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New proofs of the recent climate warming over the Tibetan Plateau as a result of the increasing greenhouse gases emissions

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Abstract A striking climate warming over the Tibetan Plateau during the last decades has been revealed by many studies, but evidence linking it to human activity is insufficient. By using historical observations, here we show that the *in situ* climate warming is accompanied by a distinct decreasing trend of the diurnal range of surface air temperature. The ERA40 reanalysis further indicates that there seems to be a coherent warming trend near the tropopause but a cooling trend in the lower stratosphere. Moreover, all these features can be reproduced in two coupled climate models forced by observed CO_2 concentration of the 20th century but cannot be produced by the fixed external conditions before the industrial revolution. These suggest that the recent climate warming over the Tibetan Plateau primarily results from the increasing anthropogenic greenhouse gases emissions, and impacts of the increased greenhouse gases emissions upon the climate change in the plateau are probably more serious than the rest of the world.

Keywords: Tibetan Plateau, climate warming, greenhouse effect, diurnal range of air temperature.

The Tibetan Plateau (TP, 75—105°E, 27.5—37.5°N) is the highest and largest highland in the world with a variety of climate and ecosystems. The TP exerts profound influences not only on the local climate and environment but also on the global atmospheric circulation through its thermal and mechanical forcing [1−5]. Wang *et al.* [6] constructed a surface air temperature series from 1880 to 1996 of the plateau by using meteorological observation and tree rings, and found two obvious warm periods in 20th century with the former in 1920 to 1960 and the latter in late 1970 to early 1980. Recently, many observational studies[7−10] have shown that a striking climate warming occurred there during the second half of the century. However, most of them focus only on the phenomenon of climate warming, and the intrinsic reason of climate warming is particularly needed because it will provide us insights to further understand the ongoing global change.

The daily mean (T_{ave}), maximum (T_{max}), and minimum (T_{min}) air temperatures in the period of January 1961 to December 2003 come from the 740 stations in China, which are the most complete station dataset in China processed by the China Meteorological Administration. In the central and eastern TP (CE-TP), we select 64 of them with the beginning year no later than 1961 and the continuous absent records no more than 3 months in this study. The geographical location and height above sea level of these stations are shown in Fig. 1(a), in which we can see that they spread uniformly and hence can depict the real case rationally.

Fig. 1(a) and (b) present the spatial distributions of the linear variation rate (LVR) of the annual mean Tave and diurnal temperature range (DTR), respectively. A universal and strong warming trend over CE-TP can be seen, and the largest amplitude appears in the north region where the average elevation is relatively high. On the other hand, the observed DTR shows a decreasing trend in most areas with almost all the minimum centres consistent with the warming centres, suggesting the warming is caused mainly by the increase of T_{min} and especially the strong night and winter warming. Actually, during the period 1961—2003, the 64-station averaged LVR of the annual mean T_{min} (0.57℃/10a) is twice larger than that of the T_{max} (0.27℃/10a), and the LVR of the T_{ave} in winter (December, January and February) is 0.44℃/10a and also nearly twice larger than the average in the rest three seasons (0.23℃/10a). Zhai and Pan[11] also found an increasing frequency of higher nocturnal air temperature in most areas of China since the mid 1980s.

The temporal evolutions of the 64 station-averaged annual mean T_{ave} and DTR anomalies are exhibited in Fig. 2(a). A distinct increasing trend in T_{ave} (0.28℃/10a) but a decreasing trend in DTR (–0.19℃/10a) over the

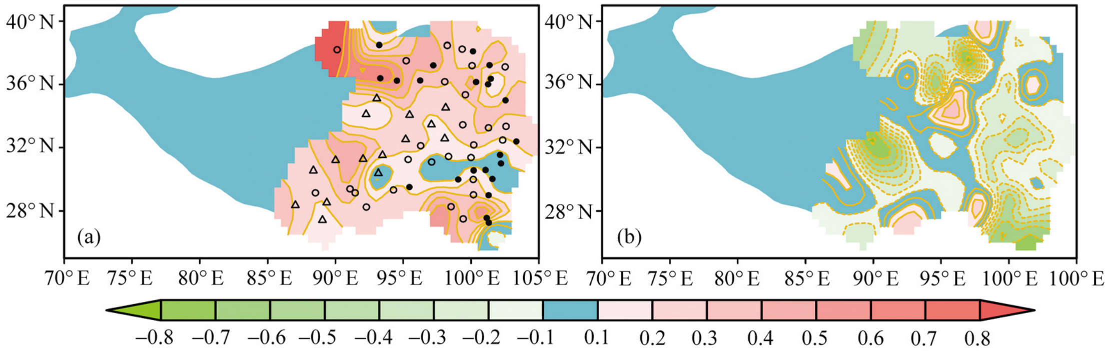

Fig. 1. Spatial distribution over the central and eastern Tibetan Plateau (CE-TP) of the linear variation rate (LVR, in ℃/10 a) of the station-based annual mean surface air temperature (a) and the diurnal range of the surface air temperature (DTR) (b) during 1961—2003. Triangles, open circles, and solid circles in (a) denote stations equal to or higher than 4000, 3000, and 2000 m, respectively. The cyan area represents the Tibetan Plateau area with the average altitude higher than 3000 m.

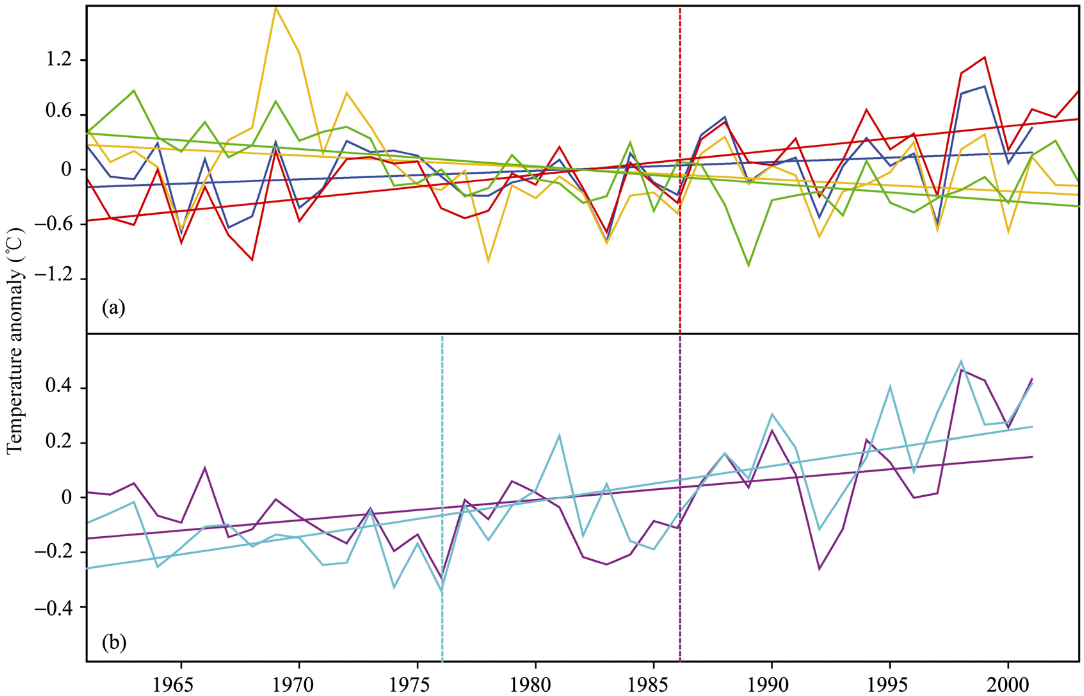

Fig. 2. Temporal evolutions of the surface air temperature and DTR anomalies in the period of 1960—2003. (a) The CE-TP area; (b) Northern subtropics and Northern Hemisphere. Red, blue, and yellow curves are observed, ERA40-, and NCEP-based temperature anomalies, and the green curve denotes the observed DTR over the CE-TP; Purple and cyan curves in (b) denote the ERA40-based temperature anomalies over the Northern Subtropics and the Northern Hemisphere, respectively. Solid and dotted lines represent the linear trends and the chief abrupt change points of the curves with the same colour.

CE-TP exist in this period with the largest amplitude appearing in 1990 s. The CE-TP grid-averaged (85—105°E, 27.5—37.5°N) T_{ave} in ERA40[12] is consistent with the observation fairly well, and the correlation coefficient between them is 0.89 and above 99% confidence level. But the warming amplitude reaches only 0.10℃/10a and is much lower than observation. It may be associated with the fact that fewer meteorological stations are included in the data assimilation scheme[13]. Nevertheless, the rapid change of T_{ave} in both ERA40 and observation happened roughly in 1986 (all the climate rapid changes in this work have passed 95% confidence level test by using moving t-test). In NCEP reanalysis data [14], however, the interannual variability of T_{ave} is different from the observation (the correlation coefficient is only 0.21 and under 90% confidence level), and the T_{ave} in the whole period even presents a cooling trend. Thus the NCEP reanalysis seems to be inferior to the ERA40 at least in the TP area.

In addition, the evolution of ERA40 annual mean T_{ave} and the corresponding linear trend in the Northern Subtropics (20—40°N) exhibit similar features to those over the CE-TP with the significant rapid warming occurring in mid 1980s (Fig. 2(b)). But for the T_{ave} averaged over the whole Northern Hemisphere, the rapid warming appears in 1976, about 10 years earlier than that in the Northern Subtropics and the CE-TP. These results imply that besides the large regional differences in the surface T_{ave} change[15], there also exist significant differences in temporal evolution with varying latitudes.

As for the western TP, only Shiquanhe Station (80°05'E, 32°30'N, and 4278 m above sea level) has the comparable record length, and thus it is used to roughly represent the case in the western TP. There exists a pronounced warming trend (0.30℃/10a) accompanied by a decreased DTR (–0.30℃/10a) as well. Hence climate warming is a widespread phenomenon over most of the TP.

Although the ERA40 reanalysis is highly dependent on data assimilation scheme and data coverage, there is no comparable observation records at the upper levels over the TP, and considering the good agreement between the ERA40-based and observed interannual variation and interdecadal trend of surface air temperature over the CE-TP, we use ERA40 to detect the signals of climate rapid change in the upper atmosphere.

As can be seen from Fig. 3, the climate warming over the CE-TP since the mid 1980s can also be detected near the tropopause (150 hPa) over the CE-TP and even the entire Northern subtropics. On the other hand, the *in situ* lower stratosphere (50 hPa) is characterized by a reversed cooling trend. As for the connection between the strong surface warming and higher temperature at tropopause as well as the lower stratosphere cooling, it may be interpreted by the strong boundary layer heating over the plateau [16] and the resultant atmospheric thermal adaptation and overshooting[17].

The decreased DTR, warmed upper troposphere, as well as the cooled lower stratosphere have been regarded as the signals of the greenhouse gases (GHGs)-induced climate warming [15]. Zhao *et al.*[18] pointed out that the climate warming in 20th century, especially in the second half of the century, is very likely induced by

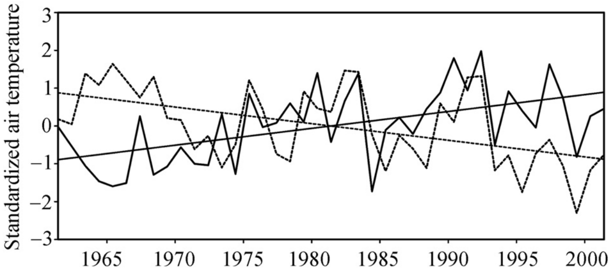

Fig. 3. Temporal evolution of the ERA40 standardized air temperature in the upper atmosphere in the period of 1961—2001. Solid and dash curves denote air temperatures at 150 hPa and 50 hPa, respectively, and tilting lines are the linear trends of the corresponding curves.

the enhanced greenhouse effect. Chen *et al.*[19] argued that the increased CO_2 will lead to cloud amount increased (decreased) at lower (higher) elevations over the relatively flat eastern TP for the winter half year, and the net effect of the changes in radiation fluxes will enhance warming in both areas. This could explain why there is a decreasing trend of the observed annual mean total cloud amount over the eastern TP since the mid 1980s [10].

By using the climate simulations for the IPCC Fourth Assessment given by two coupled global climate models, we attempt to investigate the relationship between the TP warming and enhanced greenhouse effect due to increased CO_2. The first model MIROC_3.2 is jointly developed by the Center for Climate System Research, the National Institute for Environmental Studies, and the Frontier Research Center for Global Change of Japan. The second is GFDL_CM2.1 developed by NOAA GFDL (Geophysical Fluid Dynamics Laboratory, National Oceanic Atmospheric Administration of USA). These two models can successfully reproduce the large-scale interannual variation of the surface air temperature in the experiments based on the 20th century climate (referred to as 20C3M, in which all the forcing conditions were changed by following the historical data during the 20th century). The annual mean global surface air temperature correlation coefficient from 1961 to 1999 between the MIROC_3.2 and ERA40 is 0.37, and that between GFDL_CM2.1 and ERA40 is 0.35, both above the 95% confidence level. By comparing the pre-industrial control experiment (referred to as PICNTRL, in which CO_2 concentration keeps unchanged since 1860) with the climate change scenario experiment, the role of the GHGs in the recent climate warming over the CE-TP can be qualitatively evaluated.

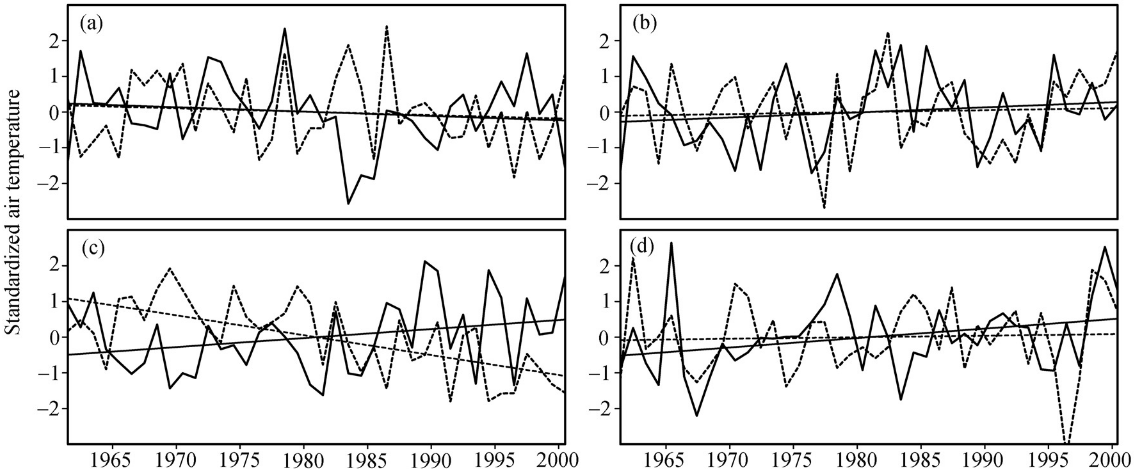

Fig. 4. Temporal evolution of the standardized annual mean surface air temperature and DTR over the CE-TP in the period of 1961—2000 simulated by the coupled climate model MIROC_3.2 ((a), (c)) and by the GFDL_CM2.1 ((b), (d)). (a) and (b) for the PICNTRL scenario; (c) and (d) for 20C3M scenario. Solid and dash curves represent the surface air temperature and the DTR.

In 20C3M scenario experiment, the LVRs of T_{ave} in 1961 — 1999 on TP given by MIROC_3.2 and GFDL_CM2.1 are 0.16 and 0.11℃/10 a, respectively, and the correlation coefficients between them and the observation are 0.43 (above 99% confidence level) and 0.30 (above 95% confidence level). The LVRs of DTR in MIROC_3.2 and GFDL_CM2.1 are –0.13 and 0.01℃/10a, respectively. The correlation coefficients between them and observation are 0.35 and 0.19. Fig. 4 shows the standardized surface air temperature and DTR over the CE-TP during the aforementioned period in the PICNTRL (Fig. 4(a), (b)) and 20C3M (Fig. 4(c), (d)) experiments given by these two models. The difference between these two scenarios is obvious. In the PICNTRL simulations, it is characterized by a flat or slightly decreasing linear trend for these two variables. On the contrary, in the 20C3M simulations, there is a pronounced warming trend accompanied by a decreased DTR over the CE-TP after 1980s just as the case shown in Figs. 2 and 3.

According to these results, we can infer that the human-activity-induced GHGs emissions should be mainly responsible for the recent climate warming over the CE-TP through changing the local radiative forcing. This is consistent with the numerical modelling results given by Chen *et al*.[19] with a regional model. They further pointed out that doubling CO_2 will weaken the winter monsoon and hence the fewer cold air intrusion.

We have investigated the main features of the recent climate warming over the TP by using both observations and reanalysis data. It is found that the evident climate warming since the mid 1980 s is accompanied by the decreasing trends of the surface air DTR and the lower stratospheric air temperature, and the increasing trend of air temperature in tropopause. Moreover, simulation results of two climate models for the IPCC Fourth Assessment further suggest that as a part of the global change, the recent climate warming over the CE-TP is likely induced by the anthropogenic CO_2 emissions.

The increase of GHGs is believed to be responsible not only for the global warming [20−23] but also for the change of year-to-year climate variability [24]. Its impacts are obviously larger than urbanization for large-scale warming [25]. Since the TP is located in a remote region and relatively free from the influences due to local urbanization and the change in land use, the recent climate warming over the TP and other high elevation sites is more closely connected with the increase of GHGs than the rest of the world.

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References

1 Wu G X. The nonlinear response of the atmosphere to large-scale mechanical and thermal forcing. J Atmos Sci, 1984, 41: 2456—2476[DOI]

2 Manabe S, Broccoli A J. Mountains and arid climate of middle latitudes. Science, 1990, 247: 192—195

3 Yanai M, Li C, Song Z. Seasonal heating of the Tibetan Plateau and its effects on the evolution of the Asian summer monsoon. J Meteor Soc Japan, 1992, 70: 319—351

4 Yeh T C, Wu G X. The role of the heat source of the Tibetan Plateau in the general circulation. Meteorol Atmos Phys, 1998, 67: 181—198[DOI]

5 Duan A M, Wu G X. Role of the Tibetan Plateau thermal forcing in the summer climate patterns over subtropical Asia. Climate Dynamics, 2005, 24: 793—807[DOI]

6 Wang S W, Ye J L, Gong D Y, et al. Construction of mean annual temperature series for the last one hundred years in China. Quarterly Journal of Applied Meteorology (in Chinese), 1998, 9: 392—401

7 Liu X, Chen B. Climatic warming in the Tibetan Plateau during recent decades. Int J Climatol, 2000, 20: 1729—1742[DOI]

8 Zhu W Q, Chen L X, Zhou Z J. Several characteristics of contemporary climate change in the Tibetan Plateau. Sci Chin Ser D-Earth Sci, 2001, 44(supp): 410—420

9 Vinnikov K Y, Grody N C. Global warming trend of mean tropospheric temperature observed by satellites. Science, 2003, 302: 269—272[DOI]

10 Niu T, Chen L X, Zhou Z J. The characteristics of climate change over the Tibetan Plateau in the last 40 years and the detection of climatic jumps. Adv Atmos Sci, 2004, 21: 193—203

11 Zhai P, Pan X. Trends in temperature extreme during 1951-1999 in China. Geophysical Research Letter, 2003, 30(17): 1913[DOI]

12 Simmons A J, Gibson J K. The ERA40 project report. ECMWF Technical Report No. 1. 2000.

13 Bengtsson L, Hagemann S, Hodges K I. Can climate trends be calculated from reanalysis data? J Geo Res, 2004, 109: D11111[DOI]

14 Kalnay E, Kanamitsu M, Kistler R, et al. The NCEP/NCAR 40-year reanalysis project. Bull Amer Meteoro Soc, 1996, 77(3): 433—471

15 IPCC. Climate change 1995: The science of climate change. In: Houghton J T, et al. eds. Cambridge: IPCC second assessment of climate change. Cambridge: Cambridge University Press, 1996, 1—362

16 Yanai M, Li C. Mechanism of heating and the boundary layer over the Tibetan Plateau. Mon Wea Rev, 1994, 122: 305—323[DOI]

17 Wu G X, Liu Y M. Thermal adaptation, overshooting, dispersion, and subtropical anticyclone, Part I: Thermal adaptation and overshooting. Chinese J Atmos Sci (in Chinese), 2000, 24(4): 433—446

18 Zhao Z C, Lou Y, Gao X J, et al. Enlightenment from detection of climate change in China for the 20th century. Newsletter on Climate Change 2003/2004, 2004, 1: 20—22

19 Chen B, Chao W C, Liu X. Enhanced climate warming in the Tibetan Plateau due to doubling CO2: a model study. Climate Dynamics, 2003, 2: 401—413

20 IPCC, Climate change 2000: The science of climate change. In: Houghton J T et al. eds. Cambridge: IPCC third assessment of climate change. Cambridge: Cambridge University Press, 2001, 1—79

21 Stott P A, Tett S F, Jones G S, et al. External control of 20th century temperature by natural and anthropogenic forcings. Science, 2000, 290: 2133—2137

22 Levitus S, Antonov J, Wang J, et al. Anthropogenic warming of earth's climate system. Science, 2001, 292: 267—270[DOI]

23 Karoly D J, Braganza K, Stott P A, et al. Detection of a human influence on North American climate. Science, 2001, 302: 1200—1203[DOI]

24 Schär C, Vidale P L, Lüthi D, et al. The role of increasing temperature variability in European summer heatwaves. Nature, 2004, 427: 332—336[DOI]

25 Parker D E. Large-scale warming is not urban. Nature, 2004, 432: 290[DOI]