

Warming over the Tibetan Plateau in the last 55 years based on area-weighted average temperature

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Abstract The Tibetan Plateau (TP), the “Third Pole” of the world, has experienced significant warming over the past several decades. Several studies have investigated the temperature change in this region, but data scarcity and the uneven distribution of meteorological stations have resulted in uncertainty concerning the warming trend. Here, we calculated a new average temperature indicator (area-weighted average temperature, T_{awa}) to quantify the warming of the TP during the period 1961–2015 and compared it with the traditionally used arithmetic average temperature (T_{aa}). The result shows that T_{awa} is

less sensitive to the irregular distribution and number of stations than T_{aa} , indicating that it can produce more reliable information on temperature change. Based on annual mean T_{awa} , the TP showed a warming rate of 0.35 °C/decade in the recent 55 years, which is higher than the corresponding rate calculated using T_{aa} (0.30 °C/decade). Seasonal warming rates of T_{awa} over the TP were also analyzed. Winter had the highest warming rate (0.44 °C/decade), followed by autumn, spring, and summer (0.38, 0.30, and 0.30 °C/decade, respectively). For comparison, the seasonal warming rates of T_{aa} gave different trends (0.43, 0.30, 0.25, and 0.25 °C/decade for winter, autumn, summer, and spring, respectively). The use of T_{awa} indicated stronger warming trends in the spring, summer, and fall seasons (but not in winter), which is important for the impact of the climate warming on vegetation growth in this region. Both T_{awa} and T_{aa} showed more prominent warming at higher elevations during 1961–2015, indicating an elevation dependence of the warming trend over the TP. Since 2001, the warming rates calculated with T_{awa} were lower than those for the previous four decades across all elevation zones, suggesting a continuing but decelerating warming tendency since the turn of the twenty-first century. This tendency was not shown in calculations using T_{aa} , which suggested faster warming since 2001. The T_{awa} , which is less sensitive to the number and spatial distribution of meteorological stations, provides an improved understanding of temperature changes on the TP.

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Introduction

As the highest and most extensive plateau in the world, the Tibetan Plateau (TP) is considered as the “Third Pole” (Qiu

2008). It exerts a profound influence on the regional and global climate through thermal and dynamic forcing mechanisms (Duan and Wu 2005; Yanai et al. 1992) and is one of the Earth's most sensitive areas for climate change (Feng et al. 1998; Liu et al. 2009). In recent decades, the TP experienced significant warming, with a variety of consequences including permafrost degradation, glacier shrinkage, and vegetation phenology change (Wu et al. 2013; Yao et al. 2012; Zhang et al. 2013). To improve our understanding and better evaluate the effect of climate warming on the ecosystem health of the plateau, it is important to quantify the rate and magnitude of warming (Tao et al. 2014).

Many studies have been carried out to quantify the temperature change in this region. Temperature data reconstructed from tree rings have been employed to study long-term climate trends, especially in pre-instrument period. Some such studies have reported no obvious warming in the recent one or two centuries (He et al. 2014; Yang et al. 2010; Xing et al. 2014), while other studies have reported significant warming trends (Chen et al. 2012; Duan et al. 2017; Duan and Zhang 2014; Shi et al. 2015; Zhu et al. 2008). Despite the resulting uncertainty concerning the long-term warming trend, most of these studies showed apparent warming in recent decades. In the 1950s, a lot of meteorological stations were put into operation over the plateau, providing more detailed information for climate change studies. Based on these data, studies have documented warming rates of annual mean temperature since the middle of the twentieth century varying from 0.16 to 0.50 °C/decade (Cai et al. 2017; Duan et al. 2015; Guo and Wang 2012; Kang et al. 2010; Lu and Liu 2010; Rangwala et al. 2009; Song et al. 2014; Wang et al. 2008; You et al. 2015). Recently, it has been suggested that the global warming featured a stagnation from 1999 to 2008 (Knight et al. 2009). Whether this warming “hiatus” existed over the TP has thus attracted attention, but meteorological elevations demonstrate that, in fact, the TP exhibited a persistent and strengthening warming since the late 1990s (Duan and Xiao 2015; Yan and Liu 2014), indicating no warming hiatus in this region. Warming trends may be elevation dependent, and most studies show that high elevations over the TP have been exhibiting more rapid warming in recent decades (Liu and Chen 2000; Liu et al. 2009; Pepin et al. 2015; Tao et al. 2014; Yan and Liu 2014), though not all studies demonstrate such elevation dependence (You et al. 2008, 2010b). Variation in the specific warming trend reported by each study can be attributed to differences in the period and meteorological datasets used. Meteorological stations are sparsely and unevenly distributed over the TP and cover a wide range of elevations, so different combinations of meteorological stations are likely to have experienced different temperature trends. The influence of station selection results in inconsistent findings concerning climate change on the TP.

To reduce the influence of selections of meteorological stations and achieve a more robust assessment of the warming

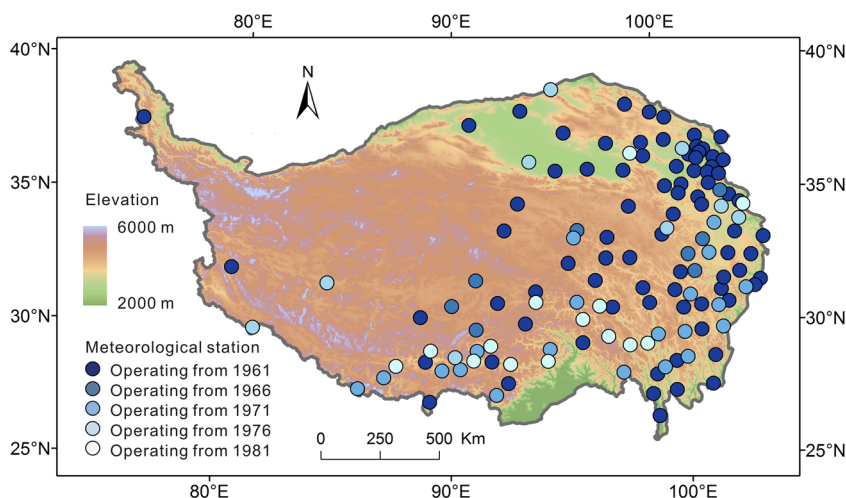
trend, a new temperature index, the area-weighted average temperature (T_{awa}), which considers the extent of the area represented by each meteorological station, was introduced in this paper. The traditional simple arithmetic average temperature (T_{aa}), which is widely used in temperature change studies, was also employed to compare with T_{awa} . Based on the temperature data from meteorological stations, T_{awa} and T_{aa} were calculated to quantify the warming trend and its dependence on elevation over the TP during the period 1961–2015. The warming trends before and after 2001 were also compared to shed further light on the question of a “warming hiatus” on this plateau since the turn of the twenty-first century.

Temperature data

Daily mean surface air temperature data were provided by the China Meteorological Administration, which have been homogenized to reduce non-climatic errors (Li et al. 2009). While this dataset contains some observations from the 1950s, most meteorological stations over the TP were not consistently operational until the 1960s so the time period from 1961 to 2015 was selected for this study to avoid excessive data scarcity. The daily temperature data from this period still contained some missing values, which required additional pre-processing to produce consistent and robust data on mean monthly and annual temperature. For this processing, stations with more than seven missing values in any given month were removed completely from the dataset, leaving 81 stations with near-complete daily data during the entire period (dark blue dots in Fig. 1). Among these 81 stations, 8 stations are located below 2000 m, 73 stations are above 2000 m, 43 stations are above 3000 m, and 12 stations are above 4000 m. Figure 1 shows that the spatial distribution of these stations is very uneven, with most stations located in the more populated eastern part of the TP and very few stations located in the western TP. Monthly mean surface air temperature was calculated for the 81 stations for the 1961–2015 period, and annual means were then calculated as the mean of these monthly means. In addition to these 81 stations, other stations with complete data for shorter periods also exist (additional dots in Fig. 1). As meteorological stations have been established on the TP, the total number of stations with near-daily data coverage has increased through time. To investigate the influence of the spatial distribution and the number of stations on the calculated average temperature over the TP, the complete set of stations with near-daily data for the periods of 1966–2015, 1971–2015, 1976–2015, and 1981–2015 was employed respectively, and their data were processed as outlined above.

Characterized by a large area (~2.5 million km²) and complex terrain with altitudes ranging from ~1500 to more than 8000 m, the TP exhibits high spatial temperature variability. The average value and trend of annual mean temperature for

Fig. 1 Spatial distributions of the meteorological stations on the TP. The stations that are valid during five different periods (1961–2015, 1966–2015, 1971–2015, 1976–2015, and 1981–2015) are represented by circles in different blue colors. The background color ramp from green to brown and lavender shows the elevation



each meteorological station during 1961–2015 are presented in Fig. 2. It can be seen that both the average temperatures and the warming trends of stations exhibit spatial patterns, indicating broad regional variability. The average annual temperature generally decreases from the southeast to the northwest. Stations located in the southeast have average temperatures generally 6 °C or higher, while stations in the middle and northwest have relatively lower temperatures (<3 °C). The warming trend on the TP was also not uniform but showed an overall spatial tendency of increasing warming from the southeast to the northwest. The slowest warming occurred in the southeastern TP, at generally below 0.2 °C/decade. The central and western stations on the TP have experienced faster warming that ranges from 0.2 to 0.5 °C/decade, and three stations have warming rates greater than 0.5 °C/decade. In addition, though the temperature and warming trends show general southeast-to-northwest tendencies, several stations do not follow these broad trends.

However, there are relatively few meteorological stations scattered over this large area. To examine the areal representativeness of these meteorological stations, Thiessen polygons were generated to reflect the contributing area of each station (Fig. 3). The temperature and warming rate within each polygon were then assumed to be equal to those of the station in it. From Fig. 3, it can be seen that different meteorological stations have very different contributing areas. To describe the distribution of contributing areas and its relation to the temperatures measured at each station, the contributing area, 55-year average temperature and warming rate for each meteorological station were calculated and compared (Fig. 4). It is clear that the stations with large contributing areas generally show lower average temperatures and higher warming rates. As the density of meteorological stations is lowest in remote high-altitude regions, the spatial representativeness analysis showed that the stations representing large areas had relatively low temperatures and high warming rates. As a result, simple arithmetic averaging of the temperature measurements of

these stations to represent the overall temperature characters of the TP will lead to underestimation of the warming trend.

Method

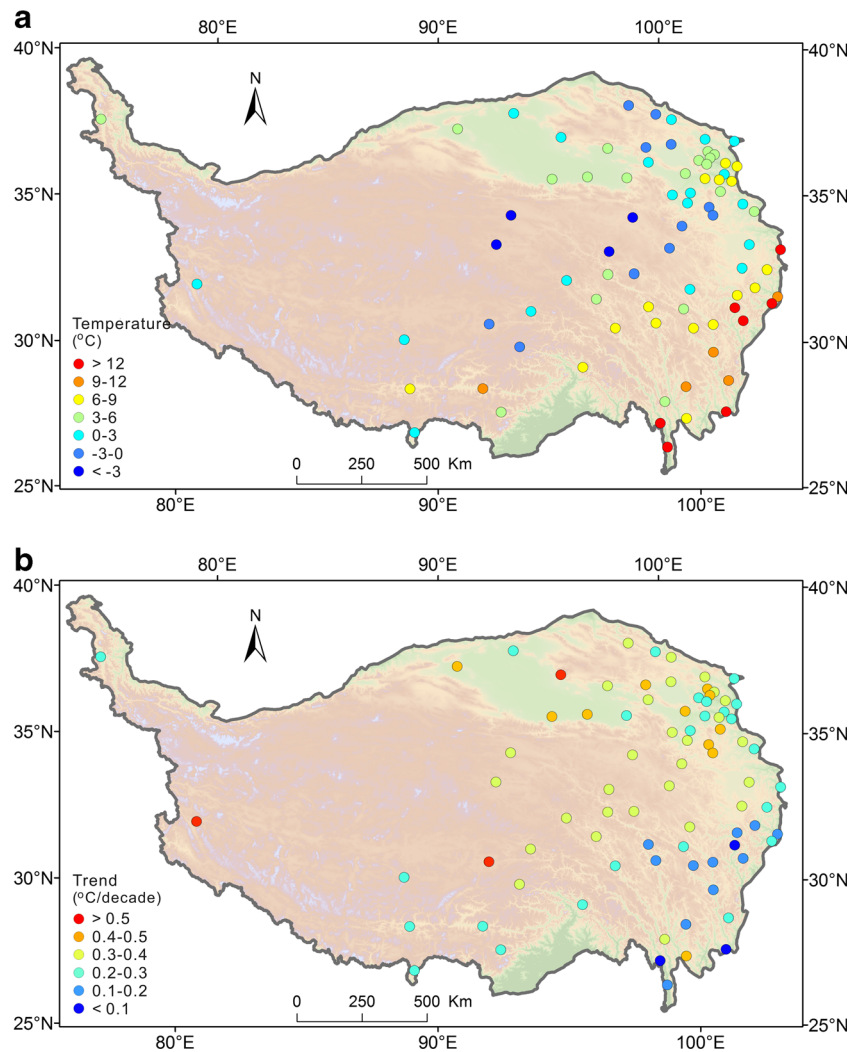
Traditionally, the arithmetic average temperature (T_{aa}) was used to depict the temperature variations. Considering the uneven distributions of meteorological stations on the TP, calculating climatological statistics for the area using arithmetic averaging will bias the results toward areas with a high density of stations, i.e., the extreme eastern part of the TP. This area, with its lower altitudes and northeasterly position, is not representative of the TP as a whole. Simply averaging the temperature of these stations may lead to a biased representation of the overall temperature and warming trend over TP, while area-weighted rather than arithmetic averaging will produce statistics that are more representative for the TP as a whole.

Based on this consideration, the area-weighted average temperature (T_{awa}) was calculated to quantify the warming of the TP during the period 1961–2015 and also compare with the traditionally used T_{aa} . T_{awa} was calculated with a Thiessen-based approach (Trombulak and Wolfson 2004). First, the Thiessen polygon network was generated based on the locations of the meteorological stations and the boundary of the TP. The area of each Thiessen polygon was calculated, and T_{awa} was then calculated as a weighted average, using the area of each polygon to weight the area represented by each meteorological station, using Eq. 1

$$T_{awa} = \frac{\sum_{i=1}^N T_i \cdot a_i}{\sum_{i=1}^N a_i} \quad (1)$$

where T_{awa} is the area-weighted average temperature, T_i is the temperature of a particular meteorological station i , N is the

Fig. 2 Spatial heterogeneity of temperature over the TP during 1961–2015. **a** The multi-year average temperature of meteorological stations. **b** The warming rates of meteorological stations, calculated from annual mean temperature with least squares fitting



number of stations over the TP, and a_i is the area of Thiessen polygon of station i .

The annual and seasonal warming trends were then estimated using simple linear regression

$$T = a \times yr + b \tag{2}$$

where T refers to the temperature or temperature anomaly, yr is the time (in years), a is the slope which represents the rate of

Fig. 3 The areas represented by meteorological stations over the TP. The Thiessen polygons represent the contributing areas for meteorological stations, which were generated based on the locations of stations. Color indicates the size of the contributing area, from light blue to dark blue

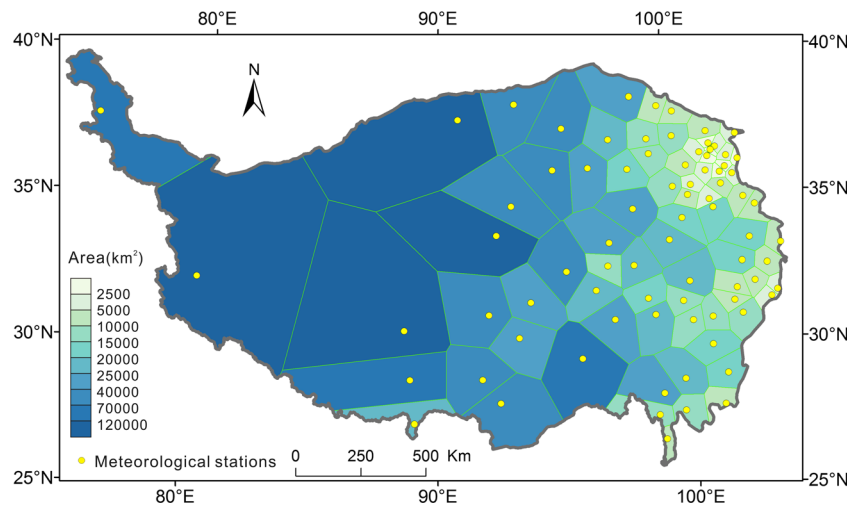
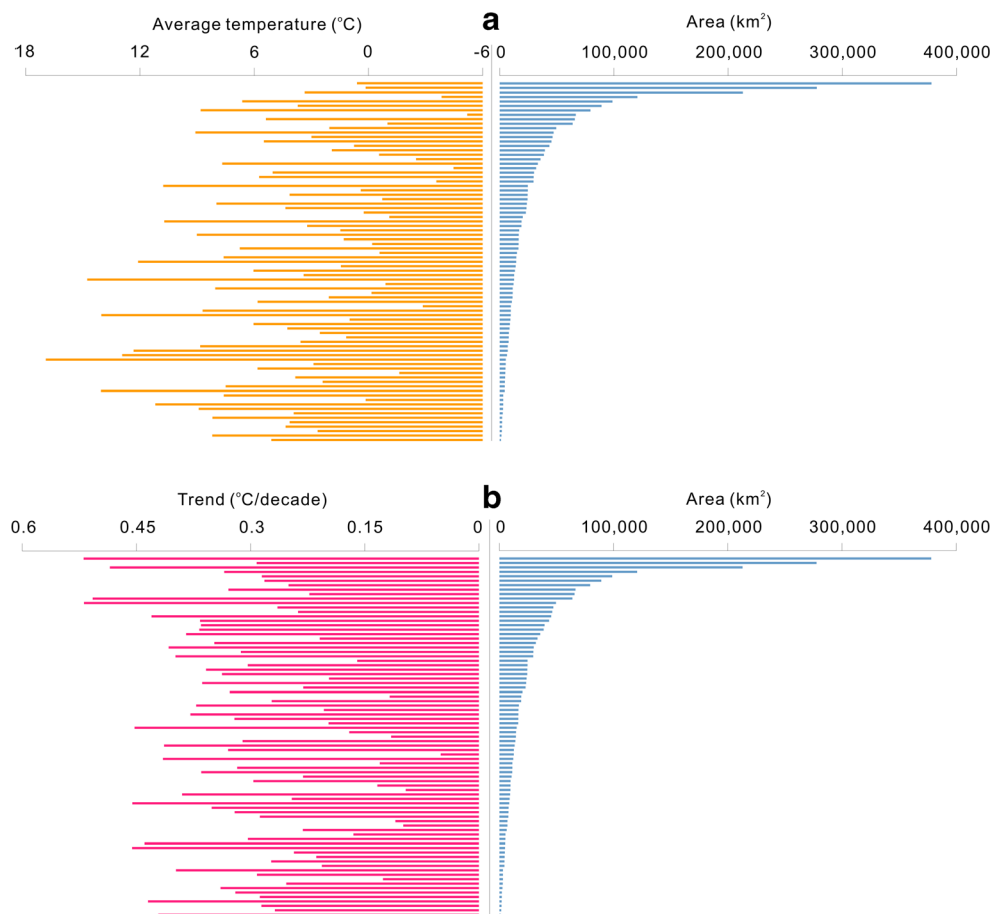


Fig. 4 Temperature characteristics vs. contributing area for meteorological stations in the TP. **a** The comparison between the multi-year average temperature and the contributing area of meteorological stations. **b** The comparison between the warming trend and the contributing area of meteorological stations. The orange bars indicate the multi-year average temperature of stations during 1961–2015, the red bars indicate the warming trend of stations during 1961–2015, and the blue bars show the contributing area of the corresponding stations



temperature change, and b is the intercept. The statistical significance of the trend was evaluated with Student's t test.

Results

To assess the influence of using T_{aa} and T_{awa} , respectively, over the TP, five different periods (1961–2015, 1966–2015, 1971–2015, 1976–2015, and 1981–2015) were considered because they had a different number of stations for which data are available (Fig. 1). At the beginning of the 1960s, most meteorological stations were installed in the eastern and central parts of the TP, especially in the northeastern TP. In the following two decades, new stations were installed mainly in the southern and southeastern parts. Therefore, the numbers and spatial distributions of stations varied in different periods, which provide a good case to assess the sensitivity of T_{aa} and T_{awa} to meteorological stations. For each period, the available meteorological data were used to calculate the two indicators of average temperature. Figure 5 shows comparisons between the temporal variations of T_{aa} and T_{awa} over the TP for these five periods. For T_{aa} , the temperature change is remarkably inconsistent due to the different numbers and spatial distributions of stations used in the calculations for each period.

However, this inconsistency is greatly reduced by using T_{awa} instead, indicating that T_{awa} is less sensitive to the number and spatial distribution of meteorological stations. In addition, T_{awa} produces an average annual temperature for the TP that is nearly 2 °C lower than T_{aa} , as the underrepresentation of areas at high altitude in the dataset is compensated by the area-weighted averaging.

The temperature anomaly of the TP during 1961–2015 was calculated based on T_{awa} and compared with that based on T_{aa} (Fig. 6). The trends of T_{aa} and T_{awa} anomalies show similar tendencies: The overall temperature of the TP increased from 1960 to the mid-1970s, followed by a relatively stable period until the mid-1980s, after which the temperature increased again. Despite the similarity in the general trend produced by these two calculations of the temperature anomaly, there are also noticeable differences. Generally, the T_{awa} anomaly was lower than the T_{aa} anomaly during the 1960s and the 1970s and higher in the 2000s. This results in a relatively stronger warming trend depicted by the T_{awa} anomaly compared to the traditionally used T_{aa} anomaly. For the whole period (1961–2015), the T_{awa} warming rate was 0.35 °C/decade while the T_{aa} warming rate was 0.30 °C/decade (both $p < 0.01$).

The seasonal temperature change on the TP, which has a substantial influence on vegetation phenology, was also

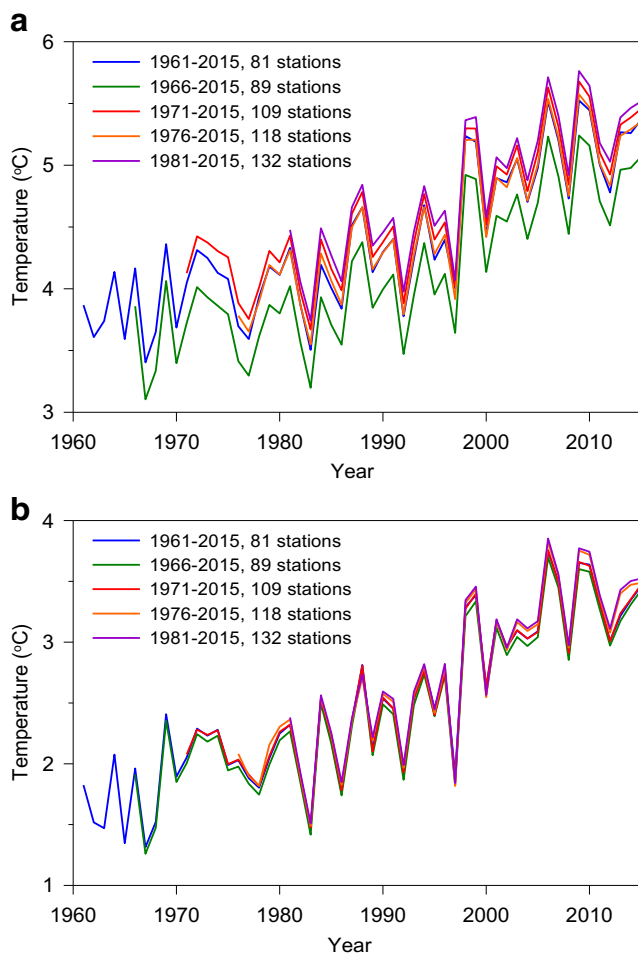


Fig. 5 Influence of selection of meteorological stations on the annual average temperatures calculated using T_{aa} and T_{awa} . Annual average temperatures of the TP based on the different numbers and spatial distributions of meteorological stations. For five different periods (1961–2015, 1966–2015, 1971–2015, 1976–2015, and 1981–2015), data are available from the different numbers of meteorological stations. For each period, the annual T_{aa} (a) and T_{awa} (b) were calculated and compared to assess the relative sensitivity of the two temperature indicators to the number and distribution of stations used for their calculation. Note the difference in the absolute values of the calculated average temperatures

examined. The warming trends for each of the four seasons, as calculated using the T_{aa} and T_{awa} anomalies, are compared in Fig. 7. Warming occurred in all seasons but varied notably between seasons. According to the warming rates calculated by the T_{aa} anomaly, winter exhibited the highest warming rate of 0.43 °C/decade, followed by autumn (0.30 °C/decade), summer (0.25 °C/decade), and spring (0.22 °C/decade, all trends $p < 0.01$). The winter warming rate was thus much greater than the other three seasons, almost double those of spring and summer, which is consistent with previous studies (Wang et al. 2014; You et al. 2010a). However, the warming rates calculated by the T_{awa} anomaly showed different tendencies. Winter still had the greatest warming rate (0.44 °C/decade), followed by autumn (0.38 °C/decade) and spring and

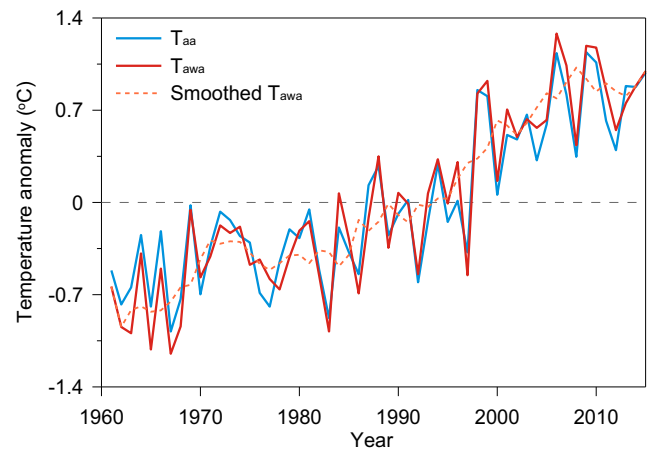


Fig. 6 Annual temperature anomaly time series (relative to the 1961–2015 baseline) calculated by T_{aa} and T_{awa} for the TP during 1961–2015. The solid blue curve is the T_{aa} anomaly, and the solid red curve is the T_{awa} anomaly. The dotted orange curve is the 5-year smoothed T_{awa} anomaly

summer (0.30 °C/decade for both, all trends $p < 0.01$), showing reduced season-to-season differences. Calculations using T_{awa} thus suggest greater temperature increases than previously indicated by T_{aa} calculations for spring (36%), summer (20%), and fall (26%). Considering that the alpine vegetation growth on the TP is highly sensitive to spring and summer temperatures (Liang et al. 2016), this finding may improve our understanding of the response of vegetation to climate change on the TP.

The elevation dependency of warming over the TP was also assessed using T_{aa} and T_{awa} . Figure 8 depicts the warming trends calculated with T_{aa} and T_{awa} for 500-m elevation ranges from 1961 to 2015. In general, both T_{aa} and T_{awa} showed more prominent warming at higher elevations than at lower elevations. This confirmed the results of other studies based on T_{aa} (Liu et al. 2009; Tao et al. 2014; Yan and Liu 2014), which

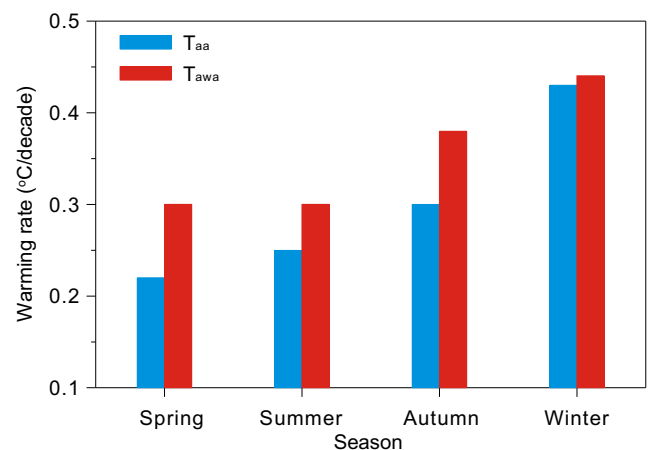


Fig. 7 Seasonal warming rates based on T_{aa} (blue bars) and T_{awa} (red bars) over the TP during 1961–2015. Spring includes March, April, and May; summer includes June, July, and August; autumn includes September, October, and November; and winter includes December, January, and February

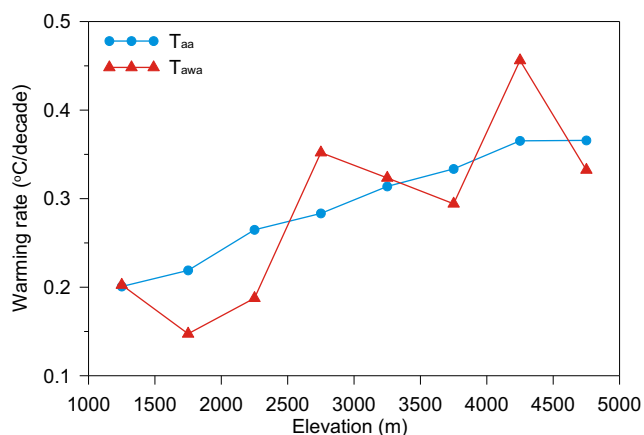


Fig. 8 Variations of warming rates of annual T_{aa} and T_{awa} with elevation zones from 1961 to 2015. The *blue curve* is the warming trend of T_{aa} , and the *red curve* is the warming trend of T_{awa}

also suggested the elevation dependency of warming over the TP since the 1960s. Moreover, T_{awa} showed more distinct elevation dependency than T_{aa} , accompanied with remarkable fluctuation.

To explore the warming hiatus and its dependence on elevation over the TP, warming rates calculated with T_{aa} and T_{awa} above 2000, 3000, and 4000 m during the period of 1961–2000 and 2001–2015 were calculated and compared (Fig. 9). The T_{aa} warming rates in all three elevation zones since 2001 (0.26, 0.29, and 0.30 °C/decade, respectively) were higher than those before 2000 (0.22, 0.22, and 0.24 °C/decade, respectively), which is consistent with Yan and Liu (2014). However, the T_{awa} warming rates in these three elevation zones since 2001 (0.20, 0.21, and 0.17 °C/decade, respectively) were lower than those before 2000 (0.29, 0.29, and 0.32 °C/decade, respectively), suggesting that the TP exhibited continued but relatively slower warming since 2001, compared to the previous period. Moreover, the high-elevation areas did not experience faster warming than low-elevation areas in the period of 2001–2015, which is different from the previous period (1961–2000). The different trends described by T_{aa} and T_{awa} are caused by the presence of a few remote stations at high elevations, which have experienced slower warming rates since 2001. This includes stations no. 55228 and no. 55472, which have the two largest contributing areas on the TP, as shown in Fig. 3. These remote stations are heavily weighted in the T_{awa} calculation, resulting in lower T_{awa} values during 2001–2015 and also at higher elevations during this period. It should also be noted that all warming trends during the period of 1961–2000 were significant at the $p < 0.01$ level, but all except one of those during the period of 2001–2015 showed no significant effect ($p > 0.1$) due to the relatively short period since 2001. Temporally changing warming rates and their variability across elevation remain an issue to be further explored. In recent years, an increasing amount of satellite data with good spatial and temporal

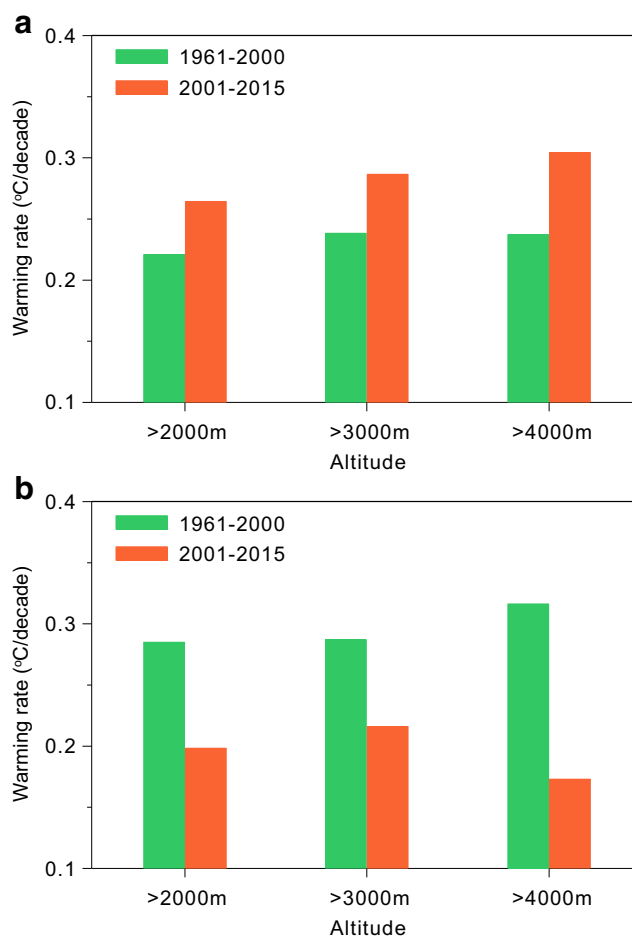


Fig. 9 Annual warming rates of T_{aa} (a) and T_{awa} (b) above 2000, 3000, and 4000 m over the TP during the periods of 1961–2000 and 2001–2015, respectively. The *green bar* indicates the warming rates during 1961–2000, and the *orange bar* indicates the warming rates during 2001–2015

resolution has become available to observe temperature in areas not covered by meteorological stations. This constitutes a new data source that can be helpful in the analyses of twenty-first century warming trends on the TP.

Conclusions

In this paper, the warming trend on the TP during 1961–2015 was examined. Considering the sparsely and unevenly distributed meteorological stations on the TP, a new area-weighted average temperature, T_{awa} , indicator was compared with the traditionally used arithmetic average temperature, T_{aa} . T_{awa} was less sensitive to the irregular distribution and varying numbers of stations than T_{aa} , suggesting its use may provide more robust information on temperature changes across the TP.

According to calculations based on T_{awa} , the TP experienced an annual warming rate of 0.35 °C/decade in the recent 55 years, which was higher than that indicated by calculations

based on T_{aa} (0.30 °C/decade). T_{awa} also indicated much higher warming rates in spring, summer, and fall, suggesting that the vegetation on the TP experienced more rapid warming during the growing season than indicated by previous studies. Elevation-dependent warming over the TP was demonstrated by both T_{aa} and T_{awa} in the period of 1961–2015, and T_{awa} indicated more distinct elevation dependency. As for the warming trend before and after 2001, T_{aa} and T_{awa} gave different patterns. T_{awa} indicated a persistent but slowing warming trend since the turn of the twenty-first century without an obvious elevation dependency, while T_{aa} showed a faster warming and stronger elevation dependency in the same period. The warming trend on the TP may be inaccurately estimated by using a simple arithmetic average, as has been done in previous studies. The use of area-weighted averaging rather than arithmetic averaging of temperature measurements provides an improved understanding of long-term temperature changes on the TP. This is likely to also be the case for other regions that have sparsely and unevenly distributed meteorological stations in an area with high spatial climate variability.

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