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Robust elevation dependency warming over the Tibetan Plateau under global warming of 1.5 °C and 2 °C

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Abstract

The Tibetan Plateau (TP) is called the “third pole” and the “Asian water tower”, and climate change over the TP is evident in recent decades. However, the elevation dependency warming (EDW, larger temperature increases with higher elevation) over the TP under global warming of 1.5 °C and 2 °C is not well understood. In this study, future changes in the monthly mean, maximum, and minimum temperature over the TP derived from 21 global climate models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) are investigated using a midrange/high emission scenario (RCP4.5/8.5) in which the global surface temperature has risen by 1.5 °C and 2 °C relative to the pre-industrial period. The multi-model ensemble mean of 21 CMIP5 models indicates that the TP has rapidly warmed to a larger degree than the global mean and the whole China. Overall, the mean temperature over the TP under RCP4.5/8.5 scenarios under global warming of 1.5 °C and 2 °C will increase by 2.11/2.10 °C and 2.89/2.77 °C, respectively, particularly in the western TP. The midrange emission scenario RCP4.5 shows larger temperature changes under global warming of 1.5 °C and 2 °C than the high emission scenario RCP8.5. Furthermore, a robust EDW over the TP is found to intensify under global warming of 1.5 °C and 2 °C, which is probably contributed by the snow/ice-albedo feedback in the elevation range between 3.5 and 4 km over the TP. The EDW over the TP raises more robust under global warming of 2 °C than 1.5 °C. This study suggests that the TP is being influenced by global warming approximately 10 years earlier than the global scale under global warming of 1.5 °C and 2 °C, and the EDW under global warming of 1.5 °C and 2 °C will have potentially serious consequences for the third pole environment.

Keywords Tibetan Plateau · Elevation dependency warming · 1.5 °C and 2 °C

1 Introduction

The Paris Agreement was adopted at the 21st Conference of Parties to the United Nations Framework Convention on Climate Change (UNFCCC), and the parties agreed to “Hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” (UNFCCC 2015). There are several studies related to the impacts of 1.5 °C and 2 °C global warming on natural and human systems; in these studies, discernible differences are found for extreme weather indices and vulnerable systems/regions (Chen and Zhou 2016; Huang et al. 2017; Hulme 2016; Schleussner et al. 2016a, b, 2017; Zhang et al. 2019). For example, it is recorded that limiting warming to 1.5 °C rather than 2 °C would perceptibly reduce the frequency of extreme heat events in Australia, which would prevent much loss of life and economic and environmental damage (King et al. 2017). Global drylands will experience greater impacts from a 2 °C global temperature increase than from a 1.5 °C increase, such as decreased maize yields and runoff, increased frequency of long-lasting droughts and more favorable conditions for malaria transmission (Huang et al. 2017). Furthermore, the Intergovernmental Panel on Climate Change (IPCC) special report from October, 2018 showed the differences between temperature increase of 1.5 °C and 2 °C, and reported the warming impacts on climate systems under different global warming levels, emission scenarios, and half-degree warming increments (Cai et al. 2017; Cai

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et al. 2018; Ge et al. 2019; Henley and King 2017; Hulme 2016; King et al. 2017; Li et al. 2018; Schleussner et al. 2017).

The Tibetan Plateau (TP) with an area of 2.5 million km^2 and an average elevation of over 4000 m above sea level, is the highest and most extensive plateau in the world (Kang et al. 2010; Yang et al. 2011, 2014; Yao et al. 2012a, b, 2019; You et al. 2013, 2016b). The TP is surrounded by massive mountains, and feeds several rivers; it is called the "third pole" and the "Asian water tower" (Kang et al. 2010; Yang et al. 2011; Yao et al. 2012a). In addition, the TP contains the largest cryospheric region outside the polar regions, and includes a large proportion of mountain glaciers and extensive permafrost, which is regarded as one of the most sensitive areas in the world (Kang et al. 2010; Yang et al. 2014; Yao et al. 2012b; You et al. 2016b). There are observational evidences that the climate and cryosphere over the TP are undergoing rapid change (Gao et al. 2019; Kang et al. 2010; Yao et al. 2012a, b; You et al. 2013). It is reported that 36 ± 7% of the glaciers in the high mountains of Asia will be lost by the end of the twenty-first century with even a 1.5 °C temperature increase (Kraaijenbrink et al. 2017). An integrated assessment of the status of glaciers over the TP that studied the reduction in glacial area of 7090 glaciers indicates that the majority of glaciers have rapidly retreated; glaciers covered an area of approximately 13,363.5 km^2 in the 1970s and 12,130.7 km^2 in the 2000s (Yao et al. 2012a). Permafrost over the TP covers an area of approximately 1.5 million km^2, and the dramatic ground surface and permafrost warming have resulted in changes in the permafrost thermal regime in the region (Wu et al. 2013; Zhao et al. 2004). Furthermore, a warmer climate will influence the amount of snowfall; the extent of snow cover over the TP has decreased in recent decades (Barnett et al. 2005; Kang et al. 2010). Thus, climate change over the TP is evident and significant.

Mounting evidences suggest that the rate of warming in high mountains is higher than that in lower elevation regions, a phenomenon referred to as elevation dependency warming (EDW) (Pepin et al. 2015; Rangwala and Miller 2012). During recent decades, the TP has tended to a warmer climate (Kang et al. 2010; Rangwala et al. 2009; You et al. 2013, 2016b), especially since the start of the twenty-first century (Yan and Liu 2014; Yan et al. 2016), which is known as the global warming hiatus period (Duan and Xiao 2015; Ma et al. 2017; You et al. 2016b), and is projected to warm in the future under different emission scenarios (Wu et al. 2019; You et al. 2016b). For example, the rate of warming over the TP since the mid-1950s ranges from 0.16 to 0.36 °C decade^{-1} and rises to 0.50–0.67 °C decade^{-1} since the 1980s (Kuang and Jiao 2016). The warming over the TP in recent decades has exceeded that of the Northern Hemisphere and other locations along the same latitudinal zone (Duan and Xiao 2015; Kang et al. 2010; Liu et al. 2009; Pepin et al. 2015; Rangwala et al. 2009; Yan et al. 2016; Yang et al. 2014). However, none of the aforementioned studies specifically address the climate changes expected over the TP as a result of 1.5 °C and 2 °C global temperature increases.

In this study, the surface mean, maximum, and minimum temperatures over the TP based on the output of the 21 global climate models (GCMs) (Table 1) participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) under different representative concentration pathway (RCP) emission scenarios are studied (Moss et al. 2010; Taylor et al. 2012). The EDW over the TP under global warming of 1.5 °C and 2 °C is investigated statistically. This study aims to answer the following scientific questions. First, how will the surface mean, maximum, and minimum temperatures over the TP in the coming century differ under different RCP scenarios? Second, when will the TP reach 1.5 °C and 2 °C warming levels, and what is the pattern of warming over the TP under global warming of 1.5 °C and 2 °C? Lastly, does EDW over the TP exist under global warming of 1.5 °C and 2 °C, and what is the potential mechanism for it?

2 Data and methods

The observational data used in this study include the monthly mean, maximum and minimum surface temperatures, which are derived from a high-quality daily temperature dataset obtained from the National Meteorological Information Center, China Meteorological Administration available through http://data.cma.cn.

The monthly mean, maximum and minimum surface temperatures datasets from 21 state-of-the-art GCMs participating in the CMIP5 are used in this study (Taylor et al. 2012). The CMIP5 models are obtained using new emission scenarios called the RCP (Moss et al. 2010), and the CMIP5 simulations are forced with specified concentrations, consistent with a high emission scenario (RCP8.5), a midrange mitigation emission scenario (RCP4.5), and a low emission scenario (RCP2.6) (Taylor et al. 2012). The numerical value assigned to each RCP indicates the approximate radiative forcing in the year 2100 in the absence of climate feedbacks (Moss et al. 2010; Taylor et al. 2012). The selection criterion of 21 GCMs is that they have the complete simulation data of two RCP scenarios (RCP4.5 and RCP8.5) for the period 2006–2099. As most CMIP5 models can not reach the global warming of 1.5 °C and 2 °C under RCP2.6, and the analysis under RCP2.6 is omitted. In this study, both the RCP8.5 and RCP4.5 emission scenarios are used to highlight the largest possible changes since these scenarios show the highest level of radiative forcing up to 8.5 W m^{-2} and 4.5 W m^{-2} from the greenhouse gas concentrations, respectively. For assessing climate change over the TP, all the CMIP5

Table 1 Information about the CMIP5 models in this study, including the model name, originating group/country, and atmospheric resolution

Model name	Modelling centre (or group)	Atmospheric resolution (lon × lat)
ACCESS1-0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	1.875° × 1.25°
BCC-CSM 1-1	Beijing Climate Center, China Meteorological Administration, China	2.8125° × 2.8125°
BNU-ESM	College of Global Change and Earth System Science, Beijing Normal University, China	2.8125° × 2.8125°
CanESM2	Canadian Centre for Climate Modelling and Analysis, Canada	2.8125° × 2.8125°
CCSM4	National Center for Atmospheric Research, USA	1.875° × 0.625°
CESM1-BGC	Community Earth System Model Contributors, USA	1.875° × 0.625°
CNRM-CM5	Centre National de Recherches Météorologiques/Centre Européen de Recherche et Formation Avancéeen Calcul Scientifique, France	1.4118° × 1.4063°
CSIRO-MK3-6-0	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia	1.875° × 1.875°
GFDL-CM3	Geophysical Fluid Dynamics Laboratory, USA	2.5° × 2°
GFDL-ESM2G		2.5° × 2°
GFDL-ESM2M		2.5° × 2°
INMCM4	Institute for Numerical Mathematics, Russia	2° × 2.5°
IPSL-CM5A-LR	Institut Pierre-Simon Laplace, France	3.75° × 1.875°
IPSL-CM5A-MR		2.5° × 1.2587°
MIROC5	The University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan	1.4063° × 1.4063°
MIROC-ESM-CHEM		2.8125° × 2.8125°
MIROC-ESM		2.8125° × 2.8125°
MPI-ESM-LR	Max Planck Institute for Meteorology, Germany	1.875° × 1.875°
MPI-ESM-MR		1.875° × 1.875°
MRI-CGCM3	Meteorological Research Institute, Japan	1.125° × 1.125°
NorESM1-M	Norwegian Climate Centre, Norway	2.5° × 1.875°

models are remapped to 1.5° × 1.5° latitude–longitude spatial resolution using a bilinear interpolation scheme, which is widely selected to calculate the multi-model ensemble mean (MMEM) of 21 CMIP5 GCMs and is used in our recent study (Wu et al. 2019).

During the Paris conference in 2015, there is no specific definition on pre-industrial levels (Schurer et al. 2017). The global warming thresholds used in this study are relative to pre-industrial levels (1850–1900), and serve to define years in which global warming would reach the 1.5 °C and 2 °C global warming levels under RCP4.5 and RCP8.5 scenarios. We calculated the global average surface temperature anomaly for the 30-year running mean based on the MMEM (21 original models). The well-established definitions of the 1.5 °C and 2 °C global warming levels are referred (King et al. 2017). The 1.5 °C period (accurate arrival year) is determined to be the time at which the 30-year running mean is 1.3–1.7 °C (crossing the 1.5 °C global warming level) warmer than the pre-industrial period. The 2 °C period is defined similarly (Wu et al. 2019; Zhang et al. 2019). We utilized the MMEM of 21 CMIP5 GCMs and two RCP scenarios to generate the 1.5 °C and 2 °C global warming levels relative to the pre-industrial world.

3 Results and discussions

3.1 Corresponding year over the TP under global warming of 1.5 °C and 2 °C

Table 2 summarizes the year in which the 21 CMIP5 models and the MMEM surface temperatures for the globe and the TP rise by 1.5 °C and 2 °C above pre-industrial levels (as represented by the 1850–1900 baseline period) under RCP4.5 and RCP8.5 scenarios, respectively. The global mean surface temperature and the TP mean temperature from the MMEM of the 21 CMIP5 GCMs stabilized at the end of the twenty-first century under the RCP4.5 scenario at approximately 2.6 °C/3.8 °C above the pre-industrial level. The increase in the global mean temperature and the TP mean temperature under RCP8.5 was up to approximately 4.7 °C/7.1 °C by the end of the twenty-first century, respectively.

On the global scale, the RCP8.5 scenario results in earlier 1.5 °C and 2 °C warming than the RCP4.5 scenario does, especially for the 2 °C warming. The RCP4.5 scenario projects the 1.5 °C period will be reached by 2017–2036 (2026), which is lightly later than the arrival

Table 2 Corresponding year in the 21 CMIP5 models and the multi-model ensemble mean (MMEM) when mean surface temperatures for the globe and the Tibetan Plateau occur global warming of 1.5 °C and 2 °C above pre-industrial levels under RCP4.5 and RCP8.5 scenarios

Model name	1.5 °C				2 °C			
	RCP4.5		RCP8.5		RCP4.5		RCP8.5	
	Globe	TP	Globe	TP	Globe	TP	Globe	TP
ACCESS1.0	2031	2022	2026	2017	2051	2032	2040	2026
BCC-CSM 1.1	2024	2017	2023	2014	2041	2026	2037	2023
BNU-ESM	2017	2015	2016	2012	2026	2025	2023	2021
CanESM2	2020	2016	2015	2010	2031	2027	2030	2019
CCSM4	2022	2015	2019	2012	2040	2024	2031	2021
CESM1-BGC	2021	2015	2017	2011	2043	2024	2033	2020
CNRM-CM5	2038	2019	2029	2013	2058	2028	2044	2022
CSIRO-MK3.6.0	2034	2027	2030	2021	2049	2038	2045	2030
GFDL-CM3	2033	2026	2028	2021	2046	2037	2039	2030
GFDL-ESM2G	2048	2031	2034	2022	2072	2049	2054	2031
GFDL-ESM2M	2049	2030	2038	2021	2073	2050	2053	2030
INMCM4	2056	2034	2042	2029	2084	2063	2059	2038
IPSL-CM5A-LR	2018	2014	2015	2012	2031	2025	2028	2021
IPSL-CM5A-MR	2020	2013	2015	2013	2036	2023	2031	2022
MIROC5	2051	2030	2033	2022	2068	2051	2051	2031
MIROC-ESM-CHEM	2024	2016	2019	2010	2038	2025	2030	2019
MIROC-ESM	2021	2014	2021	2014	2034	2024	2031	2023
MPI-ESM-LR	2028	2021	2020	2017	2045	2030	2038	2026
MPI-ESM-MR	2023	2016	2021	2016	2047	2025	2040	2025
MRI-CGCM3	2053	2034	2041	2027	2077	2056	2054	2036
NorESM1-M	2048	2029	2033	2025	2065	2047	2049	2034
MMEM	2026	2019	2024	2016	2048	2032	2038	2025

predicted by 2016–2030 (2024) under RCP8.5, based on the 30-year running mean of MMEM. Similarly, the RCP4.5 scenario projects that the 2 °C warming will occur in 2037–2059 (2048), nearly 10 years later than for RCP8.5, which projects that the warming will occur from 2031 to 2044 (2038), which is in the range of previous studies (Schleussner et al. 2016a, 2017; Zhang et al. 2017, 2019).

Over the TP, the warming is more rapid than the global average, indicating earlier corresponding year that predicted by the Paris Agreement (Fig. 1). The 30-year running average of TP mean temperatures will be 1.5 °C/2 °C warmer in the year of 2019/2032 under RCP4.5 and in the year 2016/2025 under RCP8.5. This suggests that the TP is being influenced by global warming 15 years earlier than is occurring at the global scale under global warming of 1.5 °C and 2 °C. Furthermore, the corresponding year for each CMIP5 model differs between the global warming of 1.5 °C and 2 °C, due to different physical process and parameterization schemes, suggesting the importance of MMEM for predicting climate change. For example, the difference of the earliest (IPSL-CM5A-MR model) and latest (MRI-CGCM3 and INMCM4 model) corresponding year over the TP under RCP4.5/8.5 can reach up to approximately 20 years.

3.2 Warming patterns over the TP under global warming of 1.5 °C and 2 °C

The regionally averaged mean surface temperatures over the TP under global warming of 1.5 °C and 2 °C target from the 21 CMIP5 models and the MMEM under two RCPs are summarized in Table 3. Figure 2 shows the box plots of the mean, maximum, minimum surface temperature anomalies from 21 CMIP5 models MMEM over the TP under global warming of 1.5 °C and 2 °C under two RCPs. The spatial patterns of temperatures are demonstrated in Figs. 3 and 4. The difference (RCP4.5 minus RCP8.5) is also shown, which is addressed in Wu (2019).

Under global warming of 1.5 °C, compared with pre-industrial levels under RCP4.5, the MMEM of mean, maximum and minimum surface temperatures over the TP were projected to increase in the future, and most of the CMIP5 models simulate temperatures over 1.5 °C (Figs. 2, 3). The patterns are similar to those for China but with a more rapid and greater magnitude of warming (Tian et al. 2017; Zhang et al. 2017, 2019). The temperature changes over the TP are similar in the RCP4.5/8.5 scenarios when the same global warming threshold is reached. The warming over the TP exceeds the global levels, especially for the minimum

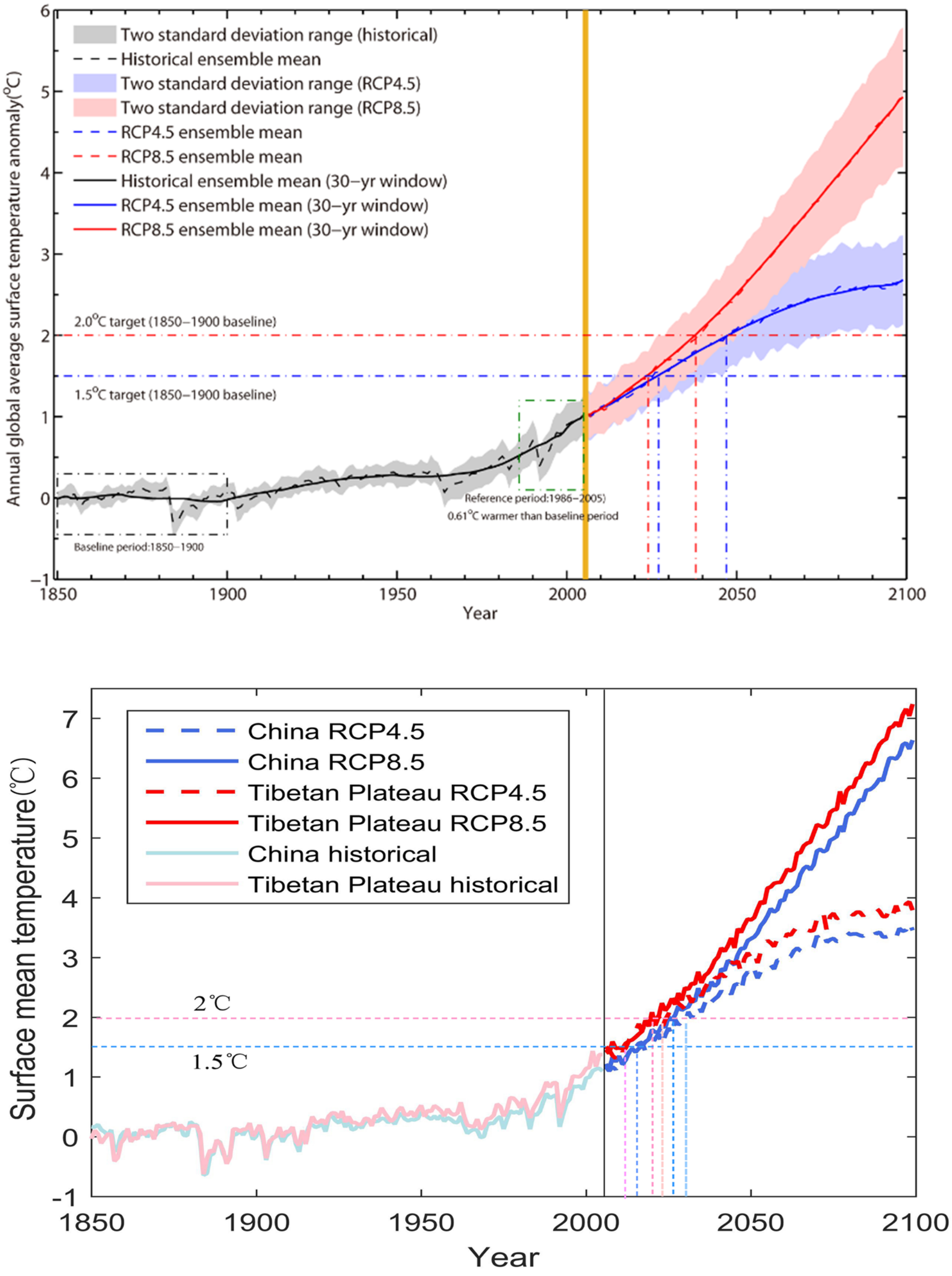


Fig. 1 Regionally averaged mean surface temperature for the globe (top panel), whole China and Tibetan Plateau (bottom panel) during 1850–2100 from the multi-model ensemble mean of 21 CMIP5 models under representative concentration pathway (RCP) scenarios (RCP8.5 and RCP4.5). The blue/red line under the two RCPs indicates that the global warming of 1.5 °C and 2 °C above pre-industrial levels (as represented by the 1850–1900 baseline period), and the vertical brown line marks the boundary between the historical and the RCP CMIP5 simulations. Both the baseline period of 1850–1900 and the reference period of 1986–2005 are marked by rectangles. This top panel is adopted from Fig. 9 in Zhang et al. (2019)

temperature, and the warming in the western TP is faster in both RCP4.5/8.5 scenarios.

Under global warming of 2 °C, the MMEM of the mean, maximum and minimum surface temperatures over the TP relative to the pre-industrial levels will increase under RCP8.5 and RCP4.5, and it is clear that warming under RCP4.5 is more obvious than that under RCP8.5 (Figs. 2, 4). Similar to the results of the 1.5 °C global warming level, warming of the minimum temperature is clear and both mean and maximum temperatures will increase slightly (Table 3). Thus, warming under global warming of 2 °C will exhibit obvious changes relative to pre-industrial levels under two RCPs.

In summary, the increase of mean, maximum and minimum temperature is 2.11 °C/2.10 °C and 2.96 °C/2.85 °C, 2.02 °C/2.02 °C and 2.89 °C/2.77 °C, 2.34 °C/2.34 °C and 3.20 °C/3.14 °C over the TP under RCP4.5/RCP8.5 scenario under global warming of 1.5 °C and 2 °C, respectively, and the more remarkable increases occur in winter (Wu et al. 2019). Moreover, rapid warming in the western TP is expected under global warming of 1.5 °C and 2 °C.

Table 3 Regionally averaged mean surface temperature over the Tibetan Plateau under global warming of 1.5 °C and 2 °C above pre-industrial levels (as represented by the 1850–1900 reference period) from the 21 CMIP5 models and the multi-model ensemble mean (MMEM) under RCP4.5 and RCP8.5 scenarios

Model name	RCP4.5			RCP8.5		
	1.5 °C	2 °C	Difference of 0.5 °C	1.5 °C	2 °C	Difference of 0.5 °C
ACCESS1.0	2.11	2.83	0.72	1.82	2.45	0.63
BCC-CSM 1.1	2.21	2.83	0.62	2.27	2.68	0.41
BNU-ESM	2.63	2.76	0.13	2.66	2.7	0.04
CanESM2	2.28	2.49	0.21	2.28	2.79	0.51
CCSM4	2.09	2.81	0.72	2.24	2.76	0.52
CESM1-BGC	2.12	2.67	0.55	2.16	2.67	0.51
CNRM-CM5	1.89	2.53	0.64	1.56	2.23	0.67
CSIRO-MK3.6.0	1.85	2.75	0.90	1.64	2.77	1.13
GFDL-CM3	2.19	2.77	0.58	1.90	2.89	0.99
GFDL-ESM2G	1.93	2.57	0.64	1.88	2.96	1.08
GFDL-ESM2M	2.03	2.65	0.62	1.96	2.45	0.49
INMCM4	2.66	3.27	0.61	1.91	3.09	1.18
IPSL-CM5A-LR	2.38	3.09	0.71	2.04	3.25	1.21
IPSL-CM5A-MR	2.43	3.10	0.67	2.50	2.7	0.20
MIROC5	2.27	3.03	0.76	2.13	2.71	0.58
MIROC-ESM-CHEM	2.23	2.92	0.69	2.24	2.58	0.34
MIROC-ESM	2.27	3.19	0.92	2.25	2.45	0.20
MPI-ESM-LR	2.36	3.10	0.74	2.34	2.98	0.64
MPI-ESM-MR	2.45	3.04	0.59	2.39	2.83	0.44
MRI-CGCM3	1.95	2.41	0.46	2.14	2.22	0.08
NorESM1-M	1.96	2.52	0.56	1.77	2.92	1.15
MMEM	2.11	2.96	0.85	2.10	2.85	0.75

The unit is °C

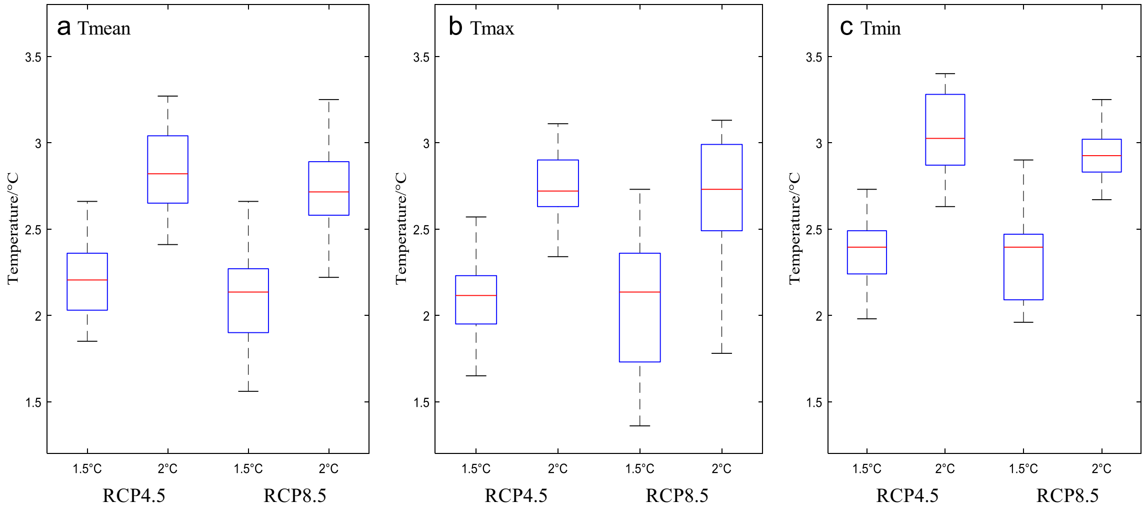


Fig. 2 Box plots of the mean, maximum, minimum surface temperature anomalies from the multi-model ensemble mean of 21 CMIP5 models over the Tibetan Plateau under global warming of 1.5 °C and 2 °C under RCP4.5 and RCP8.5. The upper and lower hinges of the boxplot represent the 25th and 75th percentile. The whiskers extend to the highest (lowest) value that is within 1.5 times the interquartile range of the upper (lower) hinge. The central line of each box plot indicates the median value

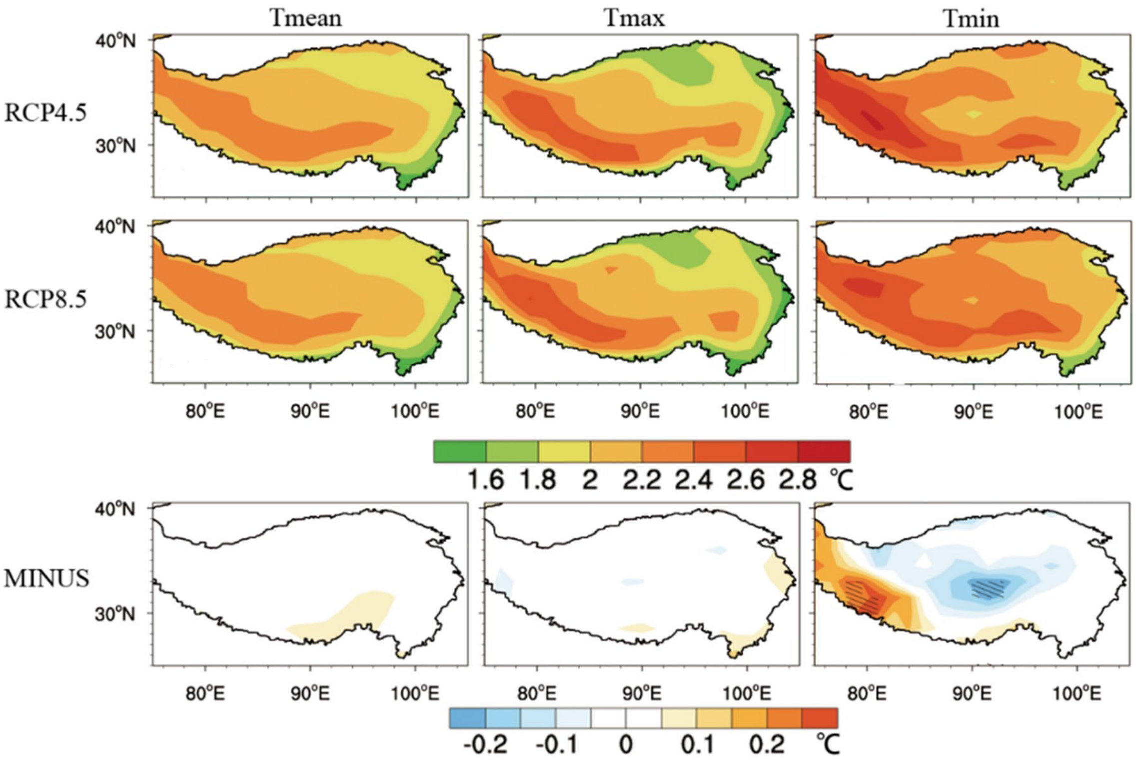


Fig. 3 Spatial patterns of mean, maximum, minimum surface temperature from the multi-model ensemble mean of 21 CMIP5 models over the Tibetan Plateau under global warming of 1.5 °C under RCP4.5 and RCP8.5. The difference (RCP4.5 minus RCP8.5) is also shown, and the differences exceeding the 0.1 significance level is marked. This is adopted from Fig. 1 in Wu et al. (2019)

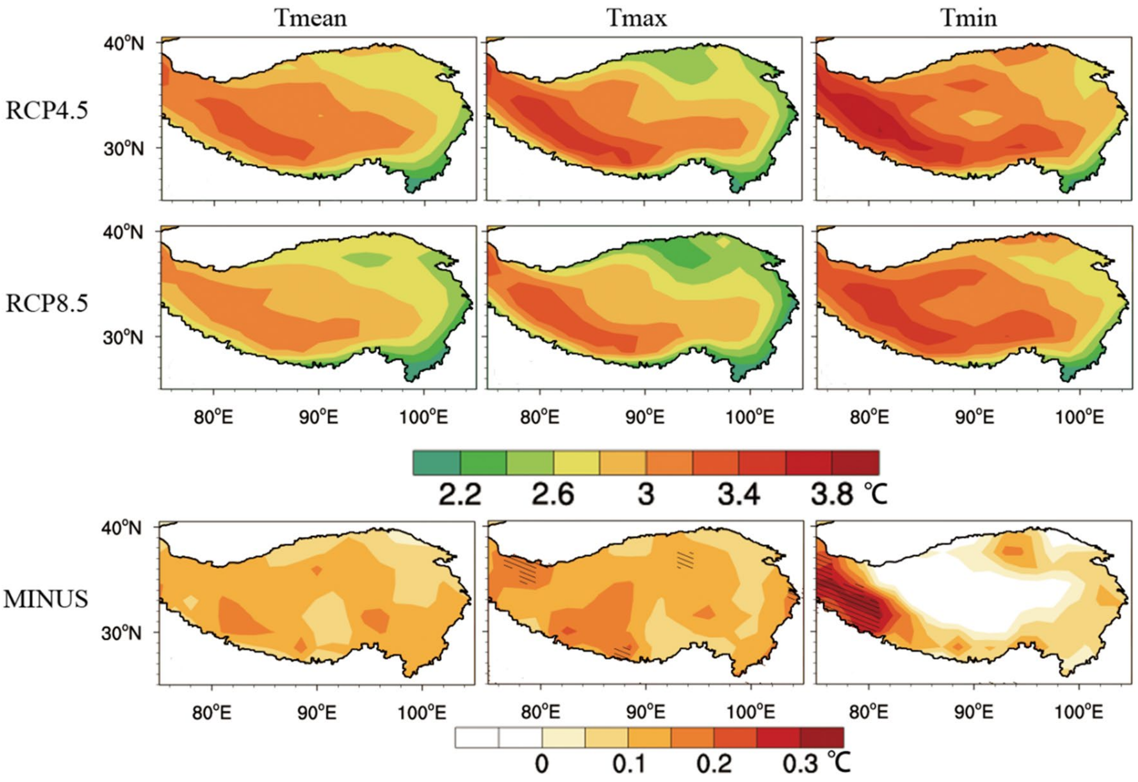


Fig. 4 Same as Fig. 3 but for global warming of 2 °C. This is adopted from Fig. 2 in Wu et al. (2019)

3.3 Difference in warming over the TP between global warming of 1.5 °C and 2 °C

Previous studies have revealed that climatic and environmental changes associated with global warming have nonlinear responses (Mitchell et al. 2016; Schleussner et al. 2016a, b). Thus, it is of great importance to assess the magnitude of warming over the TP associated with a global warming of 0.5 °C. Under RCP4.5, the differences in the mean, maximum and minimum surface temperatures over the TP are concentrated between 0.5 and 1 °C, which is close to the values found for the whole China (0.65 °C, 0.69 °C and 0.68 °C) (Zhang et al. 2017, 2019). This indicates that warming over the TP is greater than 0.5 °C in response to a global warming of 0.5 °C (Fig. 2).

Under RCP8.5, differences in the mean, maximum and minimum surface temperatures over the TP are concentrated between 0.1 and 1.6 °C, which are slightly smaller than those calculated for RCP4.5 (Zhang et al. 2017, 2019). It is noted that there are large uncertainties among the CMIP5 models. For example, the largest and smallest differences in the mean temperatures over the TP are 1.21 °C (IPSL-CM5A-LR model) and 0.08 °C (MRI-CGCM3 model), respectively. In most regions, the spatial patterns under RCP8.5 are closer to those under RCP4.5. It should be noted that the amplitude of warming over the TP will be intensified with an additional 0.5 °C increase in temperature.

3.4 Robust EDW over the TP under global warming of 1.5 °C and 2 °C

Figures 5 and 6 show scatter plots of elevation versus the mean, maximum and minimum surface temperatures over the TP from 21 CMIP5 models MMEM under RCP4.5 and RCP8.5 under global warming of 1.5 °C and 2 °C, respectively. Figures 7 and 8 show scatter plots of the historical temperatures (1986–2005) versus the mean, maximum and minimum surface temperatures over the TP from 21 CMIP5 models MMEM under RCP4.5 and RCP8.5 under global warming of 1.5 °C and 2 °C, respectively.

As shown in Figs. 5 and 6, there are positive correlations between the temperature increase and elevation, and they are all significant. This indicates that the high altitude regions over the TP appear to experience a stronger response to global warming than the low altitude regions do. Meanwhile, as shown in Figs. 7 and 8, there are negative correlations between the temperature increases and the historical temperatures, indicating that the low-temperature regions

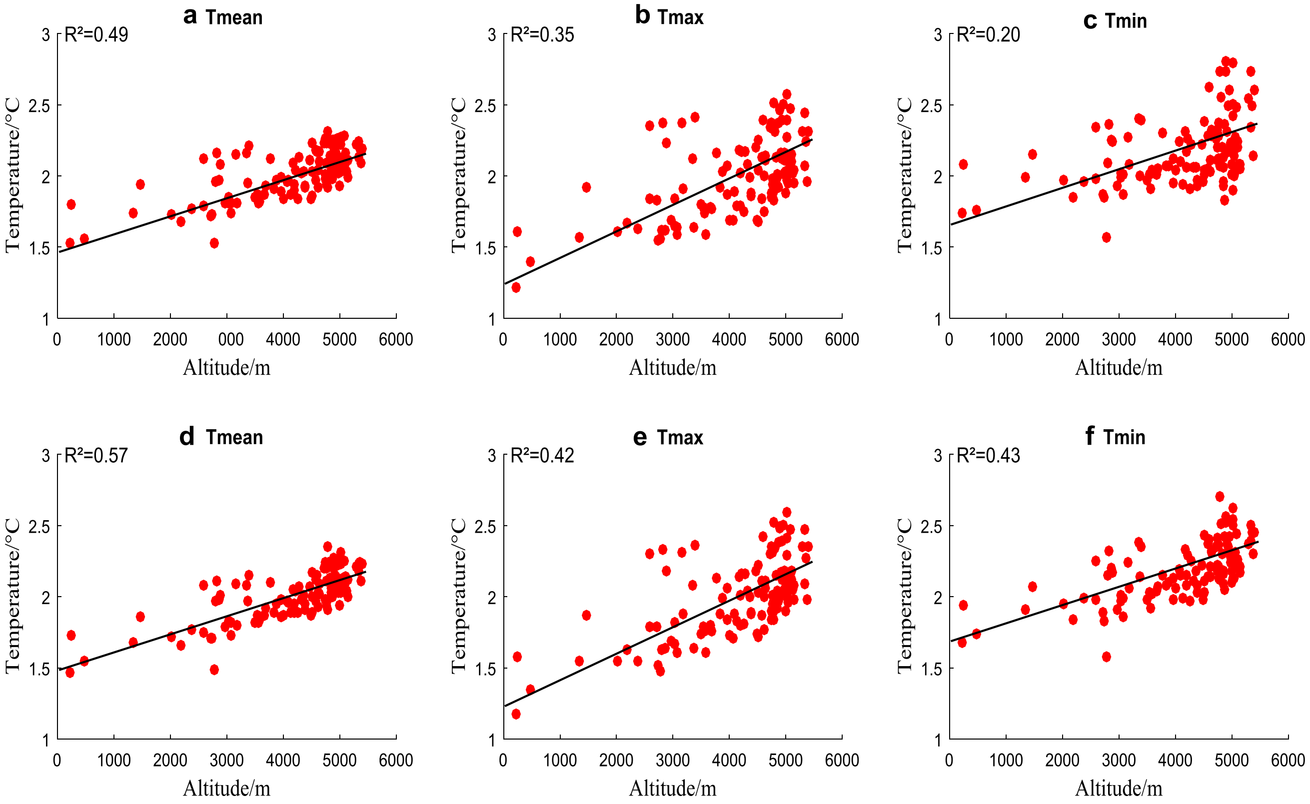


Fig. 5 Scatter plots of elevation versus the mean, maximum, minimum surface temperatures from the multi-model ensemble mean of 21 CMIP5 models over the Tibetan Plateau under RCP4.5 (**a**–**c**) and RCP8.5 (**d**–**f**) under global warming of 1.5 °C above pre-industrial levels (as represented by the 1850–1900 baseline period). The correlation coefficients are all at the $p < 0.05$ significance level

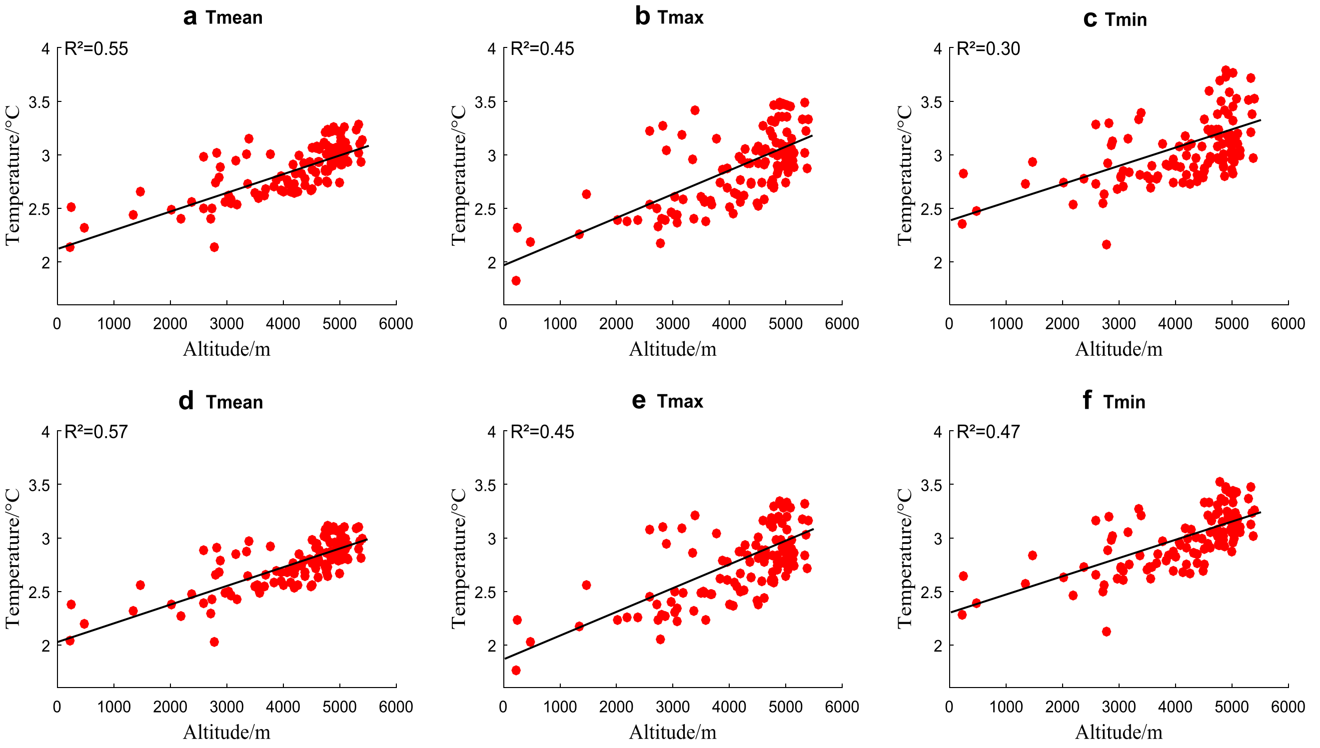


Fig. 6 Same as Fig. 5 but for global warming of 2 °C

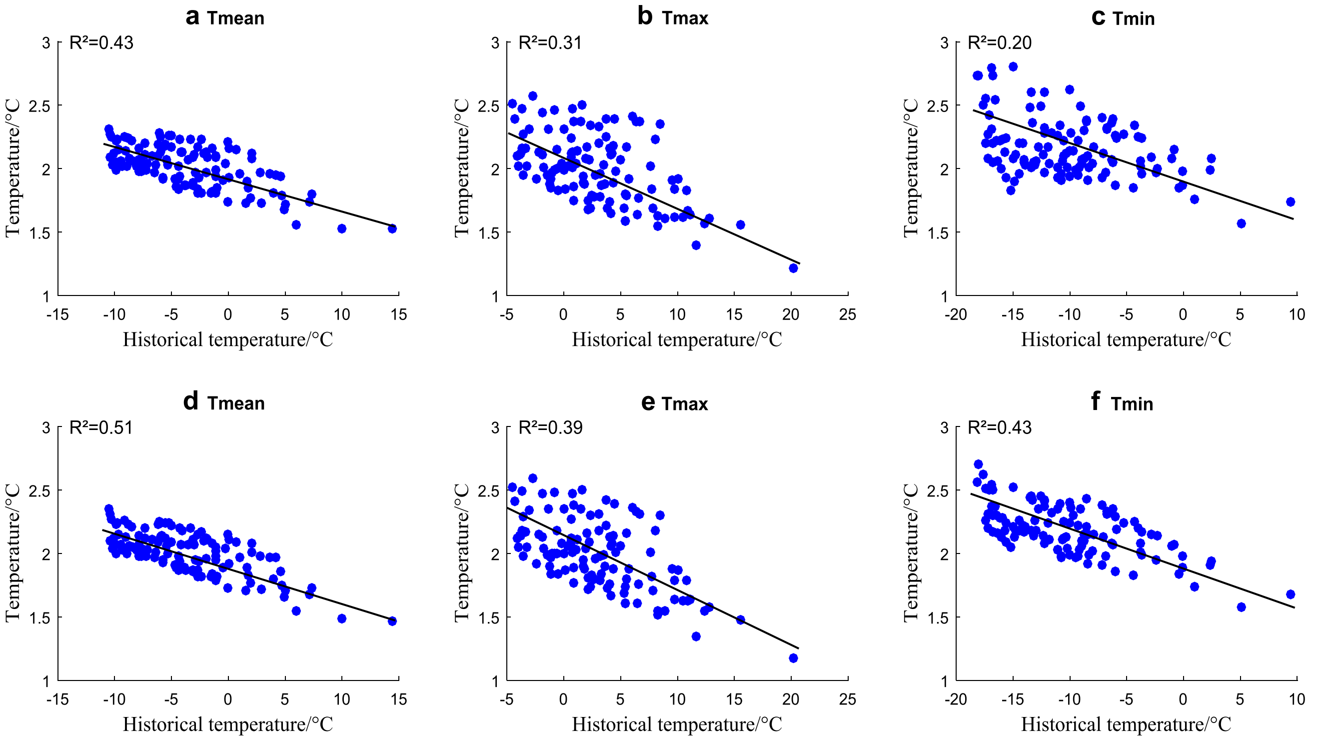


Fig. 7 Scatter plots of historical temperature (1986–2005) versus the mean, maximum, minimum surface temperatures from the multi-model ensemble mean of 21 CMIP5 models over the Tibetan Plateau under RCP4.5 (**a**–**c**) and RCP8.5 (**d**–**f**) under global warming of 1.5 °C above pre-industrial levels (as represented by the 1850–1900 baseline period). The correlation coefficients are all at $p<0.05$ significance level

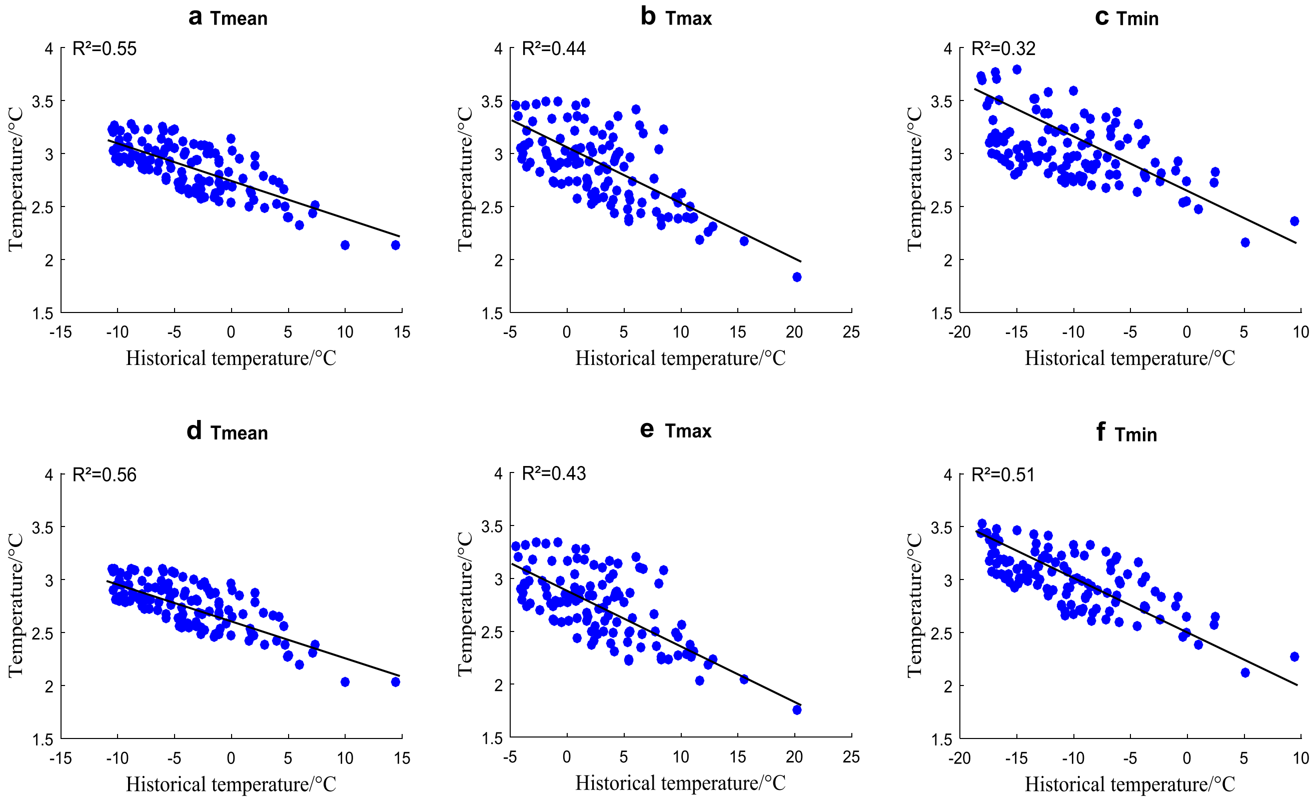


Fig. 8 Same as Fig. 7 but for global warming of 2 °C

over the TP appear to experience a stronger warming. Thus, the relationship between the increase in temperature and the elevation/historical temperature is clear and significant, suggesting that EDW over the TP under global warming of 1.5 °C and 2 °C is robust. Furthermore, more robust EDW over the TP is found under global warming of 2 °C than 1.5 °C. This is consistent with the previous observational studies (Liu and Chen 2000; Liu et al. 2009; Pepin and Lundquist 2008; Rangwala et al. 2010; You et al. 2010), which suggest that the surface albedo feedbacks, cloud, water vapor and aerosols and their elevation dependent patterns contribute to EDW over the TP (Liu and Chen 2000; Liu et al. 2009; Rangwala et al. 2010; Xu et al. 2016). However, there are limited studies on the accurate conclusions, and it is necessary to explore the implications of EDW.

3.5 Mechanisms and insights

Rapid warming over the TP has been detected in recent decades, and has complicated mechanisms. Anthropogenic greenhouse gas emissions is regarded as the main cause of for rapid warming over the TP (Chen et al. 2003; Liu et al. 2009), because the impact of increased greenhouse gas emissions on climate change over the TP is probably more severe than that on the rest of the world (Duan et al. 2006, 2012). Many other factors also contribute to the enhanced warming over the TP, such as snow/ice-albedo feedback (Liu and Chen 2000; You et al. 2010), an increase in the absorbed solar radiation influenced by decrease in snow cover (Rangwala et al. 2010), changes in cloud cover (Duan and Wu 2006), atmospheric brown clouds and black carbon aerosols (Xu et al. 2016), surface water vapor (Rangwala et al. 2009), changes in atmospheric circulation (You et al. 2016a), anthropogenic land use changes (Cui et al. 2006), the effects of human activity (You et al. 2008), and pronounced stratospheric ozone depletion (Guo and Wang 2012). The warming over the TP is a result of the interaction of many different factors. However, the proportion that each factor contributes to the pronounced warming over the TP is still unknown.

Many evidences suggest that the high-mountain and plateau experienced greater warming than lower regions did (Pepin et al. 2015; Rangwala and Miller 2012; Rangwala et al. 2009); however, the mechanisms of EDW over the TP are not fully understood. The EDW over the TP is most likely due to the combined effects of cloud radiation and snow/ice-albedo feedbacks (Chen et al. 2003; Duan and Xiao 2015; Kang et al. 2010; Liu et al. 2009; Yan et al. 2016; You et al. 2016b), which is consistent with the sharp reduction in snow depth at higher elevations among 3500–4000 m under global warming of 1.5 °C and 2 °C (Fig. 9). The doubled CO_2

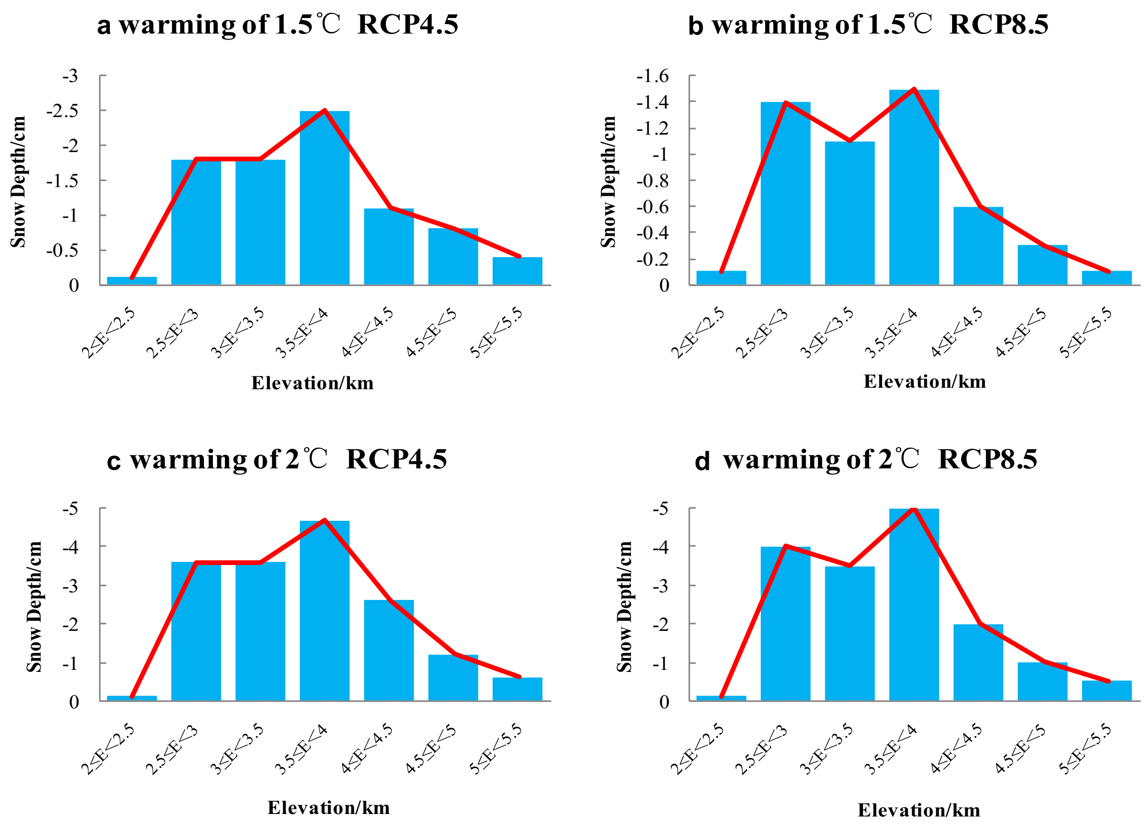
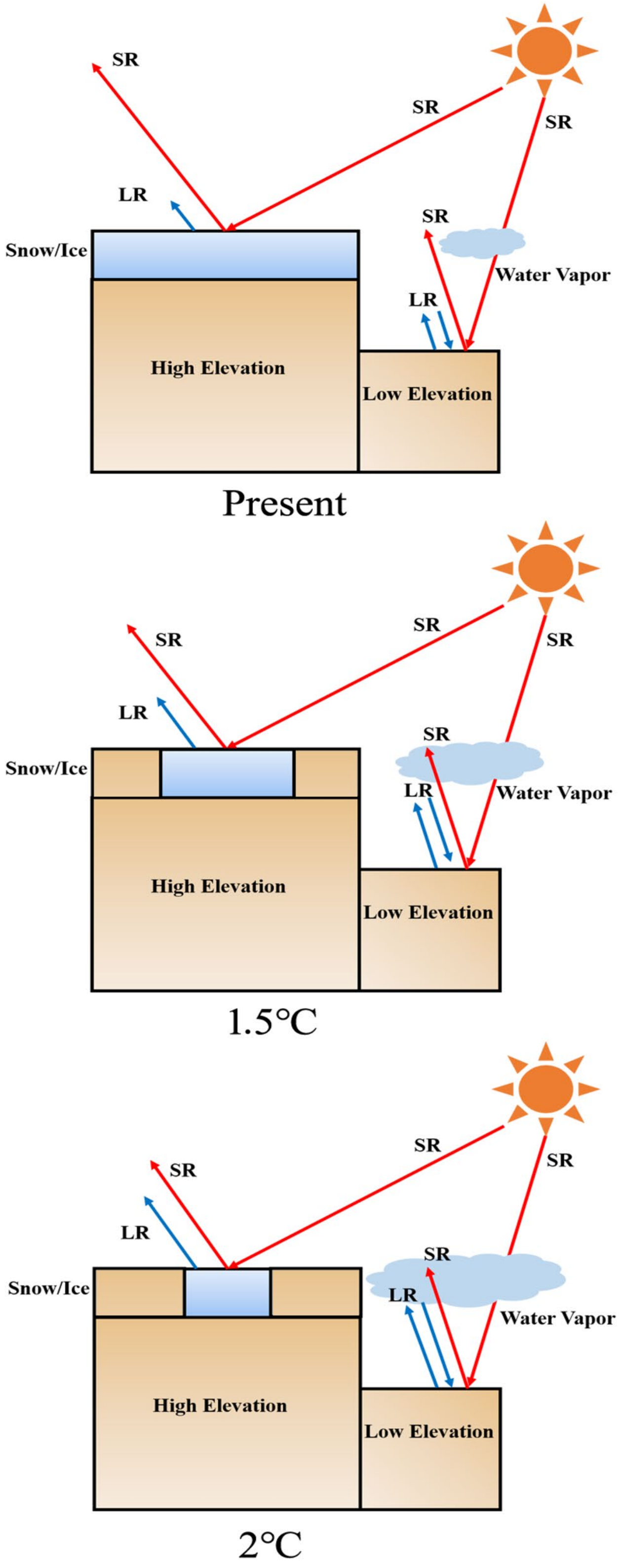


Fig. 9 Snow depth in difference elevation ranges from the multi-model ensemble mean of 21 CMIP5 models over the Tibetan Plateau under RCP4.5 (**a**, **c**) and RCP8.5 (**b**, **d**) under global warming of 1.5 °C and 2 °C above pre-industrial levels (as represented by the 1850–1900 baseline period)

recorded in the atmosphere leads to an increase/decrease in clouds at lower/higher elevations, which results in changes in the solar radiation and an enhanced surface warming at higher elevations (Chen et al. 2003; Yan et al. 2016). The decline in snow cover will tend to amplify the warming over the TP through snow and ice-albedo feedback effects (IPCC 2013). In addition, the increase in shortwave radiation resulting from the reduced snow depth and decreased cloud level is a dominant factor for the greater warming at higher elevations (Yan et al. 2016). Other factors, such as surface water vapor (Rangwala et al. 2009, 2016) and the surface versus free-air coupling (Pepin et al. 2011), also play crucial roles on the EDW over the TP. However, there are discrepancies in the current studies, indicating that the EDW needs further investigations. Due to the large heterogeneity of the terrain, the mechanism for EDW should differ in elevation band. A simple sketch of physical mechanism for the robust EDW over the TP under global warming of 1.5 °C and 2 °C is proposed in Fig. 10. At high elevation especially between 3500 and 4000 m, snow/ice-albedo feedback greatly contributes on EDW over the TP. However, at low elevation with more humid environment, the water vapor probably influences the warming patterns over the TP by modulating shortwave radiation and longwave radiation, respectively (Fig. 10). More variables of CMIP5 models under global warming of 1.5 °C and 2 °C should be derived to support the hypothesis in future.

4 Summary

In summary, there is a significant EDW over the TP under global warming of 1.5 °C and 2 °C, which reflects the unique response of this region to warming. This will have potentially serious consequences for the Third pole environment. The snow/ice-albedo feedbacks probably contribute to the robust warming and EDW over the TP at high elevation, which influence on the climate changes over the TP. Robust EDW over the TP under global warming of 1.5 °C and 2 °C is observed, and more robust EDW is clear under global warming of 2 °C, which will be useful for the sustainability of water resources of the TP and requires further research for the mechanism.



Present

1.5°C

2°C

Fig. 10 A simple sketch of possible mechanism for the robust elevation dependency warming over the Tibetan Plateau under global warming of 1.5 °C and 2 °C. SR and LR indicate the shortwave radiation and longwave radiation, respectively

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