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RESEARCH ARTICLE

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Delayed warming hiatus over the Tibetan Plateau

Wenling An¹, Shugui Hou^{1,2} , Yongyun Hu³ , and Shuangye Wu^{1,4}

Key Points:

- Warming hiatus is detected over the Tibetan Plateau regions lower than 4000 m since the late 1990s
- However, warming hiatus over the regions higher than 4000 m started in the mid-2000s, which is delayed by several years
- The delayed warming hiatus is likely due to the special regional radiative, energy and land surface processes over the high Plateau

Supporting Information:

- Supporting Information S1

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Abstract A reduction in the warming rate for the global surface temperature since the late 1990s has attracted much attention and caused a great deal of controversy. During the same time period, however, most previous studies have reported enhanced warming over the Tibetan Plateau (TP). In this study we further examined the temperature trend of the TP and surrounding areas based on the homogenized temperature records for the period 1980–2014, we found that for the TP regions lower than 4000 m the warming rate has started to slow down since the late 1990s, a similar pattern consistent with the whole China and the global temperature trend. However, for the TP regions higher than 4000 m, this reduction in warming rate did not occur until the mid-2000s. This delayed warming hiatus could be related to changes in regional radiative, energy, and land surface processes in recent years.

1. Introduction

The global mean surface air temperature has shown warming trends in recent decades [*Intergovernmental Panel on Climate Change*, 2013]. It has been reported that the global temperature is probably going through a period of warming hiatus since the late 1990s [*Easterling and Wehne*, 2009; *Solomon et al.*, 2010; *Fyfe et al.*, 2013; *Trenberth and Fasullo*, 2013; *Kosaka and Xie*, 2013; *England et al.*, 2014; *Haywood et al.*, 2014; *Watanabe et al.*, 2014; *Ying et al.*, 2015]. The reality of recent global warming hiatus remains controversial because of biases in data processing and coverage [*Cowtan and Way*, 2014; *Cahill et al.*, 2015; *Karl et al.*, 2015]. *Lewandowsky et al.* [2015] suggested that “recent hiatus” in global warming is only a routine fluctuation and is not unique. On the other hand, *Fyfe et al.* [2016] confirmed the slowdown of global surface warming since the turn of this century and emphasized the importance of examining the impact and uncertainties in decadal climate variability and key external forcings. Despite these uncertainties in global temperature change, the regional warming rate has varied remarkably in recent decade [*Feng and Wu*, 2015; *Turner et al.*, 2016]. Therefore, it is necessary to make more detailed investigations about the regional temperature change, especially at the high-elevation regions [*Mountain Research Initiative EDW Working Group*, 2015].

The Tibetan Plateau (TP) is the highest and largest highland over the world with an average elevation over 4000 m above sea level (Figure S1 in the supporting information). It has the largest number of glaciers outside the polar region, which supply water for many prominent Asian rivers. However, many of these glaciers are shrinking due to the rapid warming, affecting the discharge of many large rivers and their ecological environments [*Immerzeel et al.*, 2010; *Yao et al.*, 2012]. Previous studies showed that surface temperature on the TP has experienced a persistent rapid warming in recent years due to the elevation dependency [*You et al.*, 2008; *Liu et al.*, 2009; *Qin et al.*, 2009; *You et al.*, 2010; *Kang et al.*, 2010; *Yan and Liu*, 2014; *Duan and Xiao*, 2015; *Mountain Research Initiative EDW Working Group*, 2015]. These studies focused on the comparisons of the warming rates between the global hiatus period and other periods, while ignored the changes of warming rates with time. Moreover, despite extensive research that relates the global warming hiatus to oceanic variations, very few studies exist to examine the regional characteristics of the warming hiatus and their underlying mechanisms [*Turner et al.*, 2016; *Zhou and Wang*, 2016]. Therefore, detailed analysis on the rates of temperature change at high elevations could provide some insights into the possible mechanisms for the observed global warming hiatus. In addition, a better understanding of the warming trend has profound implications for better estimating glacier changes and hydrological processes over the TP. Here we analyzed the changes in temperature trends over the TP from 1980 to 2014 and in particular during the recent global warming hiatus period (1998–2014). The global and whole China annual mean temperature series were also evaluated for comparison.

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2. Data and Methods

2.1. Data Sets

The monthly mean temperature, wind speed, and total cloud cover amount used in this study were extracted from the China Homogenized Historical Temperature Dataset (1980–2014 period) (version 1.0), which was released in 2015 by the National Meteorological Information Center, China Meteorological Administration (NMIC/CMA). This data set is continually updated and has been widely used in climate research [Ren *et al.*, 2005; Duan and Wu, 2006; Liu *et al.*, 2009; You *et al.*, 2013; Duan and Xiao, 2015]. The data set is quality controlled and homogenized based on the procedures described in Li *et al.* [2004a, 2004b]. This study focuses on the TP and its surrounding areas (27°–41°N, 75°–104°E) for the period 1980–2014, where data from 99 weather stations are available (Figure S1). The selected 99 meteorological stations on the TP include 13 stations lower than 2000 m (higher than 1000 m), 27 stations between 2000 and 3000 m, 38 stations between 3000 and 4000 m, and 21 stations higher than 4000 m.

Meteorological stations on the TP are relatively sparse and unevenly distributed, and the majority of them are located at regions lower than 4000 m due to some natural and anthropogenic reasons [Qin *et al.*, 2009]. Records from these stations, therefore, only represent climate signal at lower elevations, which could be very different from the climatic change at regions above 4000 m due to the differences in topography and land cover. As the TP's average elevation is over 4000 m, records from these stations may not accurately capture the temperature variations for the entire TP [Wang *et al.*, 2013]. In order to fully understand the climate characteristics over the TP, we divided the weather stations into two categories based on the elevation range: stations lower than 4000 m and higher than 4000 m, to facilitate the detailed analysis of temporal trends of the temperature changes.

In addition, monthly mean 2 m surface air temperature of ERA-Interim reanalysis data was also used to verify results from weather stations, particularly for areas with patchy data coverage such as the western TP (Figure S1). The ERA-Interim data were obtained from the European Centre for Medium-Range Weather Forecasts website (<http://www.ecmwf.int/>). It captures the temperature trends very well and is reliable for climate change investigation over the TP [Gao *et al.*, 2014]. ERA-Interim is the third generation reanalysis product from the European Centre for Medium-Range Weather Forecasts, with an improved atmospheric model and assimilation systems. The data include satellite-borne instruments, observations from aircraft, ocean buoys, radiosonde, and other surface platforms, but with a declining number of radiosonde ascents since the late 1980s [Dee *et al.*, 2011]. The monthly mean 2 m surface air temperature of ERA shows high consistency with surface air temperature measurements from meteorological stations on the TP [Frauenfeld *et al.*, 2005; You *et al.*, 2013]. ERA-Interim 2 m temperatures are available from 1979 to 2014 with a higher spatial resolution of 0.75° × 0.75°. We selected grid points within the study area (Figure S1) to further verify results obtained from surface stations. The surface elevations of the grid points were extracted from GTOPO30 digital elevation data (<http://eros.usgs.gov>).

The annual mean temperature of the whole China used in this study was produced from China's climate change monitoring bulletin and released recently by the China Meteorological Administrator in 2015. The global annual mean temperature was obtained from the Goddard Institute for Space Studies (GISS) [Hansen *et al.*, 2010]. In order to examine the difference in global and regional warming hiatus, we focused on the past three decades (from 1980 to 2014), a period covering the transition from global rapid warming since 1980s to the post-2000 hiatus.

2.2. Analysis Method

In our analysis, two main statistical methods were used to examine temperature trends: the nonparametric LOcal regrESSion (LOESS) regression, based on which annual change rates were estimated, and the 11 year running trend analysis, based on which decadal change rates were calculated.

LOESS is a locally weighted regression model. It does not require the specification of a function to fit a model to all of the data in the sample. LOESS regression is more flexible than traditional simple linear regression, and it is suitable for situations when an appropriate parametric form of the regression surface was not known. Furthermore, it is also suitable for data with outliers when a robust fitting method is necessary [Cohen, 1999]. Therefore, it is ideal for modeling complex processes for which no theoretical models exist. In this study, LOESS regression is used to derive the smoothed trend lines, based on which we calculated the

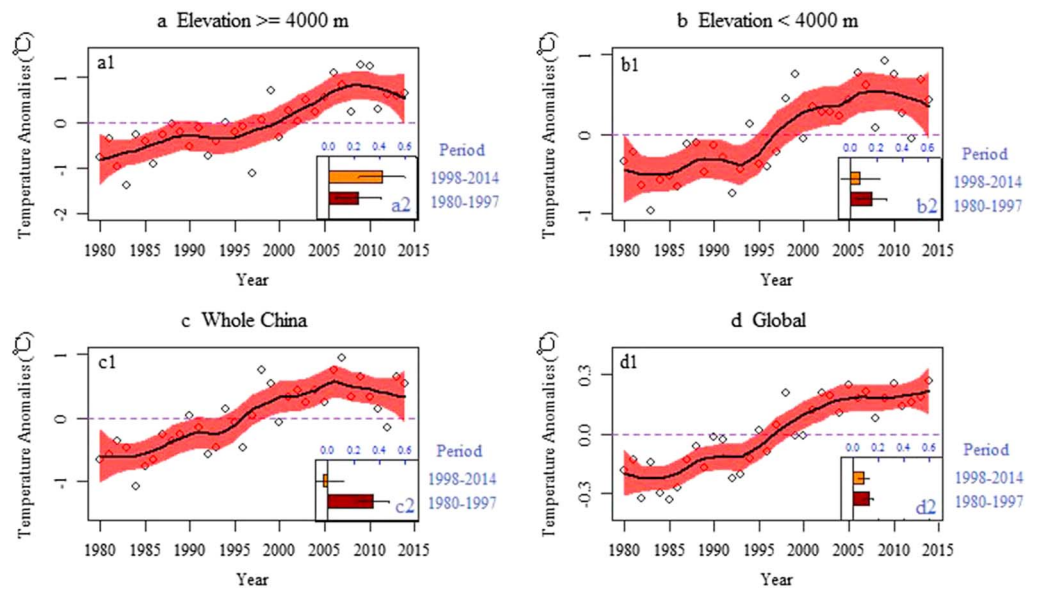


Figure 1. Observed annual mean temperature anomalies for the TP regions (a1) higher than 4000 m, (b1) lower than 4000 m, (c1) whole China, and (d1) global mean temperature during 1980–2014. Trend lines were estimated using the nonparametric LOESS regression technique with a span of 0.5; the shading area represents the 95% confidence intervals of the estimated trends. The (a2, b2, c2, and d2) insets in each figure show the decadal change rate of temperature variations ($^{\circ}\text{C}/\text{decade}$) and corresponding error bars during the period of 1980–1997 and 1998–2014.

annual change rates, i.e., the difference of modeled temperature values between two consecutive years. The model span is set to 0.5, which corresponds to a window of 17 years based on the period 1980–2014 of the observations, the approximate length of warming hiatus period. In addition, we used the bootstrap technique to test the stability of the temperature trend patterns as well as the annual change rate patterns derived from this method. The running decadal change rates were calculated by using an 11 year moving window to investigate the decadal changes of warming rate over time from 1980 to 2014. The window of 11 years was chosen with consideration of the length of the temperature series, and the trend estimation at decadal scale.

In addition, simple linear regression is also employed to calculate the trends in order to facilitate comparison with previous studies. The statistical significance of the trends is established with the two-tailed Student’s *t* test.

3. Results

3.1. Annual Mean Temperature Variations

For the global, whole China, the TP regions lower and higher than 4000 m, the annual mean temperature showed evident rapid warming since 1980 (Figures 1 and S2). Trend analysis showed relatively little temperature change for the TP regions lower than 4000 m since 1998 (Figures 1b and S2b), and similar pattern existed for the whole China and the global temperature at the same time (Figures 1c and 1d, and S2c and S2d). The temperature for the TP regions lower than 4000 m showed almost flat trend with a rate of $0.07^{\circ}\text{C}/\text{decade}$ during period 1998–2014 (Table 1). However, for the TP regions higher than 4000 m, the annual mean temperature kept increasing until the mid-2000s, followed by a significant decreasing trend in recent years (Figures 1a and S2a).

3.2. Warming Rates of Annual Mean Temperature

To examine changes in the warming rates over time, we first smoothed the temperature time series using the LOESS regression with the span of 0.5. Based on the smoothed trend lines, we calculated the annual change rate for the mean temperature of the global, the whole China, and the TP regions lower and higher than 4000 m. Consistent with the reported global warming hiatus period [Fyfe *et al.*, 2013], the increase rate of global mean temperature peaked around 1997 and started to decline. However, since about 2010, the

Table 1. Linear Trends (°C/decade) of Annual Temperature for the TP Regions Higher Than 4000 m, 3000 m, and 2000 m, As Well As Regions Between 3000–4000 m, 2000–3000 m, 2000–4000 m, and 1000–4000 m During the Periods 1980–2000, 2001–2012, 2001–2014, and 1998–2014^a

Period		≥4000 m	≥3000 m	≥2000 m	3000–4000 m	2000–3000 m	2000–4000 m	1000–4000 m
1980–2000	Decadal change rate (°C/decade)	0.36	0.35	0.38	0.35	0.44	0.39	0.37
	R ²	0.24	0.25	0.3	0.24	0.38	0.32	0.34
2001–2012	Decadal change rate (°C/decade)	0.53	0.40	0.30	0.45	0.28	0.19	0.03
	R ²	0.21	0.15	0.1	0.22	0.1	0.05	0.001
2001–2014	Decadal change rate (°C/decade)	0.35	0.29	0.25	0.23	0.16	0.19	0.09
	R ²	0.15	0.13	0.10	0.10	0.05	0.07	0.02
1998–2014	Decadal change rate (°C/decade)	0.42	0.30	0.23	0.18	0.11	0.14	0.07
	R ²	0.24	0.16	0.12	0.07	0.03	0.05	0.01
2006–2014	Decadal change rate (°C/decade)	−0.43	−0.36	−0.33	−0.30	−0.26	−0.28	−0.34
	R ²	0.10	0.09	0.07	0.07	0.05	0.06	0.08

^aTo make comparisons with previous studies, the cutoff years are chosen according to the studies of Yan and Liu [2014] and Duan and Xiao [2015], which used 2001 and 1998 as the start of the global warming hiatus period. The decadal change rates are emphasized in bold.

annual change rate of global mean temperature started to increase again, indicating the general warming trend in global temperature. By contrast, the results showed that for the TP regions lower than 4000 m and the whole China, the warming rates started to decline sharply and persistently since about 1998, indicating a significant warming slowdown (Figure 2). It seems that the TP regions lower than 4000 m responded fairly quickly to the global warming hiatus, and this temperature slowdown was intensified in recent years with negative annual change rates (Figure 2).

However, the temperature trajectory for the TP regions higher than 4000 m was different. For this region, the rapid warming continued until about 2005, when the warming rate peaked and started to decline (Figure 2). To test the robustness of this pattern, we used the bootstrap technique to create 300 random samples based on the original time series data and found similar patterns in annual mean temperature for the global, the whole China, and the TP regions lower than 4000 m, as well as the delayed reduction in warming rates since mid-2000s for the TP regions higher than 4000 m (Figure S3). In addition, we applied the 11 year running trend analysis on the data, and results also showed that the rates of increase for annual mean temperature peaked in 1997 for the global, the whole China and the TP regions lower than 4000 m (Figures S4b–S4d). However, for the TP regions higher than 4000 m, the rate of temperature increase peaked in mid-2000s (Figure S4a). These results were consistent with those from the LOESS regression analysis. In order to facilitate the following discussions, we determined the timing of the hiatus for TP regions higher than 4000 m as 2005.

We also used the ERA-Interim reanalysis data to compensate for the possible bias induced by uneven distribution of meteorological stations over the TP. Generally, ERA-Interim captured the hiatus delay for higher elevations (Figure S5). For regions higher than 5000 m and 4000 m, the annual temperature change rates showed a weak reduction since 1997 and then continued to increase until 2005 (Figure S5). Moreover, the 11 year running trend analysis also indicated that the reduction in decadal warming rates for regions higher than 4000 and 5000 m did not start until 2005 (Figures S6a and 6b), compared with 1997 when the warming

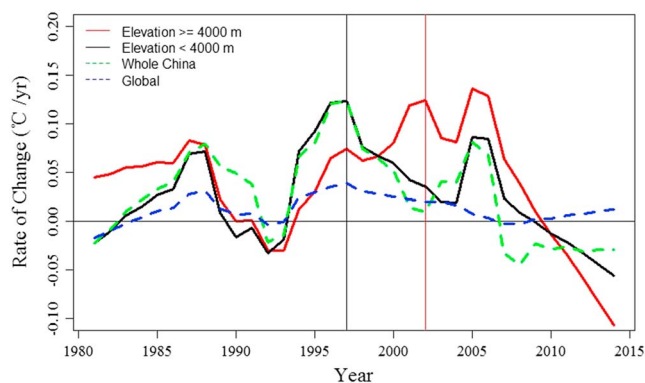


Figure 2. Comparisons of annual change rates for the TP regions higher than 4000 m, the TP regions lower than 4000 m, and global and whole China mean temperature from 1981 to 2014. The annual change rates were estimated based on the nonparametric LOESS regression technique with a span of 0.5.

rates peaked for regions lower than 4000 m (Figure S6c). This seemed to suggest that the delay of warming hiatus, characterized by a sharp reduction in warming rate, was more evident at higher regions.

Seasonally, the annual temperature change rates based on the LOESS regression followed similar patterns for both the TP regions lower and higher 4000 m during spring, summer, and autumn from 1980 to 2014 (Figures S7a–S7c). However, the winter temperature showed an apparent delay in peaking of warm rates for the TP regions higher than 4000 m, compared with regions lower than 4000 m (Figure S7d). The 11 year running trend analysis also showed that the winter warming rate peaked at 1.27°C/decade in 1997 for regions lower than 4000 m (Figure S8d), but it peaked at 3.03°C/decade in 2002 for regions higher than 4000 m (Figure S8d). These results seem to indicate the main contribution of winter temperature change pattern to the hiatus delay in annual mean temperature for regions higher than 4000 m.

4. Discussion

In this study, we found a reduction in warming over the TP regions lower than 4000 m since 1998, which is consistent with the warming hiatus over other regions of the world. However, for TP regions higher than 4000 m, warming hiatus did not occur for regions higher than 4000 m until the mid-2000s. This seems to differ from conclusions of many previous studies that suggested that the TP has experienced a stronger warming in contrast to the global warming hiatus during post-1990s [Yan and Liu, 2014; Duan and Xiao, 2015].

The difference could be a result of the different analysis methods applied. First, previous studies often used linear regression to calculate a single rate of change for time periods before and during the defined period of hiatus. This method does not allow investigation of variation of temperature change rates within the defined time periods. Our methods, on the other hand, could reveal the temporal variation of the temperature change rates. Yan and Liu [2014] suggested that the TP has experienced a persistent and more significant warming for regions higher than 3000 m and 4000 m since 2001, and no obvious pause was detected during the common “global warming hiatus period.” Based on temperature data from above 99 meteorological stations, the annual temperature indices from 1980 to 2014 for above 2000 m (TP_2km), above 3000 m (TP_3km), and above 4000 m (TP_4km) are derived from the simple arithmetic mean of the corresponding stations. The results are similar with that of Yan and Liu [2014] (Table 1), and the linear change rates during the period 2001–2012 are higher than that of the period 1980–2000 for regions higher than 2000 m, 3000 m, and 4000 m. However, by incorporating the temporal variation of warming rates, we found a reduction of warming rates since late 1990s for TP regions lower than 4000 m (Figures 2 and S4), and this reduction did not occur for regions higher than 4000 m until mid-2000s. Second, the classification of the weather stations in this study, i.e., lower and higher than 4000 m, may also have partly contributed to the difference. It was only after excluding the stations higher than 4000 m did the annual temperature show reduced increasing rates over 2001–2014 for regions lower than 4000 m, compared to the periods of 1980–2000 (Table 1). These results suggest that the analyses in this study based on localized regression and a different classification scheme may have captured more details of temporal variations of temperature changes on the TP.

Determining the recent hiatus in global warming is sensitive to the choice of trend length and starting and end dates [Cahill et al., 2015; Ying et al., 2015]. We found that the global mean temperature has resumed the increase since 2010 after the short hiatus during 1998–2009. Moreover, possible mechanisms for the warming hiatus remain unclear. Various mechanisms have been proposed, including aerosol emissions from modest volcanic eruptions [Haywood et al., 2014; Santer et al., 2014], prolonged solar minimum, atmospheric water vapor changes [Solomon et al., 2010], increases in anthropogenic sulphate aerosol emissions [Smith, 2013], and internal decadal variability in the Pacific and/or sea surface temperature over the equatorial oceans [Kosaka and Xie, 2013; Meehl et al., 2013] associated with the strengthening of trade wind [England et al., 2014], as well as the decadal changes in the deeper layers of the Atlantic and the Southern Oceans [Chen and Tung, 2014]. Many of these mechanisms could not explain the temperature patterns on the TP. For example, the cooling on the TP (both regions lower and higher than 4000 m) in response to the Mount Pinatubo eruption in 1991 was quite immediate (Figure 2); therefore, increased volcanic activities could not explain the delayed hiatus at high-elevation regions. Second, surface solar radiation over the TP declined over past three decades [Yang et al., 2014], which was opposite to the observed enhanced warming trends over this region. The teleconnections between large-scale ocean circulations on temperature changes over the TP remain uncertain at various spatial and temporal scales and therefore could not explain the

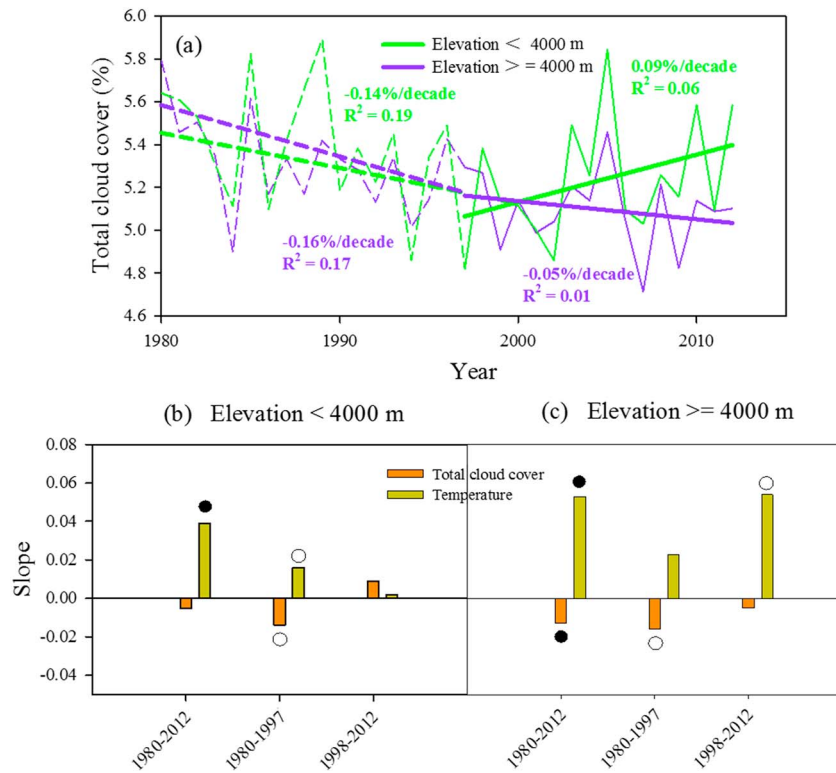


Figure 3. Observed annual mean (a) total cloud cover variations and trends during 1980–2012, and the solid purple and green lines represent the linear fits of total cloud cover for the period 1998–2014, respectively; dashed purple and green lines represent the linear fits of total cloud cover for the period 1980–1997. Regressions of total cloud cover and air temperature during three period, 1980–2012, 1980–1997, and 1998–2012 for regions (b) lower and (c) higher than 4000 m. The open (filled) circles indicate the trend is significant at 90% (95%) confidence level, based on a two-tailed Student’s *t* test. The units of the y axis (slope) in Figures 3b and 3c are %/yr for the total cloud cover and °C/yr for the temperature, respectively.

different temperature trends at high altitudes over this region. On the other hand, the TP has experienced observed changes in land surface processes that affected the surface radiative and energy balance [Yang *et al.*, 2014], such as decreasing albedo due to increasing vegetation [Zhang *et al.*, 2011; Tian *et al.*, 2014] and decreasing snow cover [Ghatak *et al.*, 2014], cloud cover changes, and wind stilling since the beginning of the 1980s [Wu *et al.*, 2015]. These changes could play a role in the delay of warming slowdown over the TP, although the exact physical mechanisms remain uncertain. Here we discussed the possible influence of cloud cover, wind speed, and land surface condition changes on surface radiative and energy balance, which could be partly responsible for the different temperature trends in regions lower and higher 4000 m.

Cloud-radiation feedback has been recognized as an important factor in modulating the atmospheric heat source and surface warming over the TP [Duan and Xiao, 2015; Wu *et al.*, 2015]. We performed correlation analyses between temperature and total cloud (Table S1). We found that over the TP total cloud had a predominantly cooling effect indicated by significant negatively correlation with temperature. Although this relationship was observed consistently for regions both higher and lower than 4000 m (Table S1), their respective temporal trends differed (Figure 3). Total cloud over the TP declined during the period 1980–1998 for regions both below and above 4000 m. However, it started to increase since 1998 for the TP regions below 4000 m but continued to decrease for regions above 4000 m until mid-2000s. This could partly explain the slowdown of the warming rates for regions lower than 4000 m but continued warming for regions above 4000 m. The cloud cover for regions above 4000 m started an increasing trend since the mid-2000s (slope = 0.03, R² = 0.13, 2006–2012), which could lead to the delayed onset of warming hiatus for regions above 4000 m.

The wind speed has been used to explain the temperature changes over the TP [Duan and Xiao, 2015]. The wind speed of the TP has experienced an evidently long-term decline since 1980 [You *et al.*, 2014]. It was

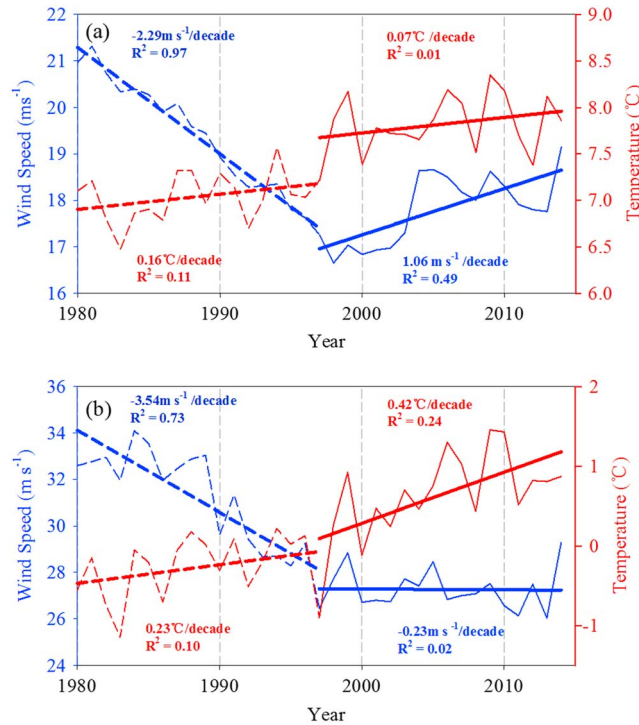


Figure 4. Annual mean temperature and wind speed over the regions (a) lower and (b) higher than 4000 m over the TP from 1980 to 2014. Solid red and blue lines represent the linear fits of annual temperatures for the period 1998–2014, respectively.

2014). For regions higher than 4000 m, wind speed declined at faster rates until 1998 and remained relatively constant since then. This could partly explain the enhanced warming at higher regions and the lack of slowdown of warming rates after the late 1990s ($0.42^{\circ}\text{C}/\text{decade}$ from 1998 to 2014). Since 2006, however, the wind speed for regions higher than 4000 m started to increase ($1.05 \text{ m s}^{-1}/\text{decade}$, $R^2 = 0.09$), and consequently, the temperature showed a cooling trend with a rate of $-0.43^{\circ}\text{C}/\text{decade}$ ($R^2 = 0.10$). Therefore, it is possible that the delay of the warming hiatus at regions above 4000 m was related to the changes in wind speed over these areas. However, it should be noted that the interactions between cloud cover, wind speed, and temperature are complicated. Although *Duan and Xiao* [2015] attribute the enhanced warming over the TP to the weakening of wind speed, *You et al.* [2014] concluded that the evident warming has altered the regional atmospheric circulation, which partly caused the observed decline of wind speed over the TP. In addition, *Duan and Wu* [2006] indicated that the potential feedback mechanism between the air temperature and cloud cover are quite complicated over the TP. All of these studies seem to suggest that the influences of cloud cover and wind speed on temperature variations over the TP remain uncertain, especially for the regions higher than 4000 m covered by snow and glaciers.

In this study, we use the cloud cover and wind speed records from the meteorological stations over the TP for our analysis. It is worth noting that cloud cover and wind speed are often poorly measured due to current measurement techniques, especially under harsh environment such as the TP. However, several previous studies have compared station measurements of wind speed and cloud cover with data from other sources (e.g., satellite and reanalysis data) and found that different datasets show great consistency for the TP region in terms of interannual variability and long-term trends [*Wu et al.*, 2015; *You et al.*, 2014]. Therefore, despite the possible uncertainties in the measurement, we are reasonably confident that the station data for total cloud cover and wind speed are suitable for our analysis and could partly account for the delayed warming hiatus for high elevations over the TP.

Changes in land surface condition could also have played an important role in the temperature over the TP because of the albedo variations driven by changes in snow cover and vegetation [*Shen et al.*, 2015; *Xu et al.*, 2016]. The influence of vegetation changes may be more evident for regions lower than 4000 m. It has been

suggested that due to this wind stilling, the latent heat released to the atmosphere from water vapor condensation subsequently declined, causing more warming for the TP [*Yang et al.*, 2014]. Moreover, the wind stilling could lead to reduced heat transfer beyond the TP, and thus, more energy remains and warming surface air [*Duan and Xiao*, 2015]. Our data also showed a significant negative correlation between annual temperature and wind speed from 1980 to 2014 for both regions higher ($r = -0.56$, $p < 0.01$) and lower than 4000 m ($r = -0.51$, $p < 0.01$) (Table S1). However, detailed analysis revealed different temporal trends for wind speed between regions lower and higher than 4000 m (Figure 4). For regions lower than 4000 m, the declining trend of wind speed was reversed around 1998 and started to increase significantly. This could contribute to the warming slowdown for the lower regions since 1998 ($0.07^{\circ}\text{C}/\text{decade}$ from 1998 to

proposed that the vegetation density over the TP increased over the period 2000–2010, which may have attenuated surface warming by the evaporative cooling effect [Shen *et al.*, 2015], rather than the positive feedback of increased vegetation on temperature through reduced albedo [Tian *et al.*, 2014]. For higher-elevation regions, the increasing deposition of anthropogenic aerosols in snow and glaciers over the past decades may have helped to enhance the warming, and thus delayed the warming hiatus for high elevations [Xu *et al.*, 2009; Jacobi *et al.*, 2015; Wu *et al.*, 2016; Xu *et al.*, 2016]. Xu *et al.* [2016] revealed that the high-altitude warming and snow cover retreat over the TP were mainly attributed to the increase of black carbon aerosols over the past decades. On the other hand, Duo *et al.* [2014] found that despite interannual variations, the snow cover over the TP remains relatively stable from 2001 to 2013 after a period of decreasing before the 2000s. The relatively small change in land surface albedo may have contributed to the slowdown of warming in the region in recent years. However, it is difficult to quantify the influence of these land surface factors on the warming hiatus, particularly at regions above 4000 m. Further research is required to understand the mechanisms between regional land surface processes and temperature change over the TP.

5. Conclusions

In this study, we investigated warming rates of the surface temperature over the TP regions lower and higher than 4000 m. The global mean surface temperature showed an overall warming trend, with a warming reduction during the period 1998–2009. However, a persistent warming reduction was observed in the temperature records for the whole China and the TP regions lower than 4000 m since 1998 and continued after 2009. Meanwhile, the reduction in warming rates for the TP regions higher than 4000 m was delayed to mid-2000s. The rapid warming of the TP has already resulted in the widespread retreat of mountain glaciers, permafrost degradation, and other related environmental deterioration. The delayed onset of the warming hiatus could potentially slow down these changes and thus be beneficial for the water supply and ecological and environmental conditions of the region. However, due to the limited length of temperature series, the likelihood of the delayed hiatus continuing into the future at higher-elevation regions over the TP remains uncertain and needs to be evaluated in more detail. Moreover, the results in the present study may provide an incomplete temperature history by focusing on the middle and eastern TP, because station records from the western TP are short and sparse. Further efforts are needed to conclusively assess the hiatus delay over high elevations at global scale.

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