

# The significant climate warming in the northern Tibetan Plateau and its possible causes

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**ABSTRACT:** We have identified the northern Tibetan Plateau as having experienced the most significant warming of any region in the entire plateau domain since 1961. Warming in the northern plateau violates the previously suggested elevation dependency of warming trends. Further analysis shows that the increase in surface air temperature in summer has played a primary role in the rapid increase of the annual mean air temperature in the northern Tibetan Plateau since the mid-1980s. In addition, the summer air temperature is correlated with ozone in the region, a result which is statistically significant. This correlation seems to have a relationship with solar radiation and ozone depletion ratios. Further discussion shows that the most significant warming in the northern plateau may be related to radiative and dynamical heating that are results of pronounced stratospheric ozone depletion. Copyright © 2011 Royal Meteorological Society

KEY WORDS Tibetan Plateau; climate warming; ozone depletion

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## 1. Introduction

The global climate has become warmer over the last century and is projected to undergo further warming during the next 100 years (e.g., Jones and Briffa, 1992; Meehl *et al.*, 2007). The observed warming has not been globally uniform, and regional differences in the surface air temperature changes are pronounced. For example, temperatures have increased more at northern high latitudes, and faster warming has occurred over land regions than over oceans (Houghton *et al.*, 1996; Meehl *et al.*, 2007). In the Northern Hemisphere, high-altitude areas seem to be especially susceptible and vulnerable to climate change (Messerli and Ives, 1997; Hansen *et al.*, 2010). The responses of climatic conditions and ecosystems in these regions to global climate change make its detection possible in the early stages (Liu *et al.*, 2009). Studying climate change and its causes in these regions can be helpful for the early detection of global climate change.

The Tibetan Plateau is nicknamed the ‘third pole’ of the Earth; it is well known for its profound influences on both regional and global climate through thermal and dynamical forcings (e.g., Ye and Gao, 1979; Manabe and Broccoli, 1990; Yanai *et al.*, 1992; Yanai and Wu, 2006). A large portion of the plateau has experienced a striking warming of the climate since the mid-1950s.

The average warming rate was approximately 0.16 °C per decade for the annual mean temperature during the period from 1955 to 1996 (Liu and Chen, 2000; You *et al.*, 2008). This warming rate was larger than that for the Northern Hemisphere and the corresponding latitudinal zone of the plateau (Jones *et al.*, 1986; Jones and Briffa, 1992). Warming of the plateau has already resulted in the widespread retreat of mountain glaciers, permafrost degradation, and associated environmental deterioration (Wang *et al.*, 2000; Yao *et al.*, 2004; Cheng and Wu, 2007).

The recent climate warming over the Tibetan Plateau has been primarily caused by increases in anthropogenic greenhouse-gas emissions. These increased emissions have led to increases in the cloud amount at lower elevations and to decreases in the cloud amount at higher elevations over the eastern Tibetan Plateau during the winter half of the year. The changes in cloud cover result in changes to the radiation fluxes of the region, which contribute in some manner to the warming in both areas (Chen *et al.*, 2003; Duan and Wu, 2006). Rangwala *et al.* (2009) found that the increase in surface water vapour (and the related increase in downward long-wave radiation) appeared to be part of the reason for the prominent winter warming trend observed over the plateau during the latter half of the twentieth century. The elevation dependency of climate warming trends over the Tibetan Plateau has been reported (Liu and Chen, 2000; Yao *et al.*, 2000; Qin *et al.*, 2009), and this relationship is most likely due to the combined effects of cloud-radiation and snow-albedo feedbacks (Liu *et al.*, 2009).

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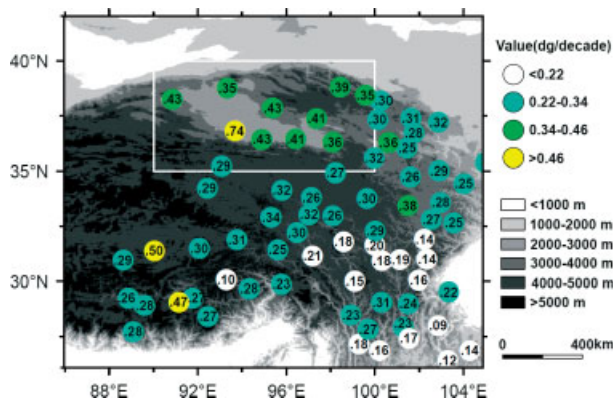


Figure 1. Distribution of the 72 meteorological stations (circles) in the eastern and central Tibetan Plateau. The labels within the circles represent the warming rate during the period from 1961 to 2007. The circles in the white rectangle represent the stations situated in the northern Tibetan Plateau in this study.

In this study, we identified stations in the northern plateau at which the data failed to follow the suggested elevation dependency. We further analysed the possible causes for the climate warming of these northern plateau stations. In Section 2, a brief description of data and methods is provided. Trends in air temperature over the Tibetan Plateau are addressed in Section 3. Possible causes of the most significant warming in the northern Tibetan Plateau are discussed in Section 4, while the main conclusions are presented in Section 5.

## 2. Data and methods

The monthly mean surface air temperatures for 72 meteorological stations were provided by the Data and Information Center, China Meteorological Administration. The distribution of the stations is uneven, and most of the stations are situated in the eastern and central Tibetan Plateau (Figure 1). The 72 stations are all at  $>2000$  m above sea level, with altitudes ranging from 2110.5 to 4700 m. Of the 72 stations, 64 had continuous records covering the period from 1961 to 2007. The remaining eight stations had a few missing records during this period. These missing values were replaced with estimated values calculated using simple linear interpolation between the two nearest known values. A basic logic test and a spatial consistency test were performed as part of data quality control. Data homogeneity was also assessed using the recently developed multiple analysis of series for homogenization method (Li and Yan, 2009) and the Easterling–Peterson techniques (Easterling and Peterson, 1995; Li *et al.*, 2004).

The daily records of surface radiation flux at Golmud ( $36.4^{\circ}\text{N}$ ,  $94.9^{\circ}\text{E}$ , 3501 m) were also provided by the Data and Information Center, China Meteorological Administration. Continuous observations of surface solar radiation flux were available during the period from 1961 to 2007 only at the Golmud station for the northern Tibetan Plateau. A basic logic test and a spatial

consistency test were also performed as part of data quality control.

Monthly column ozone data were used in this study and were constructed by merging individual total ozone mapping spectrometers (TOMS) and solar backscatter ultraviolet (SBUV and SBUV/2) satellite data sets. The combined data set provided nearly continuous global coverage with a resolution of  $5^{\circ}$  in latitude by  $10^{\circ}$  in longitude. The data set covered the period from 1979 to 2007 and was more continuous, with few gaps. This data set is available at the following Web site: <http://code916.gsfc.nasa.gov/Dataservices/merged>. The warming rate was calculated using ordinary least-squares regression by deriving the slope of the linear fit. The significance of trends was assessed using the method of Santer *et al.* (2000), which takes temporal autocorrelation effects into account.

## 3. Trends in air temperature over the Tibetan Plateau

The location and the warming rate of each station are given in Figure 1. All stations experienced warming during the period from 1961 to 2007. The magnitude of warming ranged from  $0.09^{\circ}\text{C}$  per decade to  $0.74^{\circ}\text{C}$  per decade, with an average of  $0.28^{\circ}\text{C}$  per decade for the entire period. The air temperature increase was most significant in the northern part of the plateau but also was significant in the northeastern, central, and northwestern parts of the plateau. In comparison, the southeastern part of the plateau experienced weaker warming. As previous works have reported (e.g., Liu and Chen, 2000; Yao *et al.*, 2000; Qin *et al.*, 2009), air-temperature warming trends have tended to increase with elevation over the Tibetan Plateau. However, the stations in the northern plateau showed the most significant warming despite their relatively lower elevations (Figure 1). The elevations of these stations ranged from 2767 to 3367 m (with an average of 3011 m), which was relatively lower than the average 4000 m for the entire plateau. Apparently, these northern stations violated the suggested elevation dependency of the climate-warming trends. For the 72 stations, their increased temperatures showed a statistically insignificant correlation with elevation: the correlation coefficient was 0.22 and did not exceed a significance level of 95%. However, excluding the 10 northernmost stations, the temperatures of the remaining stations had a statistically significant correlation with elevation. Their correlation coefficient reached 0.50 and exceeded a significance level of 99% (Figure 2). These results indicate that the northern stations had a strong influence on whether elevation dependency of the climate warming trends was identified or not in the whole data set.

Figure 3(a)–(c) shows the trends in mean air temperature for the northern stations during the period from 1961 to 2007. The trend in annual mean temperature was significantly positive trend during the period from

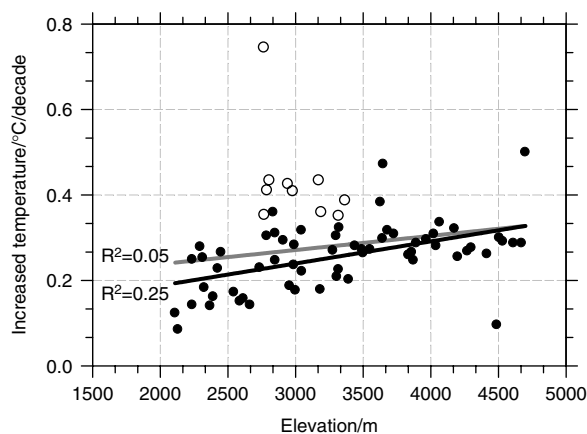


Figure 2. Relationship between the increased temperature and elevation for all 72 meteorological stations. Hollow circles represent the 10 meteorological stations in the northern Tibetan Plateau. Solid circles represent the remaining 62 meteorological stations in the other parts of the Tibetan Plateau. The black line represents the regression line of the stations excluding the northern 10 stations. The gray line represents the regression line of all the 72 stations.

1961 to 2007. A rapid increase in the annual mean temperature occurred around in 1986 (detected using the moving  $t$  test technique; and a significance level of  $>99\%$  was used throughout the study), which is consistent with the climate jump in the plateau during the mid-1980s (Niu *et al.*, 2005; Ding and Zhang, 2008). The summer (May to September) temperature trend also changed abruptly in 1986. The summer mean temperature showed almost no trend during the period from 1961 to 1986 ( $y = 0.0005x + 11.9$ ,  $R^2 = 0.0001$ ), but the summer mean temperature did experience a significantly positive and linear trend during the period from 1986 to 2007 ( $y = 0.069x + 11.9$ ,  $R^2 = 0.57$ , exceeding a statistical significance level of 99%). However, the winter (October to April) mean temperature did not change significantly in 1986. In contrast, winter mean temperature experienced significantly positive and linear trends during both the periods from 1961 to 1986 and 1986 to 2007 ( $y = 0.039x - 5.9$ ,  $R^2 = 0.25$  and  $y = 0.069x - 5.0$ ,  $R^2 = 0.33$ , respectively; all with statistical significance exceeding the 99%). Notably, the summer warming rate was  $0.69^\circ\text{C}$  per decade during the period from 1986 to 2007, which reached the warming rate of winter. These results indicate that the climate warming from 1961 to 1986 was mainly caused by the increase in winter mean temperature, and the summer seems to have contributed little to this effect; however, the increase in the summer mean temperature played a primary role in the rapid climate warming after the mid-1980s.

#### 4. Possible causes of the most significant warming in the northern plateau

##### 4.1. Analyses of ozone trends

The temperature trends of the northern stations violated the elevation dependency of the previously reported

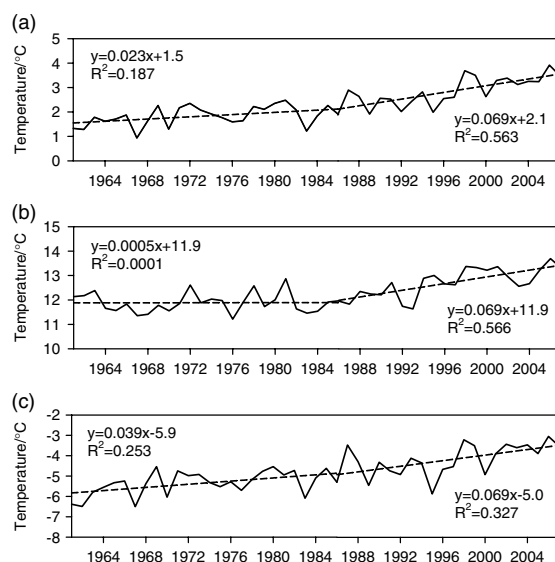


Figure 3. Air temperature trends averaged for the stations in the northern Tibetan Plateau during the period from 1961 to 2007 for the (a) annual, (b) summer (May to September), and (c) winter (October to April).

climate-warming trends. Therefore, the previously suggested causes (Liu *et al.*, 2009), that is, cloud-radiation and snow-albedo feedbacks, which were used to explain the elevation dependency of the climate-warming trends, are not fully applicable for the most significant warming in the northern Tibetan Plateau.

We note that during the summer ozone depletion is the greatest in the northern part of the Tibetan Plateau where ozone levels decreased at a rate of 4.21 DU per decade during the period from 1979 to 2007 (Figure 4). The northern portion of the plateau has also experienced a large rate of decrease in ozone levels during the winter ( $-5.02$  DU per decade), which had the second greatest decrease behind the eastern plateau ( $-5.22$  DU per decade).

Ozone anomalies averaged for the northern stations had significant decreasing linear trends (Statistical significance  $>99\%$ ) in summer ( $y = -0.42x + 6.30$ ,  $R^2 = 0.27$ ) and in winter ( $y = -0.49x + 7.3$ ,  $R^2 = 0.25$ ) during the period from 1979 to 2007 (Figure 5). Comparatively, temperature anomalies averaged for the northern stations exhibited a significant increasing linear trend (Statistical significance  $>99\%$ ) in summer ( $y = 0.06x - 0.90$ ,  $R^2 = 0.60$ ) and in winter ( $y = 0.58x - 0.9$ ,  $R^2 = 0.39$ ) during the period from 1979 to 2007 (Figure 5).

##### 4.2. Correlation between ozone and air temperature

The correlation coefficients between the temperature and the amount of ozone over the northern plateau were  $-0.44$  in the summer (statistical significance  $>98\%$ ) and  $-0.32$  in the winter (statistical significance  $>90\%$ ). In addition, the summer correlation coefficients between the temperature and the amount of ozone at the northern stations were the following: at six of the stations, the correlation coefficient was above 0.43 (statistical significance  $>98\%$ ); at two stations, the correlation coefficient

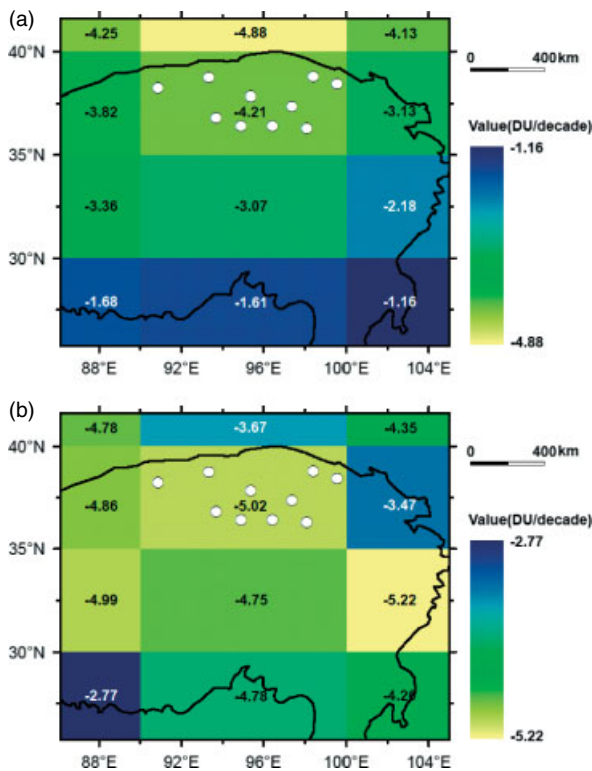


Figure 4. Distribution of ozone depletion rates in (a) the summer (May to September) and (b) the winter (October to April) during the period from 1979 to 2007. The figures represent the ozone depletion rates of the corresponding grid. The black line represents the boundary of the Tibetan Plateau. The circles represent the meteorological stations in the northern Tibetan Plateau.

was above 0.38 (statistical significance  $>95\%$ ); and at two stations, the correlation coefficient was above 0.31 (statistical significance  $>90\%$ ; Table I). In winter, the correlation coefficients at four of the stations were above 0.38 (statistical significance  $>95\%$ ), while the remaining stations had lower correlation coefficients ( $<0.31$ ) that did not exceed the 90% significance level. The correlation coefficients between the temperature and the amount of ozone were low and did not exceed the 95% significance level in the other parts of the Tibetan Plateau except for the north. It should be noted that a spatial mismatch exists in the correlation coefficients because they were based on temperature data from individual stations and gridded ozone data with a coarser resolution. Despite this weakness, these results indicate that air temperature had a statistically significant negative correlation with the amount of ozone in the summer and a relatively weak negative correlation with the amount of ozone in the winter during the studied period.

The correlation coefficients between temperature and the amount of ozone varied by month (Figure 6). The correlation coefficients for April to September were statistically significant at the 98% level. The correlation coefficients of the remaining months were distinctly low except for February (0.37). The correlation coefficient for October was an insignificant and positive. Because October is the transitional period from the cold

to the warm season, the reason behind its warming is complex and requires further research. Note that these monthly correlation coefficients (excluding October) had a strong correlation with the monthly mean of short-wave radiation received at the land surface (correlation coefficient 0.83, statistical significance  $>99\%$ ). In other words, if the solar radiation increased, the correlation between the ozone amount and surface air temperature was stronger. This result is also consistent with the finding that the correlation between the temperature and ozone anomaly was greater in the summer than in the winter.

#### 4.3. Further discussion on the relationship between ozone and air temperature

Numerical simulation results from previous studies have demonstrated that ozone depletion in the stratosphere could affect surface climate changes (e.g., Chen *et al.*, 1998; Graf *et al.*, 1998; Volodin and Galin, 1998, 1999; Gillett and Thompson, 2003). Graf *et al.* (1998) found that the surface air temperature responded to stratospheric ozone depletion, but simulated increases in the surface temperature were much weaker than observations. They attributed this weakness to the late cooling of the polar area in their model run. Using observed ozone data from 1977 to 1994 to constrain the atmospheric general circulation model, Volodin and Galin (1999) found that increases in the surface temperature on the Eurasian continent were very consistent with the observed data. When simulating the impact of stratospheric ozone depletion on climate in the Antarctic Peninsula, Gillett and Thompson (2003) found that the simulated surface temperature forced by ozone depletion was very consistent with observations. Gillett and Thompson (2003) strongly suggested that anthropogenic emissions of ozone-depleting gases had demonstrably affected Earth's surface climate over the past few decades.

Zhou and Zhang (2005) indicated that the decrease of ozone means that more ultraviolet radiation is able to reach the troposphere and the surface, leading to additional heating of the surface. When simulating the impact of the Antarctic ozone hole on global climate, Chen *et al.* (1998) found that surface air temperature was generally higher at the high latitudes of the Southern Hemisphere when the ozone hole was considered. They postulated that the increase in surface air temperature occurred because more solar radiation was reaching the Earth's surface. The Golmud station was used as an example to investigate solar radiation changes in the northern plateau (Figure 7(a) and (b)). The radiation flux showed significantly positive linear trends in both summer and winter during the period from 1979 to 2007, and the positive trends were also larger in summer than in winter. Therefore, the most significant warming in the northern Tibetan Plateau may be partly explained by increases in radiative heating due to the pronounced ozone depletion in the region.

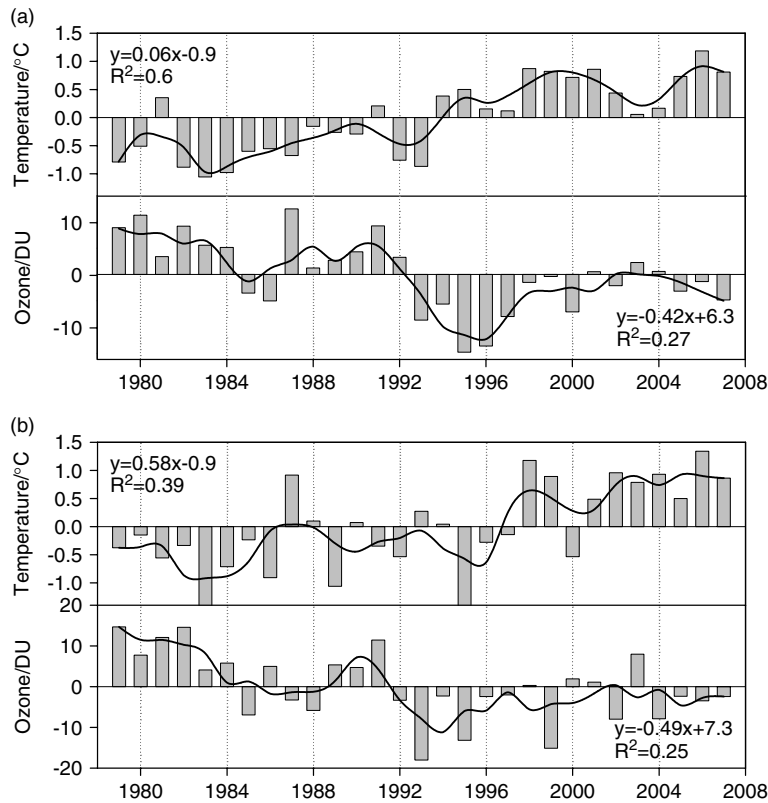


Figure 5. Trends of the ozone and temperature anomaly in (a) the summer (May to September) and (b) the winter (October to April) during the period from 1979 to 2007. The temperature anomaly is the average for the stations in the northern Tibetan Plateau. The solid lines represent the running mean over 3 years.

Table I. The correlation coefficients between the ozone amount and surface air temperature for each station in the northern Tibetan Plateau in summer (May to September) and winter (October to April).

| Station Name | Mangya       | Lenghu | Xiaozaoahuo  | Dachaidan    | Delingha     | Golmud       | Nuomuhong    | Dulan        | Tuole        | Yeniugou     |
|--------------|--------------|--------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| Summer       | <b>-0.49</b> | -0.31  | -0.34        | <b>-0.44</b> | <b>-0.46</b> | <b>-0.40</b> | <b>-0.44</b> | <b>-0.44</b> | <b>-0.47</b> | <b>-0.42</b> |
| Winter       | <b>-0.37</b> | -0.28  | <b>-0.38</b> | -0.17        | -0.22        | -0.29        | -0.25        | -0.25        | <b>-0.39</b> | <b>-0.44</b> |

Bold type represents a statistical significance >95%.

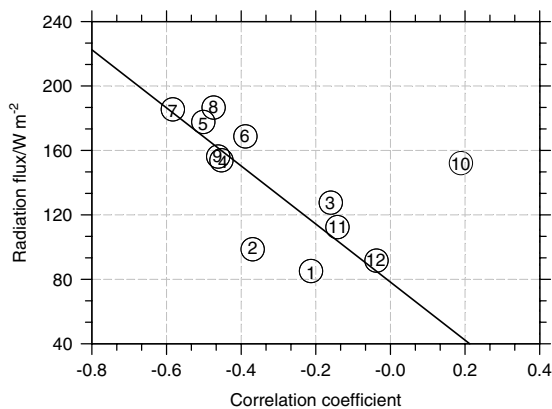


Figure 6. Comparison of monthly mean radiation flux received at the land surface and correlation coefficients between the ozone amount and surface air temperature averaged for the stations in the northern Tibetan Plateau. The labels in the circles represent the months of the year (e.g., '1' denotes January, '2' denotes February, etc.). The black line represents the regression line of these months (excluding October).

Hu and Tung (2003) proposed that stratospheric ozone depletion affected surface temperatures through changing stratospheric temperature and wind distribution as well as the related wave–mean-flow interaction. Volodin and Galin (1998) explained that the response of surface temperature to stratospheric ozone depletion was caused by the anomaly of radiative heating induced by the anomaly of ozone. This heating anomaly was compensated for by vertical motion in the lower stratosphere, which excited the first mode of mid-latitude low-frequency variability and induced near-surface temperature anomalies of dynamics. These dynamically induced near-surface temperature anomalies did not cancel perfectly and this resulted in climate warming. These aforementioned explanations may also be applicable to the linkage of the surface air temperature with ozone in the northern Tibetan Plateau. Other factors not discussed here may also contribute to the most significant climate

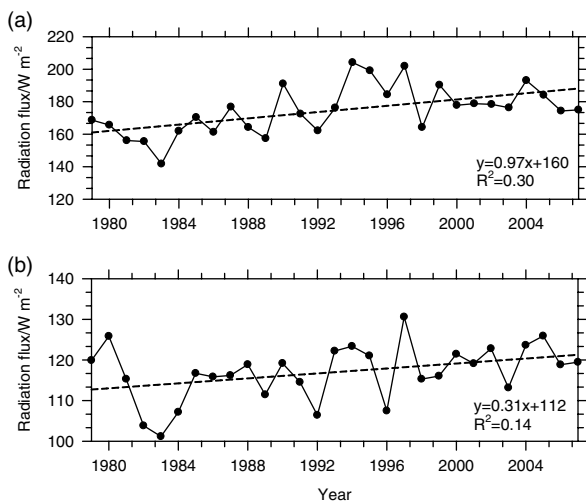


Figure 7. Trends of the horizontal direct radiation flux received by the land surface in (a) the summer (May to September) and (b) the winter (October to April) at Golmud during the period from 1979 to 2007.

warming in the northern Tibetan Plateau. These factors require further evaluation in the future.

## 5. Concluding remarks

The significant climate warming on the northern Tibetan Plateau and its possible causes were analysed. The following insights were gained in this study:

1. The plateau surface air temperature has undergone a significantly positive trend during the period from 1961 to 2007. The warming rate ranged from  $0.09^{\circ}\text{C}$  per decade to  $0.74^{\circ}\text{C}$  per decade, with an average of  $0.28^{\circ}\text{C}$  per decade for 71 meteorological stations. The northern plateau demonstrated the most significant warming, while the southeastern plateau had experienced relatively weak warming. Our further analyses indicated that the northern stations had a strong influence on whether elevation dependency of the climate warming trends was identified or not for the whole plateau data set.
2. In the northern Tibetan Plateau, a rapid increase in the annual mean temperature occurred around in 1986. Such an abrupt change in 1986 was also detected in the mean summer temperature, but was not detected in the mean winter temperature. The summer temperature showed almost no change during the period from 1961 to 1986, but summer temperature did experience a significantly increasing trend ( $0.69^{\circ}\text{C}$  per decade) during the period from 1986 to 2007, where the trend reached that of the winter. These data indicate that the summer temperature increase played a primary role in the rapid climate warming that occurred in the mid-1980s.
3. Of the entire Tibetan Plateau domain, the ozone depletion rate in the northern part was the greatest ( $-4.21$  DU per decade) in summer and the second greatest ( $-5.02$  DU per decade) in the winter

during the period from 1979 to 2007. The summer air temperature showed a statistically significantly negative correlation with ozone in the northern part of the plateau, with a correlation coefficient of  $-0.44$ . Such a correlation seems to have a relationship with the solar radiation and the ozone depletion ratio.

Further discussion showed that the most significant warming in the northern portion of the plateau may be related to radiative and dynamical heating that are the results of the pronounced stratospheric ozone depletion. If this is fully established, a deduction with caution is that the ozone amount has experienced a significant, long-term decreasing trend in the middle latitudes. This decreasing trend has been particularly noticeable over the polar regions since the beginning of the 1970s (e.g., Zou, 1996; Staehelin *et al.*, 2001, 2002). If the ozone amount continues to decrease in these regions in the future, it will likely contribute to at least part of the continued, rapid climate warming in the regions. However, in the present study, we only discussed the possible impact of ozone depletion in the stratosphere on the surface climate based on literature reviews. Our continued work will be to use the climate model to test the role of ozone depletion in the stratosphere in the significant climate warming of the northern Tibetan Plateau.

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