Time-dependent warming amplification over the Tibetan Plateau during the past few decades

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Abstract
It is reported that surface warming over the Tibetan Plateau (TP) has been faster than the global average, but exactly how much faster remains controversial. This study investigates the time dependency of warming amplification over the TP using CRU_TS4.01 grid dataset during 1961–2016 with a consideration of its consistency with the global average. We find that the magnitude of warming on the TP and its consistency with the global average have been variable. Compared to the global average, the TP warming during 1983–2016 is faster than in the period of 1961–1983, and has a higher consistency with the global average in the period of 1983–2016. The TP warming has a seasonal amplification of 1.1–1.4 times than the global average during 1983–2016, while warming amplification during 1961–1983 is relatively less evident. Generally, the magnitude of warming on the TP is smaller than in the northern high-latitudes, but larger than in the Southern Hemisphere and the Tropics. Based on current scientific understanding, the possible contribution of snow/ice-albedo feedback may have played an important role in warming amplification on the TP since the 1980s.

KEYWORDS
global warming, regional warming amplification, snow/ice-albedo feedback, Tibetan Plateau

INTRODUCTION

Climate warming has occurred widely in the globe in the last decades, and a regional difference of the rate of surface air warming has also been reported (IPCC, 2013). Typically, the Arctic has an evident warming amplification in the last decades (Screen and Simmonds, 2010; Serreze and Barry, 2011), while a relatively smaller rate of surface air warming occurred in the low latitudes (Wang et al., 2018). Moreover, the increase of surface air temperature in the high-elevation regions is larger than their low elevation counterparts (Wang et al., 2014). The Tibetan Plateau (TP) with an average elevation more than 4,000 m above sea level (asl) is the highest and largest plateau in the world, and it is also named the “Third Pole” (Kang et al., 2010; Duan et al., 2015). In recent decades, surface air temperature on the TP has a significant increase (Liu and Chen, 2000; Duan et al., 2006; Kang et al., 2010; Lu and Liu, 2010; Duan and Zhang, 2014; Duan et al., 2015; Kuang and Jiao, 2016; Liu et al., 2017; Xu et al., 2017).
Duan et al. (2006) reported that the TP experienced a striking warming in the last decades and it is a result of the increasing greenhouse gases (GHGs) emissions. Similar to other mountain regions in the world, warming on the TP has an elevation-dependent effect (Liu et al., 2009; Qin et al., 2009; You et al., 2010; Rangwala and Miller, 2012; Pepin et al., 2015). Based on records of meteorological stations, Liu and Chen suggested that warming occurred earlier on the TP than in the Northern Hemisphere and the global average, and they also argued that the rate of warming on the TP exceeds those for the Northern Hemisphere and the same latitudinal zone during 1955–1996 (Liu and Chen, 2000). Based on the analyses of observed records, Duan et al. (2015) and Kuang and Jiao (2016) suggested that the rate of warming on the TP is greater since the 1980s than the earlier period (i.e., 1960s–1980s). Moreover, the TP experienced an accelerated warming during 1998–2008 when the global warming had a hiatus (Duan and Xiao, 2015). These studies indicate that climate warming on the TP varies both linking to temporal changes and existing divergent trends with the global average. However, it is unclear whether there is a time-dependent warming amplification on the TP.

In addition to the temporal characteristics of warming on the TP, seasonal difference has also been reported (Liu and Chen, 2000; Duan et al., 2015; Wang et al., 2018). Seasonal difference of warming on the TP has induced a weakening of temperature seasonality (Duan et al., 2017; 2019a; 2019b). These previous studies provide important knowledge for understanding seasonal warming over the TP, but it is not fully clear that how did the rate of seasonal warming depend on time. In this study, we investigate warming amplification over the TP compared to the other land grid cells of the globe in each season based on considerations of both the time-dependent warming on the TP and its consistency with the global average.

2 DATA AND METHODS

Gridded data of CRU_TS4.01 land surface air temperature at a spatial resolution of 0.5° by 0.5° covering the time period of 1900–2016 (Harris and Jones, 2016) were used in this study. This dataset covers all land areas, excluding the Antarctica. It was constructed using the Climate Anomaly Method based on station data (Harris et al., 2014). Station anomalies were interpolated into 0.5° latitude/longitude grid cells, and combined with an existing climatology to obtain absolute monthly values. To be included in the gridding operations, each station series include enough data for normal to be calculated. Further details can be found in Harris et al. (2014). Considering that this dataset uses records of meteorological stations over the TP which started since the 1960s, all analyses in this study were performed within the period of 1961–2016. The scope of the TP in this study was defined as the area with an elevation more than 2,000 m asl (Figure 1). The TP scope includes 1,028 grid cells, accounting for 10.5% of the global land grid cells of CRU_TS4.01 dataset.

The representativeness of CRU_TS 4.01 dataset over the TP was examined using observations of annual mean temperature from 79 meteorological stations located above 2,000 m asl on the TP (Duan et al., 2015). The comparison of warming rate between station records and corresponding grids shows a significant but not strong enough relationship (Figure 2a). This is mainly due to the relatively large difference of warming rate among the

![Figure 1](image-url)  
**Figure 1** The scope of the TP (red area) with an elevation more than 2,000 m a.s.l. defined in this study. The black dots show the locations of the 79 meteorological stations located within the scope of the TP.
79 stations resulted from the different elevation of station locations (elevation-dependent warming), while such difference is less obvious among the corresponding grids. Specifically, the CRU grid data did not capture successfully the anomalous local warming recorded in a few meteorological stations. For example, the lowest warming rate from the 79 stations is $-0.20^\circ\text{C} \cdot \text{decade}^{-1}$ (station: $37.4^\circ\text{N}, 101.6^\circ\text{E}$), while the warming rate from the corresponding CRU grid is $0.10^\circ\text{C} \cdot \text{decade}^{-1}$ (Figure 2a). The highest warming rate from the 79 stations is $0.67^\circ\text{C} \cdot \text{decade}^{-1}$ (station: $36.8^\circ\text{N}, 93.68^\circ\text{E}$), while the warming rate from the corresponding CRU grid is $0.32^\circ\text{C} \cdot \text{decade}^{-1}$. However, the regional average of annual mean temperature derived from the station and grid records shows a good agreement both for the full analysis period and the two sub-periods (Figure 2b). This indicates that the anomalous local warming shown in a few meteorological stations does not influence the regionally-averaged result largely, and the regionally averaged CRU grid data can represent the regional TP warming reasonably well. In this study, we treat the TP as a whole and not focus on the individual grid, and thus we think that the CRU grid dataset can be used to perform analyses.

Moreover, we notice that a few extremes of station records are smaller than the CRU data before 1990, but are greater after 1990 (Fig. 2b). This induces a little greater magnitude of warming derived from station data than the CRU data (0.07 and 0.12$^\circ\text{C}$ for the early and late periods, respectively). This might be related to the limited number of meteorological stations located on the TP and their uneven spatial distribution. To examine this difference whether is significant, we performed the significance test of variance changes between the two series both for the full period and the two sub-periods (i.e., the early and late periods). The results show that the difference between station records and

**FIGURE 2** (a) Scatter plot based on warming rate of annual mean temperature derived from the 79 stations and the corresponding grids. (b) Comparison between annual mean temperature anomalies (wrt 1981–2010) on the TP derived from observations (79-station average) and CRU grid data

**FIGURE 3** Variation of annual mean temperature anomalies (wrt 1981–2010) over the Tibetan Plateau during 1961–2016 and its consistency with the global average. (a) Annual mean temperature variation over the Tibetan Plateau during 1961–2016. (b) 11-year moving average of annual mean temperature over the TP during 1961–2016. (c) 11-year moving correlation coefficients of annual mean temperature between the TP and the global average
CRU data is not significant for the full period \( (p = .60) \), the early period \( (p = .06) \) and the late period \( (p = .57) \). These results indicate that the CUR data can represent the observations reasonably well in the regional scale. The minor differences between them and the much more accurate representativeness of the CRU grid dataset on the whole TP are expected to be studied in the future with much richer metrological station data.

In the analyses, we first considered temporal-dependent changes in the rate of warming on the TP as well as its consistency with the global average. Then, we investigated the difference of magnitudes of seasonal warming between the TP and the other land grid cells of the globe, and calculated the seasonal warming amplification on the TP. The difference of magnitude of warming between the whole TP and each land grid cell (i.e., the magnitude of warming on the whole TP minus the magnitude of warming in each land grid cell) was calculated in different time periods. The magnitude of warming in individual grid was calculated as the rate of warming multiplies the number of years included in the analysis period. The magnitude of warming of the whole TP was calculated as the rate of warming of the regional temperature series multiplies the numbers of years included in the analysis period.

3 | RESULTS

3.1 | Warming of annual mean temperature over the TP and its consistency with the global average

Trend of annual mean temperature shows that the TP experienced a significant temperature increase since 1961, but the rate of warming is greater since 1983 (0.33°C/10 years) than in the period of 1961–1983 (0.08°C/10 years) (Figure 3a). An accelerated warming over the TP since the 1980s was also found in previous studies using both observations (Duan et al., 2015; Kuang and Jiao, 2016) and tree ring-density reconstruction (Duan and Zhang, 2014). The 11-year smoothing average indicates a similar trend as the warming rate (Figure 3b). Moreover, the consistency of warming of annual mean temperature over the TP with the global average is higher since 1983 than during 1961–1983 (Figure 3c). Based on
these results, warming amplification on the TP compared to the other land grid cells of the globe was investigated in both the whole period (i.e., 1961–2016) and the two sub-periods (i.e., 1961–1983 and 1983–2016).

### 3.2 Difference of the magnitude of warming between the TP and the other land grid cells of the globe

Magnitude of warming over the TP is different from other regions of the world both in the seasons and in different time intervals (Figures 4–6). In the whole period of 1961–2016, the magnitude of warming over the TP is smaller than about two thirds land of the globe in spring and summer (Figure 4). In autumn and winter, the magnitudes of warming over the TP are greater than 36.4 and 58.1% land areas of the globe during 1961–2016, respectively. 1961–1983 and 1961–2016 for spring and summer (Figures 4 and 5). The general feature is that the magnitudes of spring and summer warming over the TP (in 1961–2016 and 1961–1983) are greater than part of South America, Australia and the Tropics, but smaller than part of the northern high-latitudes and most of the Eurasia. Magnitudes of autumn and winter warming over the TP during 1961–1983 are greater than about 60% land of the globe (Figure 5). The positive difference (the magnitude of warming over the TP minus the magnitude of warming in other land cells) mainly occurs in South America, Europe, Greenland, and the negative difference occurs in the central Eurasia and northwest America. In winter, the positive difference occurs in most of the Southern Hemisphere and the Greenland, but the negative difference occurs in Eurasia and most of the North America.

In the period of 1983–2016, the positive difference of magnitudes of warming between the TP and the other land grid cells presents a larger percentage than in both the earlier period (i.e., 1961–1983) and the whole period of 1961–2016, except autumn in 1961–1983 (Figure 6). In spring and summer of the period 1983–2016, the magnitudes of warming on the TP are larger than approximately half of the global land, and their spatial patterns are basically similar (i.e., the positive difference mainly occurs in most of the Southern Hemisphere and part of North America). The magnitude of autumn warming on the TP during 1983–2016 is greater than 40% area of the

![FIGURE 5](image_url) The difference of magnitude of warming between the TP and each land grid cell of the globe (i.e., the magnitude of warming on the whole TP minus the magnitude of warming in each land grid cell) during 1961–1983. (a) Spring, (b) summer, (c) autumn and (d) winter. The grid cells with a negative value indicate that the magnitude of warming on the TP is less than those grid cells, and vice versa. The percentage in right-down corner of each panel indicates how many land grid cells with a magnitude of warming smaller than the TP during 1961–1983. The red line shows the outline of the TP. The unit of color bar is °C.
other global land, which mainly appears in the Southern Hemisphere and some areas of East Asia. The magnitude of warming in winter on the TP during 1983–2016 shows the greatest positive difference with the other part of the global land compared to the other three seasons, which comes up to 63.2%. The feature of warming during 1983–2016 is that the magnitude of warming over the TP is smaller than in the northern high-latitudes in any season. The grid cells with a negative value indicate that the magnitude of warming on the TP is less than those grid cells, and vice versa. The percentage in right-down corner of each panel indicates how many land grid cells with a magnitude of warming smaller than the TP during 1983–2016. The red line shows the outline of the TP. The unit of color bar is °C.

**TABLE 1** Seasonal warming amplification over the TP compared to the northern mid-high latitudes and the global average

|          | NMH_Spr | NMH_Sum | NMH_Aut | NMH_Win | Glo_Spr | Glo_Sum | Glo_Aut | Glo-win |
|----------|---------|---------|---------|---------|---------|---------|---------|---------|
| 1961–1983 | −0.108  | −1.085  | 2.025   | 0.911   | −0.349  | −0.661  | 1.575   | 2.214   |
| 1983–2016 | 0.821   | 0.822   | 0.600   | 1.143   | 1.186   | 1.312   | 1.116   | 1.368   |
| 1961–2016 | 0.633   | 0.647   | 0.710   | 0.883   | 0.918   | 0.878   | 0.965   | 1.371   |

*Note: NMH means the northern mid-high latitudes (30°–89.75°N), Glo means the global average. Spr, Sum, Aut and Win mean spring, summer, autumn and winter, respectively. The unit is times.*

Generally, the magnitude of warming on the TP is smaller than in the northern mid-high latitudes (NMH) in spring and summer in all the three analysis periods (Table 1). In autumn, the magnitude of warming is greater on the TP than in the NMH during 1961–1983, but smaller than in the NMH during 1983–2016 and 1961–2016. In winter, the TP has a warming amplification compared to the NMH during 1983–2016, but slightly smaller than the NMH in the periods of 1961–1983 and 1961–2016. Compared to the global average, the TP has a warming amplification in
winter in all the three analyses periods, and in autumn in the periods of 1961–1983 and 1983–2016. The TP has a warming amplification in all the four seasons about 1.1–1.4 times compared to the global average during 1983–2016.

4 | DISCUSSION

A few driving mechanisms have been reported about warming on the TP in the last decades (Chen et al., 2003; Duan et al., 2006; Duan and Wu, 2006; Rangwala et al., 2009; Lau et al., 2010; Rangwala et al., 2010). Besides the increased GHG concentrations (Chen et al., 2003; Duan et al., 2006), cloud amount changes (Duan and Wu, 2006), snow albedo and surface-based feedbacks (Lau et al., 2010), changes in surface water vapor (Rangwala et al., 2009) and atmospheric aerosol (Rangwala et al., 2010) have also been suggested as important factors contributing to the recent surface air warming on the TP. In this study, we found that the rate of surface air warming on the TP is greater during 1983–2016 than in the period of 1961–1983 and the TP has a much more evident warming amplification relative to the global average in the period of 1983–2016 than in the period of 1961–1983. This is concurrent with the accelerated retreat of glacier fronts on the TP since the 1980s (Duan et al., 2010). The accelerated retreat of glacier fronts has induced a reduction in glacier areas over the TP. Reduction in glacier area can reduce the surface albedo with a subsequent increase in absorbed solar radiation, leading to an increase in the surface air temperature. Such snow/ice-albedo feedback mechanism has been simulated successfully in the future changes of surface air temperature on the TP and the surrounding high elevation regions (Lau et al., 2010). Moreover, such feedback mechanism primarily occurs during spring and summer (Giorgi et al., 1997; Lau et al., 2010). Our results show that the largest positive difference of TP warming amplification between the period of 1983 and 2016 and the other periods (i.e., 1961–1983 and 1961–2016) also occurs in spring and summer (Figure 7). Therefore, we speculate that the rapid reduction in glacier area on the TP since the 1980s possibly contributed to the warming amplification of the TP. Further model simulations are needed to validate this speculation in the future.

5 | CONCLUSIONS

In this study, we analyzed the magnitude of seasonal warming on the TP during 1961–2016 using the gridded dataset of CRU_TS4.01. Comparisons between the CRU_TS4.01 data and meteorological station records show a good coherence between their regional series, indicating a good representativeness of the gridded dataset on the TP. Variation of annual mean temperature on the TP has a higher consistency with the global average since 1983 than in the earlier period (i.e., 1961–1983), and surface air warming on the TP is also greater in the period of 1983–2016 than in the period of 1961–1983. Compared to the other land grid cells of the globe, the TP warming has a seasonal amplification (1.1–1.4 times compared to the global average) during 1983–2016, while such a warming amplification during 1961–1983 is relatively less evident. Generally, the magnitude of warming on the TP is smaller than in the northern high-latitudes, but greater than in the Southern Hemisphere and the Tropics. Based on current scientific understanding, our results emphasize the possible contribution of snow/ice feedback on warming amplification over the TP since the 1980s.

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CONFLICT OF INTEREST
The authors declare no conflicts of interest.

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