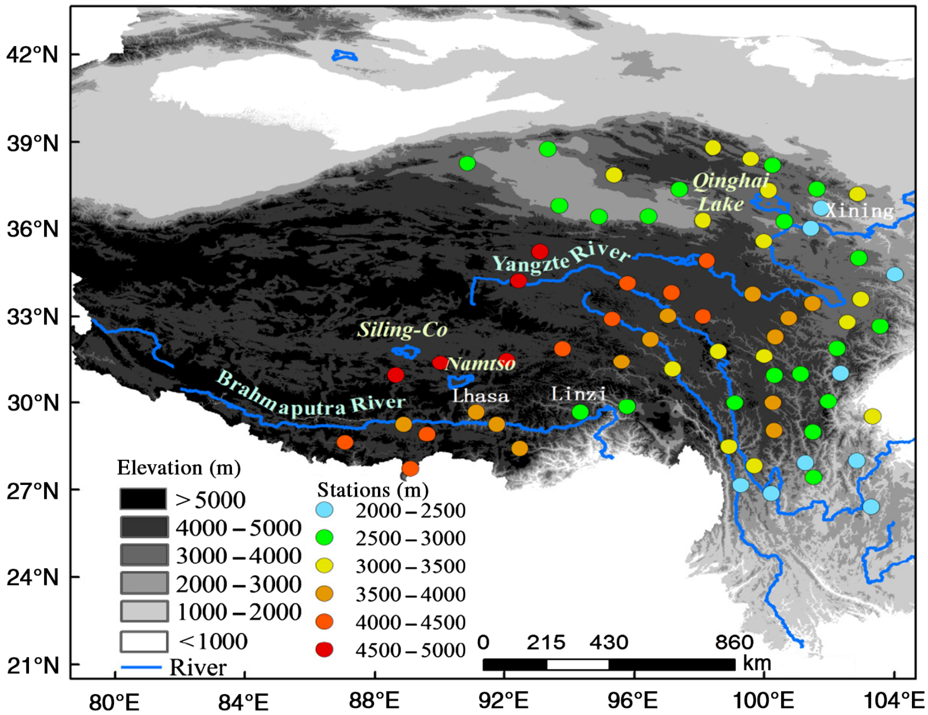

Figure 1. The distribution of 71 stations and the elevation information.

may lead to reduced water resources for the downstream regions in the future (Immerzeel *et al.*, 2010). Therefore, climate change in the TP is of societal importance to both the local and surrounding people (Kang *et al.*, 2010; Yao *et al.*, 2012; Yang *et al.*, 2014).

In this study, the recent warming in the TP is examined using a new homogenized observational data set and the state-of-the-art climate models, which have been made publicly available through the Coupled Model Intercomparison Project phase 5 (CMIP5). It expands on previous studies (Liu *et al.*, 2006; You *et al.*, 2008a; Rangwala *et al.*, 2009; Kang *et al.*, 2010; Duan *et al.*, 2012; Su *et al.*, 2013) through the use of a more reliable observational data set and by evaluating the performance of the latest CMIP5 model simulations. This study is aimed at answering the following questions: (1) how much has the TP warmed in recent decades? (2) how well do the CMIP5 models reproduce this historical warming in the TP? (3) does the warming hiatus after 2000 exist in the TP? Our results will lead to a better understanding of climate change impact assessments in the TP.

2. Data set and method

Homogenized monthly mean temperature, maximum temperature and minimum temperature from 71 stations are provided by the National Meteorological Information Center, China Meteorological Administration (Figure 1). This data set is extended from the China Homogenized Historical Temperature Data Sets and has been adjusted for homogeneity and abrupt discontinuities (Li *et al.*, 2004, 2009; Li and Dong, 2009). After carefully assessing the data quality, reliability and homogeneity, the adjustments have improved the reliability of the data and decreased uncertainties in the study of observed climate change in China (Li and Dong, 2009; Li *et al.*, 2014).

The selection of the 71 stations (Figure 1) from the homogenized data set was based on the selection procedures described in previous studies (You *et al.*, 2008a, 2008b). Most of the stations are situated in the eastern and central TP, which were installed in the 1950s. The elevations of these stations are all above 2000 m above sea level ranging from 2109.5 to 4700 m. In order to obtain comparable length time series, only data during 1961–2012 are selected for further analysis.

The CMIP5 Project represents the latest and most ambitious coordinated international climate model intercomparison exercise (Taylor *et al.*, 2012). CMIP5 includes a wide range of experiments addressing cloud feedbacks, carbon cycle feedbacks and palaeoclimate, and focuses on the ability of the latest generation of climate models to capture observed trends and features of the physical climate system (Van Vuuren *et al.*, 2011; Wuebbles *et al.*, 2014). In this study, simulations from 26 global climate models (listed in Table 1) were obtained from the CMIP5 data archive (http://cmip-pcmdi.llnl.gov/cmip5/index.html). Specifically, outputs from the 'historical' simulations are used, which cover the period 1901–2005. For comparison with the observation, the period 1961–2005 was extracted.

The Mann–Kendall test for trend and Sen's slope estimates is used to detect and estimate trends in the temperature series in this study (Sen, 1968). A trend is considered to be statistically significant if it is significant at the 5% level. The Mann–Kendall test has been popularly used to assess the significance of trend in time series. The

© 2015 Royal Meteorological Society

Table 1. CMIP5 GCMs participating in IPCC-AR5 used in this study.

Number	Model name	Modelling centre
1	bcc-csm1-1	Beijing Climate Center and China Meteorological Administration, China
2	BNU-ESM	Beijing Normal University, China
3	CanESM2	Canadian Centre for Climate Modeling and Analysis, Canada
4	CCSM4	National Center for Atmospheric Research, United States
5	CESM1-CAM5	National Center for Atmospheric Research, United States
6	CNRM-CM5	National Centre for Meteorological Research and European Centre for Research and Advanced Training in Scientific Computation, France
7	CSIRO-Mk3-6-0	Queensland Centre for Climate Change Excellence and Commonwealth Scientific and Industrial Research Organization, Australia
8	EC-EARTH	EC-Earth consortium, Europe
9	FGOALS-g2	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
10	FIO-ESM	The First Institute of Oceanography, SOA, China
11	GFDL-CM3	National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory, United States
12	GFDL-ESM2G	National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory, United States
13	GFDL-ESM2M	National Oceanic and Atmospheric Administration Geophysical Fluid Dynamics Laboratory, United States
14	GISS-E2-H	National Aeronautics and Space Administration Goddard Institute for Space Studies, United States
15	GISS-E2-R	National Aeronautics and Space Administration Goddard Institute for Space Studies, United States
16	HadGEM2-AO	Met Office Hadley Centre, UK
17	HadGEM2-ES	Met Office Hadley Centre, UK
18	IPSL-CM5A-LR	Institute Pierre Simon Laplace, France
19	IPSL-CM5A-MR	Institute Pierre Simon Laplace, France
20	MIROC5	University of Tokyo, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan
21	MIROC-ESM-CHEM	University of Tokyo, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan
22	MIROC-ESM	University of Tokyo, National Institute for Environmental Studies and Japan Agency for Marine-Earth Science and Technology, Japan
23	MPI-ESM-LR	Max Planck Institute for Meteorology, Germany
24	MPI-ESM-MR	Max Planck Institute for Meteorology, Germany
25	MRI-CGCM3	Meteorological Research Institute, Japan
26	NorESM1-M	Norwegian Climate Centre, Norway

purpose of the Mann–Kendall test is to statistically assess if there is a monotonic upward or downward trend of the variable of interest over time. A monotonic upward (downward) trend means that the variable consistently increases (decreases) through time, but the trend may or may not be linear. An advantage over the linear regression is that the Mann–Kendall test is a nonparametric (distribution-free) test, whereas a linear regression assumes residuals from the fitted regression line being normally distributed (Sen, 1968).

3. Results

3.1. Time evolution and trends of observed temperature series

Figure 2 shows the spatial patterns of trends of annual mean temperature, maximum temperature and minimum temperature calculated by the Mann–Kendal method and Sen's slope estimate for the 71 stations in the TP. It is clear that the mean temperature, maximum temperature and minimum temperature in the TP have significant warming trends, with the rates (the average values over the 71 stations) of 0.27, 0.19 and 0.36 °C decade^{-1}, respectively.

The overall warming in the TP has been unequivocal since the 1960s, which is in line with the global warming reported by the IPCC AR5 (IPCC, 2013). The observed changes of temperature are unprecedented in the TP, coincided with both the concentrations of greenhouse gases have increased and the amounts of glacier/snow/ice have diminished (Kang *et al.*, 2010; IPCC, 2013). Furthermore, the rapid warming of temperature has been revealed in previous studies (You *et al.*, 2008a, 2010; Kang *et al.*, 2010). Meanwhile, the warming in the northern TP has larger trend magnitudes of temperature, which is consistent with the patterns of temperature extremes (You *et al.*, 2008a).

Minimum temperatures have warming almost twice as fast as maximum temperature in the TP. This observed phenomenon is similar to the previous studies in the TP (Liu *et al.*, 2006; You *et al.*, 2010, 2014). Liu *et al.* (2006) revealed that both maximum temperature and minimum temperature during 1961–2003 in the TP display warming trends, and the warming trends in minimum temperature (0.41 °C decade^{-1}) are greater than that in maximum

© 2015 Royal Meteorological Society

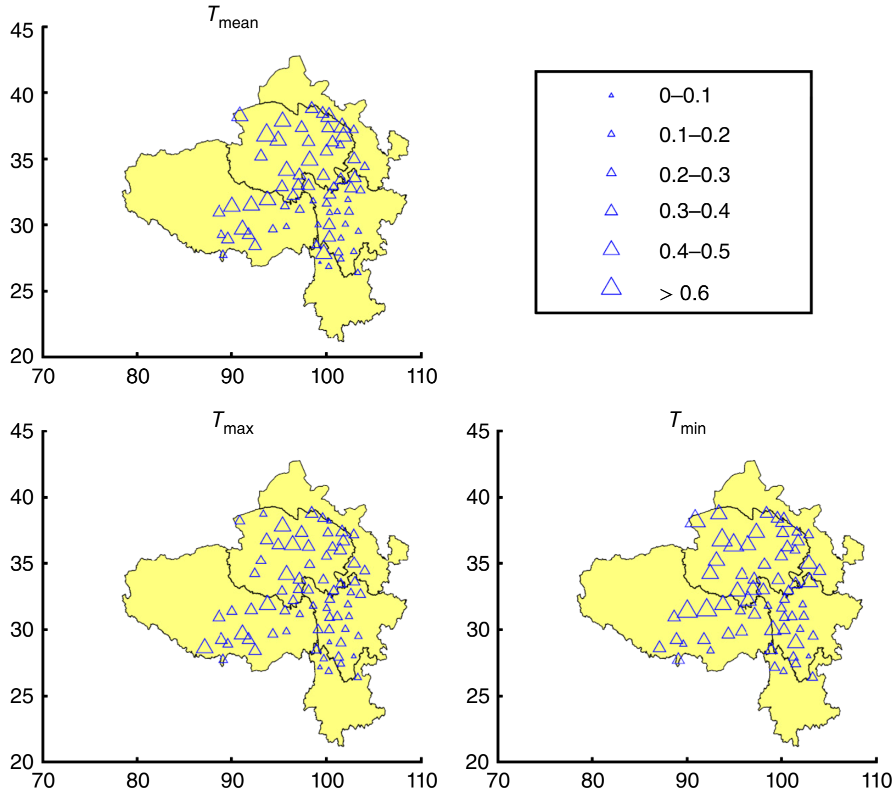

Figure 2. Spatial patterns of trends (T) of annual mean temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}) calculated by the Mann–Kendal method and Sen's slope estimation based on the 71 stations in the TP during 1961–2005. The unit is °C decade^{-1}.

temperature (0.18 °C decade^{-1}). The phenomenon is also similar to that on the global scale, which can be influenced by cloud cover, precipitation, soil moisture and atmospheric circulation (Vose *et al.*, 2005).

3.2. Temperature series from CMIP5 models and comparison with observations

Figures 3–5 show the time series of annual mean temperature, annual mean maximum temperature and annual mean minimum temperature from observations and the 26 CMIP5 general circulation models (GCMs) in the TP during 1961–2005. The corresponding trend estimates are provided in Table 2 and are calculated by the Mann–Kendal method with trends significant at the 90 and 95% levels highlighted.

The simulated mean temperature, maximum temperature and minimum temperature from the 26 CMIP5 GCMs can reproduce the warming trends in the TP during 1961–2005, with the CMIP5 mean rates of 0.21, 0.19 and 0.23 °C decade^{-1}, respectively. For the mean temperature, all the CMIP5 models simulate the warming trends in the TP, ranging from 0.07 °C decade^{-1} (CNRM-CM5) to 0.34 °C decade^{-1} (IPSL-CM5A-MR and MPI-ESM-MR). There are four GCMs with warming trends <0.1 °C decade^{-1}, which are CNRM-CM5, GISS-E2-H, HadGEM2-ES and MRI-CGCM3, respectively.

Similar to the mean temperature, most CMIP5 models correctly simulate the warming trend of the maximum temperature in the TP. There are five GCMs with warming trends <0.1 °C decade^{-1}, which are CNRM-CM5, HadGEM2-ES, MIROC5, MIROC-ESM-CHEM and MRI-CGCM3, respectively. There are two GCMs (IPSL-CM5A-MR and MPI-ESM-MR) with warming trends >0.3 °C decade^{-1}, which are the same models that display the fastest rates of the mean temperature warming.

For the minimum temperature, the simulated trends from CMIP5 models are larger than these for the mean temperature and maximum temperature, consistent with the observations. There are six GCMs with warming trends >0.3 °C decade^{-1}, which are CanESM2 (0.33 °C decade^{-1}), CESM1-CAM5 (0.36 °C decade^{-1}), FGOALS-g2 (0.3 °C decade^{-1}), IPSL-CM5A-LR (0.32 °C decade^{-1}), IPSL-CM3A-MR (0.35 °C decade^{-1}) and MPI-ESM-MR (0.36 °C decade^{-1}), respectively. There are only three GCMs (GISS-E2-H, GISS-E2-R and HadGEM2-ES) with warming trends <0.1 °C decade^{-1}.

Table 2 provides the correlation coefficients between the 5-year running mean of observed and simulated temperature time series in the TP during 1961–2005, and the corresponding root mean squared error (RMSE). In most cases, the correlation coefficients of the mean temperature, maximum temperature and minimum temperature between observations and CMIP5 models are significantly positive, leading to a multi-model mean correlation coefficient of 0.96, 0.87 and 0.95, respectively. This indicates that the CMIP5 models can capture the mean temperature, maximum temperature and minimum temperature evolution in recent decades. The RMSE of the

© 2015 Royal Meteorological Society

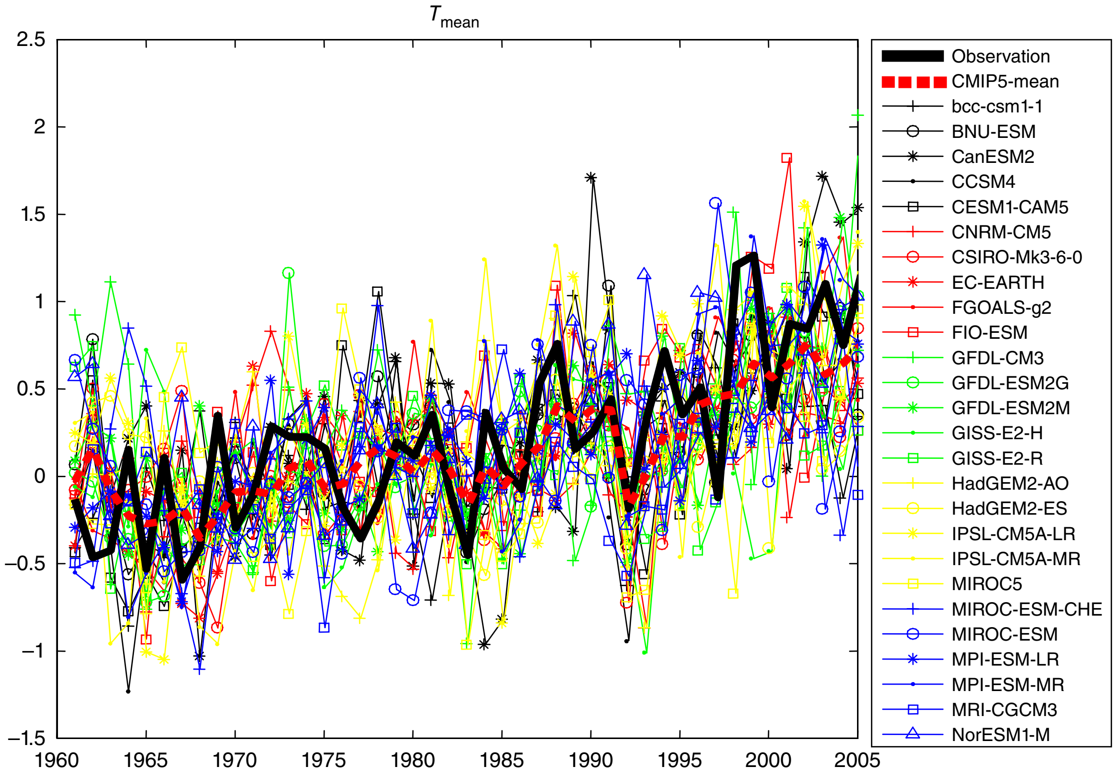

Figure 3. Time series of annual mean temperature (T_{mean}) from observations and 26 CMIP5 GCMs in the TP during 1961–2005.

mean temperature, maximum temperature and minimum temperature between observations and CMIP5 models are 0.45, 0.23 and 0.53 °C, respectively. Among the 26 CMIP5 models, there are three GCMs (CNRM-CM5, GISS-E2-H and MRI-CGCM3) with the RMSE >1 °C (for mean temperature).

Figure 6 demonstrates the relationship between trends and anomaly of annual mean temperature, maximum temperature and minimum temperature from observations and 26 CMIP5 GCMs in the TP during 1961–2005. The anomaly means the difference between the averages of the period 1961–2005 and the period 1961–1990. It is clear that the majority of CMIP5 models underestimate the warming rates of observations for the mean temperature, maximum temperature and minimum temperature, which confirmed the previous results based on what models and what observations (Su *et al.*, 2013; Fyfe and Gillett, 2014). Moreover, there are significant positive correlations between the trend magnitudes and the anomaly of the mean temperature, maximum temperature and minimum temperature, with the correlation of 0.85, 0.86 and 0.87, respectively. This suggests that both the larger anomaly of temperature and the internal variability result in larger trend magnitudes of warming.

3.3. Rapid warming in the TP during the hiatus period

As the historical experiments of CMIP5 stop in 2005, the comparison between observations and CMIP5 models has so far focused on the period 1961–2005. However, observed trend since 2005 are of great interest, especially in light of the recent global warming hiatus (Fyfe *et al.*, 2013; Meehl *et al.*, 2014). Figure 7 shows the time series of annual mean temperature, maximum temperature and minimum temperature from five stations (Naqu, Tuotuohe, Wudaoliang, Zhenzha and Bangge) with elevation over 4500 m in the TP during 1961–2012, 1961–1998 and 1999–2012, respectively. The green lines show the trends over the hiatus period, defined here as 1999–2012. It is obvious that the mean temperature, maximum temperature and minimum temperature in the TP show rapid warming during 1999–2012, which is larger than in the previous periods. Thus, the TP has continued to warm rapidly post-2000 in contrast to the global mean temperature over this period. Both the observations and models can reproduce the rapid warming in the latest decade. This phenomenon in the TP is unlike the global mean temperature. It is found that the observed global warming is significantly less than that simulated by CMIP5 models over a global hiatus period, which might be explained by some combination of errors in external forcing, model response and internal climate variability (Fyfe *et al.*, 2013).

4. Discussion and conclusions

In this study, the annual mean temperature, annual mean daily maximum temperature and annual mean daily minimum temperature in the TP have been analysed during 1961–2005, based on the updated version of China Homogenized Historical Temperature Data Sets (Li *et al.*, 2004, 2009; Li and Dong, 2009). The temporal variations in the mean temperature, maximum temperature

© 2015 Royal Meteorological Society

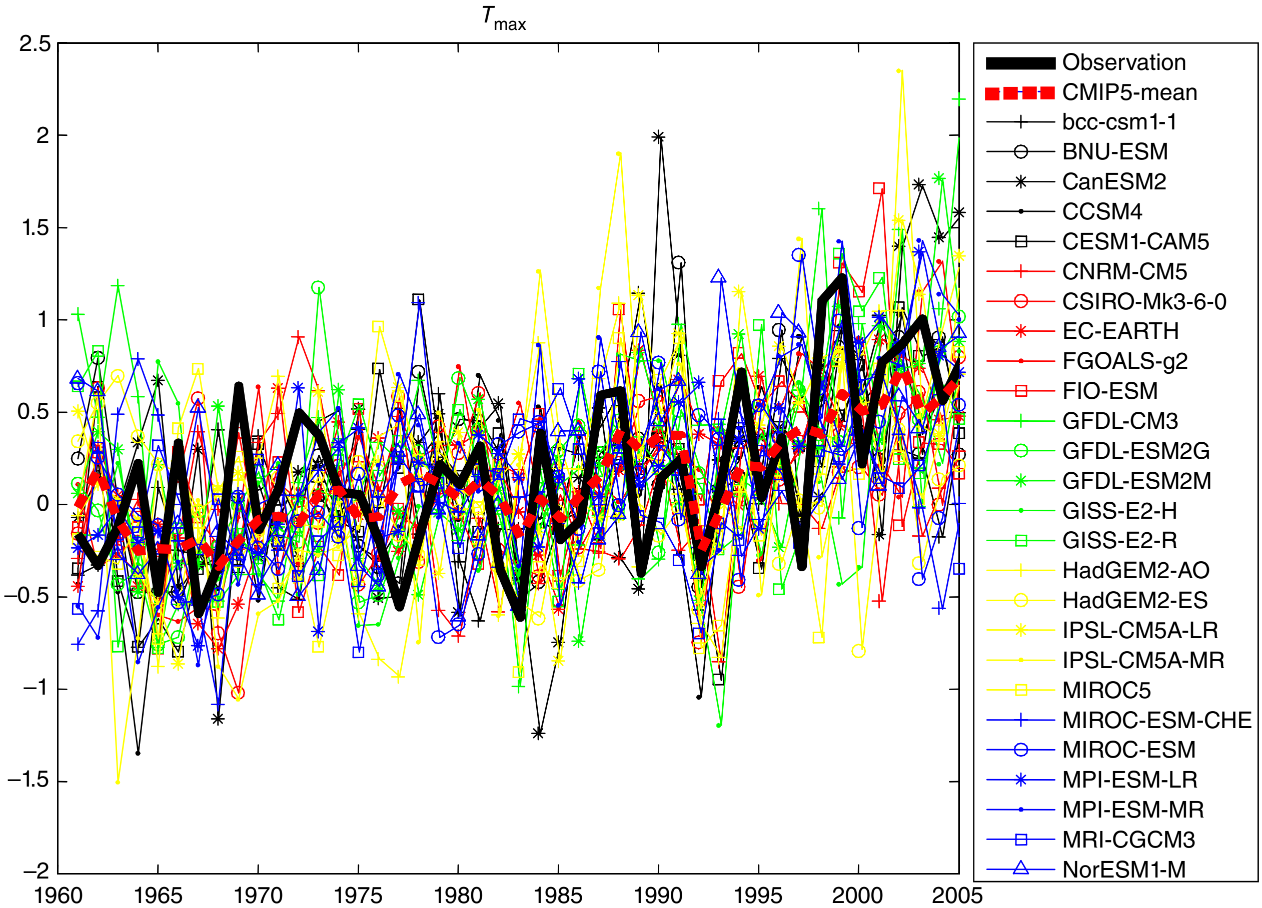

Figure 4. Time series of annual maximum temperature (T_{max}) from observations and 26 CMIP5 GCMs in the TP during 1961–2005.

and minimum temperature for the TP show a statistically increasing trend since the 1960s, especially after the 1980s, with the annual rates of 0.27, 0.19 and 0.36 °C decade^{-1}, respectively. The asymmetrical pattern of greater warming trends in minimum temperature than in maximum temperature in the TP confirms the findings on the global scale (Vose *et al.*, 2005) and over high latitudes (Screen, 2014). The annual mean rapid warming in the TP is greater than that observed at other longitude within the same latitudinal zone (Liu and Chen, 2000), especially in winter and autumn (You *et al.*, 2010). Spatially, the largest trend magnitudes occur in the northern TP, consistent with previous studies by means of temperature extremes and EOF sub-regional analysis (You *et al.*, 2008a, 2010). To summarize, the warming in the TP revealed in this study is in phase with the characteristics on the global scale before the hiatus period, but the warming trend is more sensitive and accelerated (Liu and Chen, 2000; Liu *et al.*, 2006; You *et al.*, 2008a, 2010; Rangwala *et al.*, 2009; Kang *et al.*, 2010; Duan *et al.*, 2012).

The performance of mean temperature, maximum temperature and minimum temperature from 26 GCMs available in the CMIP5 (Taylor *et al.*, 2012) is evaluated by comparing with observations in the TP during 1961–2005. Most CMIP5 models can capture the temporal variations of the observed mean temperature, maximum temperature and minimum temperature, and have significant positive correlations with observations ($R > 0.5$) with RMSE <1 °C. Previous study also reveals that most CMIP5 models are able to detect the summer monsoon signals in the southeastern TP and western wind system in winter and spring (Su *et al.*, 2013). Su *et al.* (2013) demonstrates that the CMIP5 models have cold biases (largest cold bias in winter) in comparison with the observations. This underestimate is inconsistent with studies in Northern Eurasia, Arctic region and Northern Hemisphere (Miao *et al.*, 2014), which shows that the CMIP5 models overestimate the observations, due to overestimation of the responses to the anthropogenic forcing (IPCC, 2013). However, most CMIP5 models tend to underestimate the observed temperature increase rate. Thus, it is concluded that the majority of CMIP5 models can reproduce the historical warming in the TP, many of them underestimate the observed warming rates.

It is reported that the inaccurate way that CMIP5 model operating cloud covers and stratospheric water vapour is the main reason for the discrepancy between CMIP5 models and observations (Solomon *et al.*, 2010; Fyfe *et al.*, 2013; Miao *et al.*, 2014; Santer *et al.*, 2014), which influence the energy budget and positive feedbacks on the planet during the simulation (Fyfe *et al.*, 2013; Fyfe and Gillett, 2014; Miao *et al.*, 2014). Other factors are

© 2015 Royal Meteorological Society

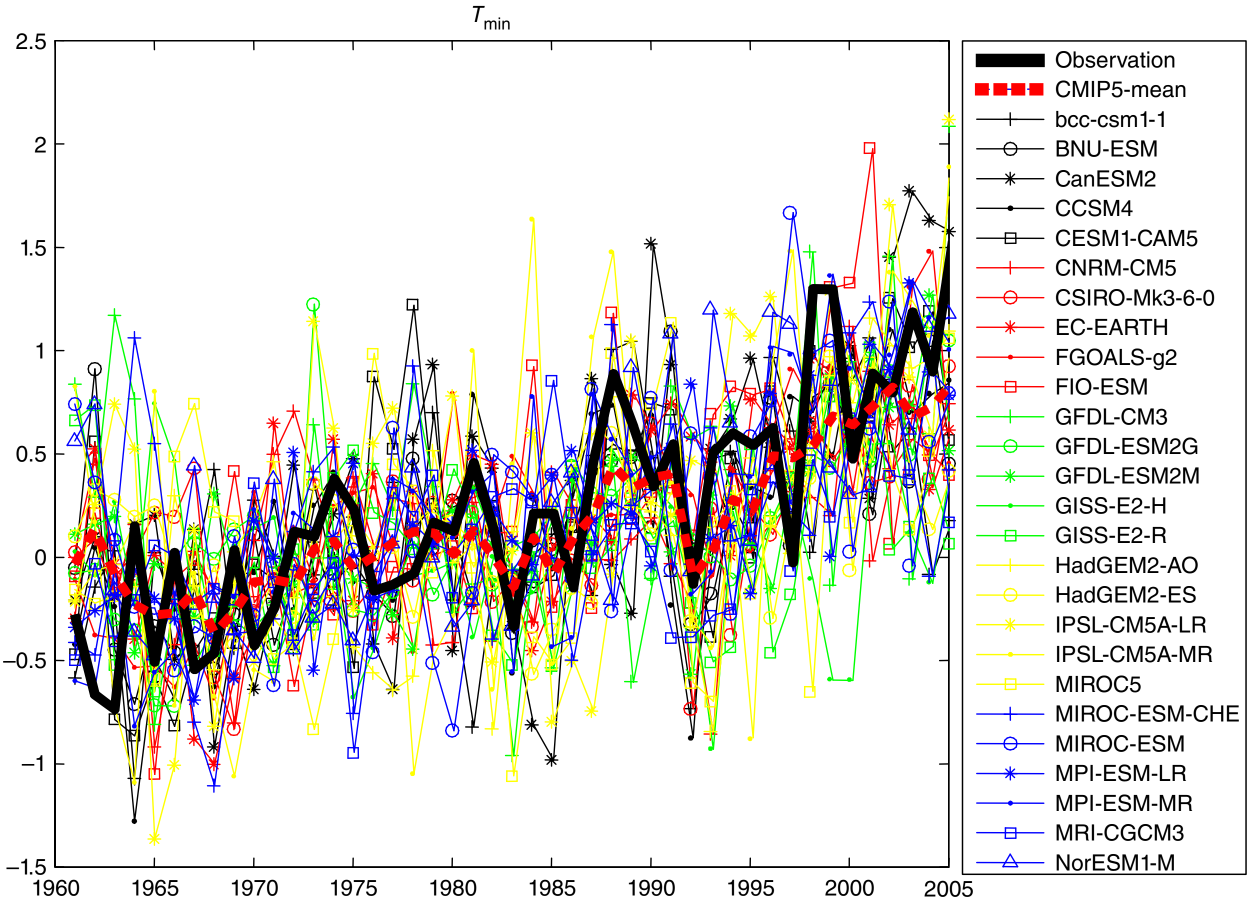

Figure 5. Time series of annual minimum temperature (T_{min}) from observations and 26 CMIP5 GCMs in the TP during 1961–2005.

not excluded. For example, the stratospheric aerosol concentration has increased during recent decades due to the volcanic eruptions, while none of the CMIP5 models take eruption-specific properties of volcanic aerosols into account (Solomon *et al.*, 2010, 2011; Santer *et al.*, 2014).

Global mean surface temperature warming has decreased in recent decade, although the causes of the global warming hiatus are still under debate (IPCC, 2013; Fyfe and Gillett, 2014; Meehl *et al.*, 2014; Watanabe *et al.*, 2014). The principal drivers of the hiatus are categorized into as follows: the minimum in the 11-year solar cycle (Kaufmann *et al.*, 2011), the increase in stratospheric aerosols (Solomon *et al.*, 2011), decrease in stratospheric water vapour (Solomon *et al.*, 2010), accumulation from minor volcanic eruptions (Santer *et al.*, 2014), little increase in the sum of anthropogenic and natural forcing (Kaufmann *et al.*, 2011), a cyclical change from an El Nino to a La Nina period (Kaufmann *et al.*, 2011), La-Niña-like decadal cooling (Kosaka and Xie, 2013), intake of ocean heat content (OHC) at depths above approximately 700 (Levitus *et al.*, 2009), the natural transition of Pacific Decadal Oscillation from positive to negative phase (Trenberth *et al.*, 2014), interdecadal Pacific Oscillation (Meehl *et al.*, 2014) and the net top of atmosphere energy imbalance (Watanabe *et al.*, 2014). For example, the radiative forcing by greenhouse gases has never stopped being in effect and heat remaining in the system does not result in a rise of global mean surface temperature (Levitus *et al.*, 2009). Observations of OHC and of sea level have shown that this additional heat has been absorbed in the ocean, and changes in the heat transports from the upper to the deep ocean and vice versa appear to be at least partly responsible for the pause in surface warming (Levitus *et al.*, 2009; Watanabe *et al.*, 2014), and observations suggest that the Pacific Ocean may play a key role (Meehl and Teng, 2014; Trenberth *et al.*, 2014).

The TP is the highest and the largest highland in the world, and has its unique characteristics of climate change. In this study, it is found that the mean temperature, maximum temperature and minimum temperature in the TP show rapid warming during 1999–2012, indicating that there is no hiatus of warming in the TP, in contrast to the global mean surface temperature (IPCC, 2013; Trenberth *et al.*, 2014; Watanabe *et al.*, 2014). One possible reason for the continued (and accelerated) warming in the TP is positive feedbacks associated with a diminishing cryosphere. You *et al.* (2010) summarized the factors determining the recent climate warming in the TP: anthropogenic greenhouse gas emissions, the snow/ice-albedo feedback and changes of environmental elements (such as cloud amount, specific humidity, Asian brown clouds and land use changes). Furthermore, although it is currently

© 2015 Royal Meteorological Society

Table 2. Trends (*T*), correlation coefficients of the 5-year running mean of temperature time series (*R*) and RMSE of annual mean temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}) from observations and 26 CMIP5 GCMs in the TP during 1961–2005. The trend is calculated by the Mann–Kendal method, and the trend with a significance level greater than 95 and 90% is highlighted with the mark. The unit is °C decade^{-1}.

Model number	T_{mean}			T_{max}			T_{min}		
	T	*R*	RMSE	*T*	*R*	RMSE	*T*	*R*	RMSE
Observation	0.27**	–	–	0.19**	–	–	0.36**	–	–
CMIP5 mean	0.21**	0.96	0.45	0.19**	0.87	0.23	0.23**	0.95	0.53
bcc-csm1-1	0.17**	0.80	0.67	0.18**	0.72	0.35	0.18**	0.77	0.81
BNU-ESM	0.19**	0.85	0.50	0.17**	0.68	0.13	0.23**	0.88	0.63
CanESM2	0.25**	0.85	0.12	0.21**	0.75	0.25	0.33**	0.90	0.25
CCSM4	0.28**	0.91	0.41	0.27**	0.80	0.16	0.28**	0.92	0.51
CESM1-CAM5	0.28**	0.82	0.39	0.23**	0.69	0.37	0.36**	0.86	0.24
CNRM-CM5	0.07*	0.63	1.08	0	0.35	1.08	0.12**	0.76	1.02
CSIRO-Mk3-6-0	0.14**	0.80	0.83	0.12**	0.68	0.62	0.15**	0.78	0.93
EC-EARTH	0.22**	0.83	0.25	0.21**	0.71	0.01	0.24**	0.84	0.29
FGOALS-g2	0.26**	0.88	0.20	0.23**	0.77	0.04	0.30**	0.89	0.22
FIO-ESM	0.22**	0.82	0.02	0.18**	0.73	0.20	0.26**	0.82	0.00
GFDL-CM3	0.18**	0.66	0.04	0.20**	0.61	0.49	0.18**	0.62	0.22
GFDL-ESM2G	0.22**	0.93	0.44	0.21**	0.82	0.12	0.21**	0.90	0.67
GFDL-ESM2M	0.21**	0.88	0.32	0.21**	0.86	0.09	0.20**	0.83	0.63
GISS-E2-H	0.08	0.54	1.26	0.12**	0.63	0.79	0.04	0.27	1.65
GISS-E2-R	0.12**	0.63	0.81	0.17**	0.64	0.19	0.07	0.43	1.28
HadGEM2-AO	0.21**	0.81	0.59	0.16**	0.80	0.38	0.24**	0.81	0.59
HadGEM2-ES	0.02	0.46	1.07	−0.06	0.02	1.15	0.08**	0.68	0.94
IPSL-CM5A-LR	0.28**	0.87	0.30	0.26**	0.80	0.49	0.32**	0.84	0.41
IPSL-CM5A-MR	0.34**	0.84	0.10	0.33**	0.65	0.09	0.35**	0.81	0.32
MIROC5	0.12*	0.57	0.97	0.10*	0.45	0.79	0.13*	0.63	1.05
MIROC-ESM-CHEM	0.15**	0.67	0.76	0.07	0.33	0.88	0.19**	0.77	0.62
MIROC-ESM	0.20**	0.70	0.29	0.16**	0.48	0.29	0.24**	0.71	0.32
MPI-ESM-LR	0.25**	0.93	0.11	0.25**	0.84	0.23	0.27**	0.94	0.31
MPI-ESM-MR	0.34**	0.94	0.16	0.34**	0.85	0.44	0.36**	0.94	0.03
MRI-CGCM3	0.09**	0.49	1.14	0.06	0.23	1.02	0.15**	0.65	1.15
NorESM1-M	0.22**	0.75	0.09	0.19**	0.55	0.07	0.26**	0.78	0.05

*Significant at the 0.01 level. **Significant at the 0.05 level.

difficult to determine the relative contribution of each of these factors, the anthropogenic greenhouse gas emission is regarded as the main cause of the climate warming in the TP, and impacts there are probably more serious than the rest of the world (Kang *et al.*, 2010; You *et al.*, 2010). The TP has the largest cryospheric extent (glaciers and ice caps, snow, river and lake ice and frozen ground) outside the polar region (Kang *et al.*, 2010). The glaciers have exhibited a rapid shrinkage in both length and area in recent decades (Yao *et al.*, 2012), coinciding with the rapid warming in the TP. An important feature related to high-elevation climatic warning is elevation dependency, i.e. more pronounced warming occurs at higher elevations (Giorgi *et al.*, 1997; Chen *et al.*, 2003; Liu *et al.*, 2009). Some researchers put forward to that the effects of snow/ice feedback can be used to explain the altitude dependence of climate change. Under the background of climate warming, the snow/ice on the surface is reduced and the surface absorption of solar radiation will be improved, strengthening to warming at higher altitude (Giorgi *et al.*, 1997; Chen *et al.*, 2003; Berthier and Toutin, 2008; Liu *et al.*, 2009).

In order to substantiate this conjecture, more profound changes occur in surface stations with higher elevation, which support evidences for the possible mechanism. During the study period, the rapid warming is consistent with decreasing snow cover and albedo in the same stations (Figure 8). This coincides with the widespread albedo decreasing and induced melting of Himalayan snow/ice since 2000 (Ming *et al.*, 2015). It is proposed that the global warming tends to decrease snow/ice cover and hence the albedo, increasing both the snow line position and the amount of solar energy absorbed, leading to more warming (Figure 9). Therefore, the positive snow/ice-albedo feedbacks may account for the recent warming, and the feedbacks deserve special concerns due to limited observation in the high terrain region in the TP. This effect has served to amplify the summer ice retreat in terms of the recent trend of declining Arctic Sea ice (Deser *et al.*, 2000). It is also possible that deficiencies in simulated cryospheric changes and/or feedback processes in the CMIP5 models may account for the discrepancies in the warming rates between observations and models. Due to the limited observation and snow/ice/albedo from reanalysis, there may have uncertainties for explaining the intensified warming in TP during the hiatus, and further study is required to confirm this hypothesis.

© 2015 Royal Meteorological Society

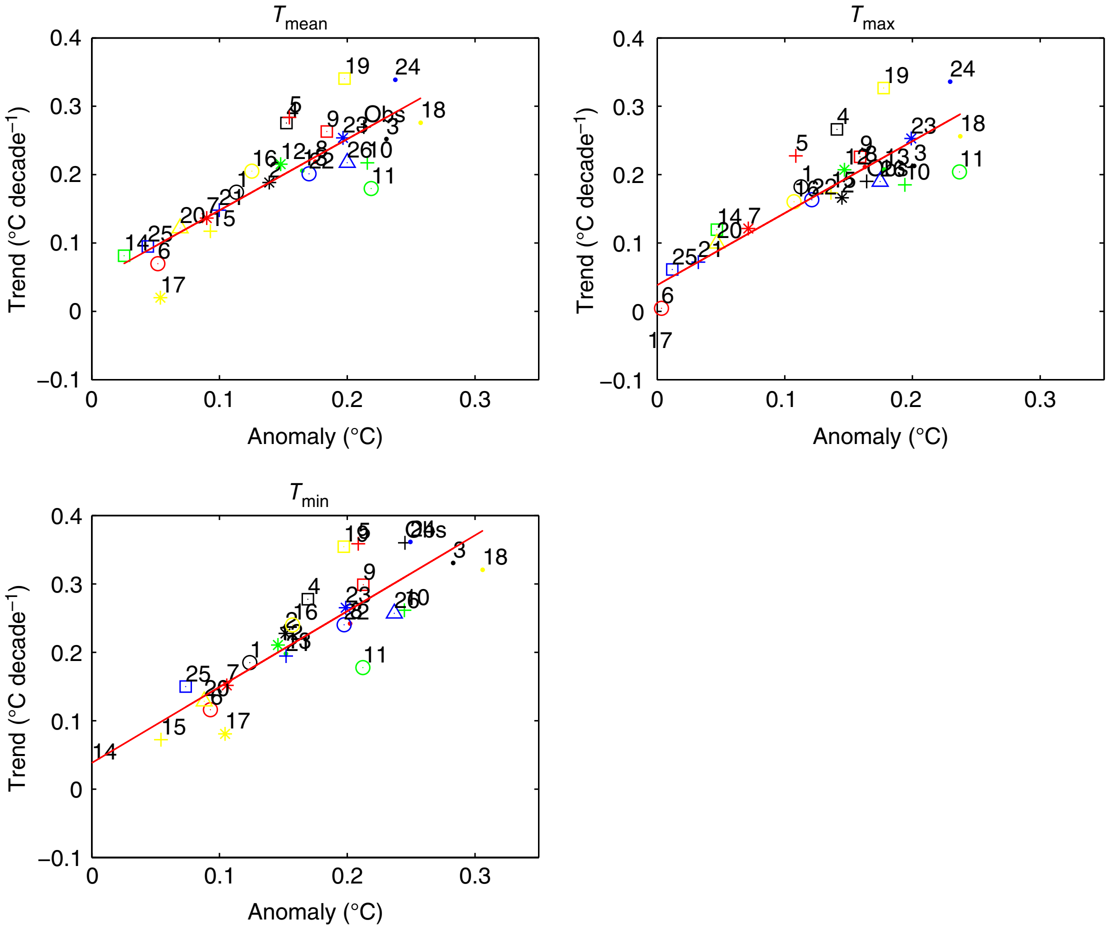

Figure 6. Relationship between trends and anomaly of annual mean temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}) from observations and 26 CMIP5 GCMs in the TP during 1961–2005. The colour and the serial number are 26 CMIP5 GCMs provided in Table 1. The trend is calculated by the Mann–Kendal method, and the unit is °C decade^{-1}. The anomaly is relative to the period 1961–1990.

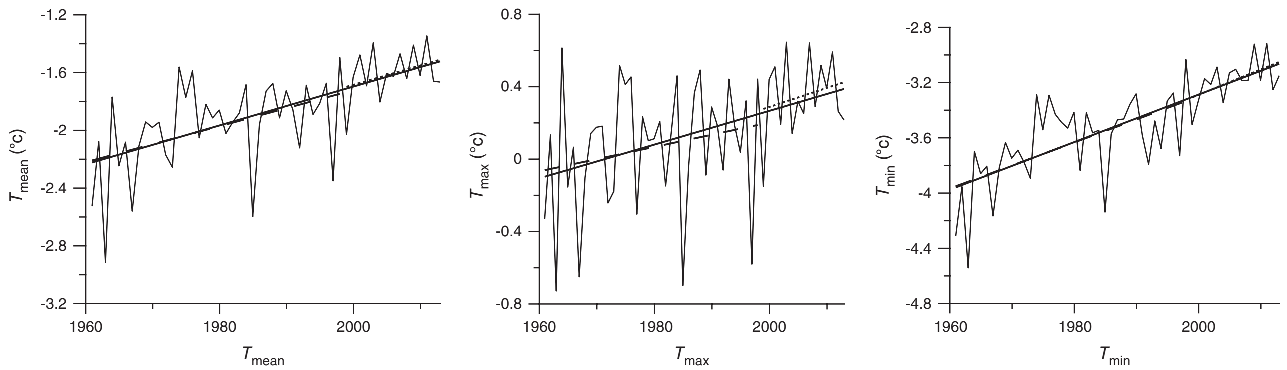

Figure 7. Time series of annual mean temperature (T_{mean}), maximum temperature (T_{max}) and minimum temperature (T_{min}) from observations (Naqu, Tuotuohe, Wudaoliang, Zhenzha and Bangge) with elevation over 4500 m in the TP during 1961–2012 (solid line), 1961–1998 (dash line) and 1999–2012 (dot line). The unit is °C.

Acknowledgements

This study was supported by the State Key Program of National Natural Science Foundation of China (41230528), National Natural Science Foundation (91437216 and 41201072), Jiangsu Specially-Appointed Professor, Jiangsu Natural Science Funds for Distinguished Young Scholar 'BK20140047', the Priority Academic Program Development of Jiangsu Higher Education Institutions (PAPD) and Jiangsu Shuang-Chuang Team Award. We are very grateful to Dr James Screen from College of Engineering, Mathematics and Physical Sciences, University of Exeter, for his thoughtful suggestions and editing the English language. We are very grateful to the reviewers, Y Jiao, HB Lin, L Kong, for their constructive comments which helped to improve the manuscript. This is the ESMC contribution Number 066.

© 2015 Royal Meteorological Society

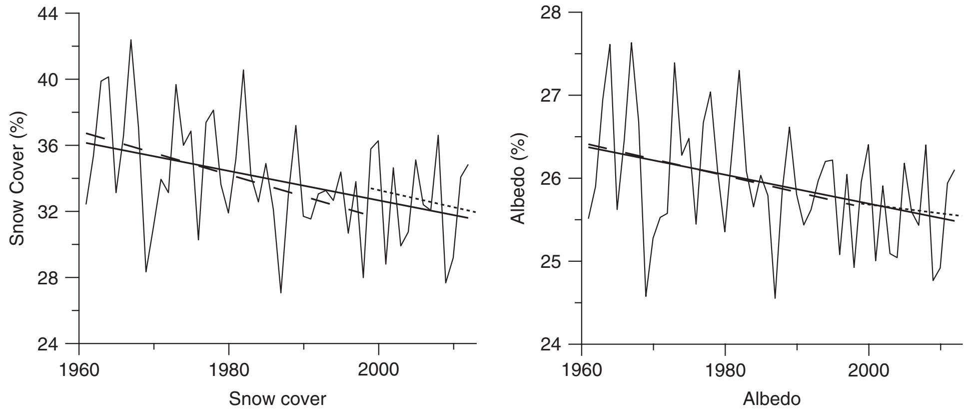

Figure 8. The annual snow cover and albedo from five stations (Naqu, Tuotuohe, Wudaoliang, Zhenzha and Bangge) with elevation over 4500 m in the TP during 1961–2012 (solid line), 1961–1998 (dash line) and 1999–2012 (dot line). Both the snow cover and albedo are derived from Monthly NOAA-CIRES 20th Century Reanalysis (available from http://www.esrl.noaa.gov). The unit for both snow cover and albedo is percent (%).

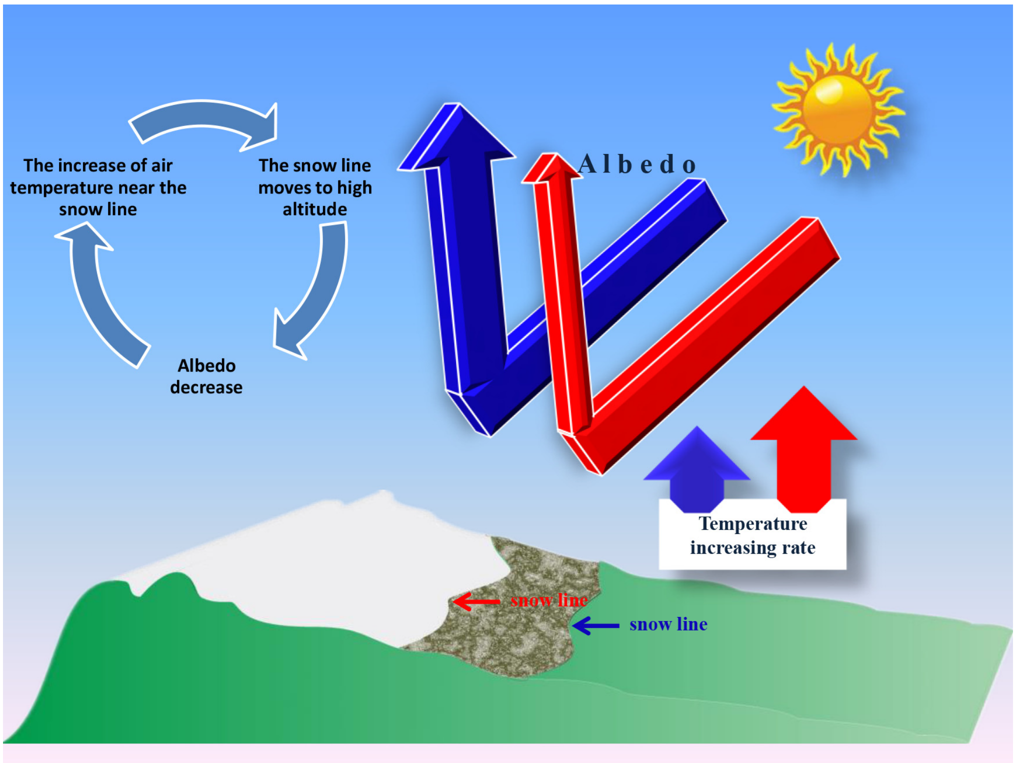

Figure 9. The schematic representation of the snow/ice-albedo feedback during the hiatus period.

References

Berthier E, Toutin T. 2008. SPOT5-HRS digital elevation models and the monitoring of glacier elevation changes in North-West Canada and South-East Alaska. *Remote Sens. Environ.* **112**(5): 2443–2454.

Chen B, Chao WC, Liu X. 2003. Enhanced climatic warming in the Tibetan Plateau due to doubling CO2: a model study. *Clim. Dyn.* **20**(4): 401–413, doi: 10.1007/s00382-002-0282-4.

Deser C, Walsh JE, Timlin MS. 2000. Arctic Sea ice variability in the context of recent atmospheric circulation trends. *J. Clim.* **13**(3): 617–633.

Duan AM, Wu G, Liu Y, Ma Y, Zhao P. 2012. Weather and climate effects of the Tibetan Plateau. *Adv. Atmos. Sci.* **29**(5): 978–992, doi: 10.1007/s00376-012-1220-y.

Fyfe JC, Gillett NP. 2014. Recent observed and simulated warming. *Nat. Clim. Change* **4**(3): 150–151, doi: 10.1038/nclimate2111.

Fyfe JC, Gillett NP, Zwiers FW. 2013. Overestimated global warming over the past 20 years. *Nat. Clim. Change* **3**(9): 767–769.

Giorgi F, Hurrell JW, Marinucci MR, Beniston M. 1997. Elevation dependency of the surface climate change signal: a model study. *J. Clim.* **10**(2): 288–296, doi: 10.1175/1520-0442(1997)010 <0288:edotsc>2.0.co;2.

Hawkins E, Edwards T, McNeall D. 2014. Pause for thought. *Nat. Clim. Change* **4**(3): 154–156.

Immerzeel WW, van Beek LPH, Bierkens MFP. 2010. Climate change will affect the Asian Water Towers. *Science* **328**(5984): 1382–1385, doi: 10.1126/science.1183188.

IPCC. 2013. *Summary for Policymakers of Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK.

Kang SC, Xu YW, You QL, Flugel WA, Pepin N, Yao TD. 2010. Review of climate and cryospheric change in the Tibetan Plateau. *Environ. Res. Lett.* **5**(1): 015101, doi: 10.1088/1748-9326/5/1/015101.

Kaufmann RK, Kauppi H, Mann ML, Stock JH. 2011. Reconciling anthropogenic climate change with observed temperature

1998–2008. *Proc. Natl. Acad. Sci.* **108**(29): 11790–11793, doi: 10.1073/pnas.1102467108.

Kosaka Y, Xie S-P. 2013. Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature* **501**(7467): 403–407.

Levitus S, Antonov J, Boyer T, Locarnini R, Garcia H, Mishonov A. 2009. Global ocean heat content 1955–2008 in light of recently revealed instrumentation problems. *Geophys. Res. Lett.* **36**(7): L07608.

Li QX, Dong WJ. 2009. Detection and adjustment of undocumented discontinuities in Chinese temperature series using a composite approach. *Adv. Atmos. Sci.* **26**(1): 143–153, doi: 10.1007/s00376-009-0143-8.

Li QX, Zhang H, Liu X, Huang J. 2004. Urban heat island effect on annual mean temperature during the last 50 years in China. *Theor. Appl. Climatol.* **79**(3–4): 165–174, doi: 10.1007/s00704-004-0065-4.

Li QX, Zhang H, Liu X, Chen J, Li W, Jones P. 2009. A mainland China homogenized historical temperature dataset of 1951-2004. *Bull. Am. Meteorol. Soc.* **90**(8): 1062–1065, doi: 10.1175/2009 BAMS2736.1.

Li QX, Huang J, Jiang Z, Zhou L, Chu P, Hu K. 2014. Detection of urbanization signals in extreme winter minimum temperature changes over Northern China. *Clim. Change* **122**(4): 595–608, doi: 10.1007/s10584-013-1013-z.

Liu XD, Chen BD. 2000. Climatic warming in the Tibetan Plateau during recent decades. *Int. J. Climatol.* **20**(14): 1729–1742.

Liu XD, Yin ZY, Shao XM, Qin NS. 2006. Temporal trends and variability of daily maximum and minimum, extreme temperature events, and growing season length over the eastern and central Tibetan Plateau during 1961-2003. *J. Geophys. Res. Atmos.* **111**(D19): D19109, doi: 10.1029/2005jd006915.

Liu XD, Cheng Z, Yan L, Yin Z-Y. 2009. Elevation dependency of recent and future minimum surface air temperature trends in the Tibetan Plateau and its surroundings. *Glob. Planet. Change* **68**(3): 164–174.

Meehl GA, Teng H. 2014. CMIP5 multi-model hindcasts for the mid-1970s shift and early 2000s hiatus and predictions for 2016–2035. *Geophys. Res. Lett.* **41**(5): 1711–1716.

Meehl GA, Teng H, Arblaster JM. 2014. Climate model simulations of the observed early-2000s hiatus of global warming. *Nat. Clim. Change* **4**: 898–902.

Miao C, Duan Q, Sun Q, Huang Y, Kong D, Yang T, Ye A, Di Z, Gong W. 2014. Assessment of CMIP5 climate models and projected temperature changes over Northern Eurasia. *Environ. Res. Lett.* **9**(5): 055007.

Ming J, Wang YQ, Xu XB, Zhang T, Guo WQ, Xiao CD. 2015. Widespread albedo decreasing and induced melting of Himalayan snow and ice in the early 21st century. *PLoS One* **10**(6): e0126235.

Rangwala I, Miller JR, Xu M. 2009. Warming in the Tibetan Plateau: possible influences of the changes in surface water vapor. *Geophys. Res. Lett.* **36**: L06703, doi: 10.1029/2009gl037245.

Santer BD, Bonfils C, Painter JF, Zelinka MD, Mears C, Solomon S, Schmidt GA, Fyfe JC, Cole JN, Nazarenko L. 2014. Volcanic contribution to decadal changes in tropospheric temperature. *Nat. Geosci.* **7**(3): 185–189, doi: 10.1038/NGEO2098.

Screen JA. 2014. Arctic amplification decreases temperature variance in northern mid-to high-latitudes. *Nat. Clim. Change* **4**: 577–582.

Sen PK. 1968. Estimates of regression coefficient based on Kendall's tau. *J. Am. Stat. Assoc.* **63**: 1379–1389.

Solomon S, Rosenlof KH, Portmann RW, Daniel JS, Davis SM, Sanford TJ, Plattner G-K. 2010. Contributions of stratospheric water vapor to decadal changes in the rate of global warming. *Science* **327**(5970): 1219–1223, doi: 10.1126/science.1182488.

Solomon S, Daniel J, Neely R, Vernier J-P, Dutton E, Thomason L. 2011. The persistently variable "background" stratospheric aerosol layer and global climate change. *Science* **333**(6044): 866–870, doi: 10.1126/science.1206027.

Su F, Duan X, Chen D, Hao Z, Cuo L. 2013. Evaluation of the global climate models in the CMIP5 over the Tibetan Plateau. *J. Clim.* **26**(10): 3187–3208.

Taylor KE, Stouffer RJ, Meehl GA. 2012. An overview of CMIP5 and the experiment design. *Bull. Am. Meteorol. Soc.* **93**(4): 485–498, doi: 10.1175/bams-d-11-00094.1.

Trenberth KE, Fasullo JT, Branstator G, Phillips AS. 2014. Seasonal aspects of the recent pause in surface warming. *Nat. Clim. Change* **4**: 911–916.

Van Vuuren DP, Edmonds J, Kainuma M, Riahi K, Thomson A, Hibbard K, Hurtt GC, Kram T, Krey V, Lamarque J-F. 2011. The representative concentration pathways: an overview. *Clim. Change* **109**: 5–31.

Vose RS, Easterling DR, Gleason B. 2005. Maximum and minimum temperature trends for the globe: an update through 2004. *Geophys. Res. Lett.* **32**(23): L23822, doi: 10.1029/2005gl024379.

Watanabe M, Shiogama H, Tatebe H, Hayashi M, Ishii M, Kimoto M. 2014. Contribution of natural decadal variability to global warming acceleration and hiatus. *Nat. Clim. Change* **4**: 893–897, doi: 10.1038/NCLIMATE2355.

Wu G, Liu Y, He B, Bao Q, Duan A, Jin F-F. 2012. Thermal controls on the Asian summer monsoon. *Sci. Rep.* **2**: 404.

Wuebbles D, Meehl G, Hayhoe K, Karl TR, Kunkel K, Santer B, Wehner M, Colle B, Fischer EM, Fu R. 2014. CMIP5 climate model analyses: climate extremes in the United States. *Bull. Am. Meteorol. Soc.* **95**(4): 571–583.

Yang K, Ye BS, Zhou DG, Wu BY, Foken T, Qin J, Zhou ZY. 2011. Response of hydrological cycle to recent climate changes in the Tibetan Plateau. *Clim. Change* **109**(3–4): 517–534, doi: 10.1007/s10584-011-0099-4.

Yang K, Wu H, Qin J, Lin C, Tang W, Chen Y. 2014. Recent climate changes over the Tibetan Plateau and their impacts on energy and water cycle: a review. *Glob. Planet. Change* **112**: 79–91.

Yao TD, Thompson L, Yang W, Yu WS, Gao Y, Yang XX, Duan KQ. 2012. Different glacier status with atmospheric circulations in Tibetan Plateau and surroundings. *Nat. Clim. Change* **2**(9): 663–667, doi: 10.1038/nclimate1580.

You QL, Kang SC, Aguilar E, Yan YP. 2008a. Changes in daily climate extremes in the eastern and central Tibetan Plateau during 1961-2005. *J. Geophys. Res.-Atmos.* **113**: D07101, doi: 10.1029/2007jd009389.

You QL, Kang SC, Pepin N, Yan YP. 2008b. Relationship between trends in temperature extremes and elevation in the eastern and central Tibetan Plateau, 1961-2005. *Geophys. Res. Lett.* **35**: L04704, doi: 10.1029/2007gl032669.

You QL, Kang S, Pepin N, Flügel W-A, Sanchez-Lorenzo A, Yan Y, Zhang Y. 2010. Climate warming and associated changes in atmospheric circulation in the eastern and central Tibetan Plateau from a homogenized dataset. *Glob. Planet. Change* **72**(1): 11–24.

You QL, Min JZ, Fraedrich K, Zhang W, Kang SC, Zhang L, Meng XH. 2014. Projected trends in mean, maximum, and minimum surface temperature in China from simulations. *Glob. Planet. Change* **112**: 53–63.

© 2015 Royal Meteorological Society