

Air Temperature Changes over the Tibetan Plateau and Other Regions in the Same Latitudes and the Role of Ozone Depletion*

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ABSTRACT

Using radiosonde and satellite observations, we investigated the trends of air temperature changes over the Tibetan Plateau (TP) in comparison with those over other regions in the same latitudes from 1979 to 2002. It is shown that over the TP, the trends of air temperature changes in the upper troposphere to lower stratosphere were out of phase with those in the lower to middle troposphere. Air temperature decreased and a decreasing trend appeared in the upper troposphere to lower stratosphere. The amplitude of the annual or seasonal mean temperature decreases over the TP was larger than that over the whole globe. In the lower to middle troposphere over the TP, temperature increased, and the increasing trend was stronger than that over the non-plateau regions in the same latitudes in the eastern part of China. Meanwhile, an analysis of the satellite observed ozone data in the same period of 1979–2002 shows that over the TP, the total ozone amount declined in all seasons, and the ozone depleted the most compared with the situations in other regions in the same latitudes. It is proposed that the difference between the ozone depletion over the TP and that over other regions in the same latitudes may lead to the difference in air temperature changes. Because of the aggravated depletion of ozone over the TP, less (more) ultraviolet radiation was absorbed in the upper troposphere to lower stratosphere (lower to middle troposphere) over the TP, which favored a stronger cooling in the upper troposphere to lower stratosphere, and an intenser heating in the lower to middle troposphere over the TP. Therefore, the comparatively more depletion of ozone over the TP is possibly a reason for the difference between the air temperature changes over the TP and those over other regions in the same latitudes.

Key words: the Tibetan Plateau, air temperature changes, ozone depletion

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1. Introduction

Thermal and dynamic forcing of the Tibetan Plateau (hereafter referred to as TP) impacts on the atmospheric general circulation and climate as well as their variations over China, Asia, and even the globe (Ye et al., 1958, Ye and Wu, 1998; Huang, 1985; Yanai et al., 1992). As a result, the climate and associated variations over the TP have attracted great attention of the scientific community. Many investigators have studied temperature changes over the TP based on observational data (Lin and Zhao, 1996; Zhu et al., 2001; Niu et al., 2002, 2004; Cai et al., 2003; Wei et

al., 2003; Zhou and Zhang, 2005; Bian and Du, 2006; Li et al., 2006). These studies have shown that in the last several decades, surface temperature over the TP generally shows an ascending trend, and the trend is stronger than that in other parts of China. Changes of surface temperature across the TP exhibit a mixed spatial and temporal difference, with the largest temperature ascending occurring in both spring and summer. Over most parts of the TP, a noticeable warmer period since the 1980s is observed. However, there is also an opposite temperature changing trend over there in the lower stratosphere and at the tropopause where air temperature has decreased (Ge et al., 1999;

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Zhou et al., 2003; Zhou and Zhang, 2005).

Many scientists examined the causes of the climate change over the TP. Yao et al. (2000) highlighted the role played by the variation of underlying ice and snow in the TP climate change, proposing that both the expansion and disappearance of ice and snow have served as a major cause for the large-scale climate change across the plateau. Some studies suggested that the climate change trends across the plateau were associated with the greenhouse effects augmented by the CO₂ increase. Liu et al. (1998) analyzed model outputs for 100 yr with/without an annual CO₂ increase of 1%. If only the impact of increased CO₂ was considered, the climate change trend over the regions with an elevation of 2000 m above sea level was similar to that of the globe, namely getting warmer and wetter. However, in the middle latitude regions (20°–60°N), over the TP, a temperature increase higher than that over other regions in the same latitudes is noticed. Gao et al. (2003) examined the impacts of doubled CO₂ on the climate in China by using a regional climate model (RegCM2) nested in a global model. Their results showed that over the TP, a marked temperature rise of 2.6–2.8°C appeared, higher than the nation's average. Zhou and Zhang (2005) analyzed the possible impact of reduced ozone concentration on the interdecadal climate variability across the TP, and found a possible physical connection between the total ozone depletion and the interdecadal temperature variation over the plateau. They proposed that the reduced ozone over the plateau resulted in less ultraviolet solar radiation to be absorbed by the stratosphere, and more radiation reaching down the troposphere and land surface, causing temperature in the lower stratosphere to drop and that in the troposphere to rise.

Ozone is one of the important trace gases in the earth's atmosphere. Its variation can affect the radiation budget at the earth's surface and in the troposphere. Scientists have paid much attention to the climate effect of ozone. Many previous studies showed that ozone depletion was closely associated with the climate change over both Arctic and Antarctic regions

(Angell, 1986; Newman and Randel, 1988; Langematz et al., 2003). Compared with the situations in other regions in the same latitudes, ozone changes over the TP have unique characteristics. For example, over the plateau, there existed a noticeably reduced ozone concentration, or the ozone valley (Zhou et al., 1995). Since ozone variations were closely associated with the climate change over the plateau on an interdecadal time scale (Zhou and Zhang, 2005), it is natural to ask the following questions: Are there any differences between the climate change over the TP and that over other regions in the same latitudes? If yes, how do they differ and what are the causes? This paper will address these questions based on the findings of a previous paper (Zhou and Zhang, 2005).

A description of the data and methods used in the study is provided in Section 2. Comparisons of the temperature and ozone changes over the TP with those over other regions in the same latitudes are discussed in Sections 3 and 4, respectively. Through analyzing the relationship between ozone and temperature variations, in Section 5, an attempt is made to explain the possible role played by the difference between the ozone depletion over the TP and that over other regions in the same latitudes. Conclusions are given in Section 6.

2. Data and methods

Monthly mean air temperature is obtained by using upper air sounding data archived at the National Meteorological Information Center, China Meteorological Administration (CMA). Twelve stations with consecutive observational data for a period of at least 20 yr (within the 1979–2002 period) in the TP region are selected. All these stations are located within 28°–39°N, 87°–103°E, with an averaged elevation of 3560 m above sea level. In the non-plateau regions in the same latitudes in the eastern part of China (east of 110°E), 16 radiosonde stations with data for at least 20 yr are also selected. All of them have an elevation of less than 300 m above sea level.

Ozone data used in our study are the 24-yr global

monthly mean merged satellite column ozone data¹ (10° longitude $\times 5^\circ$ latitude) from the TOMS/SBUV (Total Ozone Mapping Spectrometers/Solar Backscatter Ultraviolet) measurements during the period of 1979–2002 (Steinbrecht et al., 2003). Satellite MSU monthly mean air temperature (5.0 version) for the same period is also used. The data are consolidated by University of Alabama at Huntsville (UAH)², with a horizontal coverage of -88.75° – 88.75° N, -178.75° – 179.25° E and a horizontal resolution of $2.5^\circ \times 2.5^\circ$. The MSU three-channel data, namely MSU2R, MSU2, and MSU4, give the monthly mean air temperature in the middle and upper troposphere (850–300 hPa), up-

per troposphere (300–100 hPa), and lower stratosphere (100–50 hPa), respectively.

For the station observation, we calculate the area mean for the temperature sounding data of 12 radiosonde stations in the TP and those of 16 radiosonde stations in the non-plateau region in the same latitudes, respectively. Analysis is focused on the vertical range between 500 and 20 hPa after the elevation of the TP and the altitude of sounding balloons are taken into consideration. As to the satellite observation, the data covering 27.5° – 37.5° N and 75° – 105° E are selected for the plateau region. A global latitudinal belt across 27.5° – 37.5° N with the part of 75° – 105° E

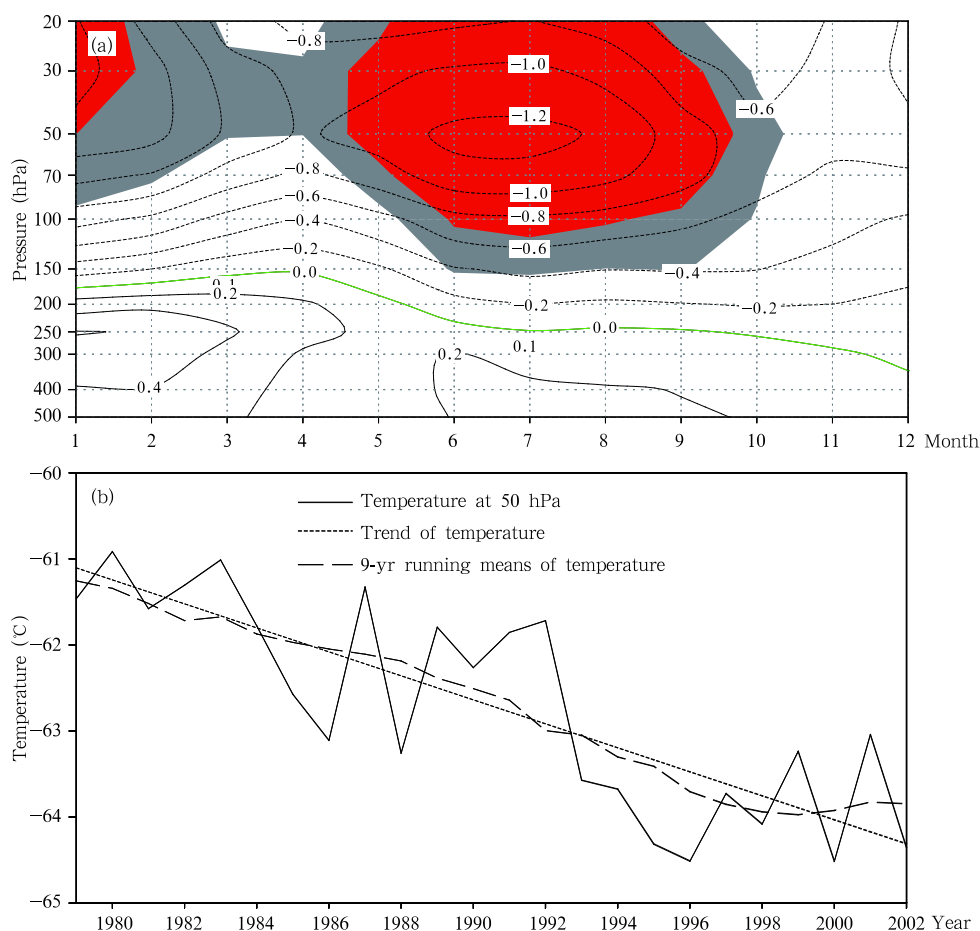


Fig. 1. (a) Multi-year (1979–2002) mean seasonal evolution of air temperature changes ($^\circ\text{C}/\text{decade}$) at various vertical levels (500–20 hPa) over the TP based on observations from 12 radiosonde stations. Red and grey shadings represent areas exceeding the 0.05 and 0.1 significance levels (from Zhou and Zhang, 2005). (b) Year-to-year variation of June–August mean air temperature at 50 hPa (real line). Dotted and dashed lines are the linear trend and 9-month running mean, respectively.

¹http://code916.gsfc.nasa.gov/Data_services/merged/mod_data.public.html

²<http://www.nsstc.usu.edu/public/>

removed is selected as the non-plateau regions in the same latitudes, according to the method proposed by Zou (1996). The data in the two regions are averaged and area-weighted for producing the data series that can represent the time variations of the plateau and non-plateau regions.

3. Trends of temperature changes

Figure 1 shows the monthly variation of air temperature changes over the TP during the period of 1979–2002 (Fig. 1a) (Zhou and Zhang, 2005), and the annual variation of the 50-hPa temperature in summer (June–August) (Fig. 1b), based on the observations at the 12 radiosonde stations across the TP. It is apparent in Fig. 1a that temperature changes are negative above 170 hPa in January–April and above 250 hPa in May–December, indicating that decreased air temperature appeared in the upper troposphere and lower stratosphere all year round. Both winter and summer are featured with larger temperature drops, with two major descending centers sitting at 30 hPa in January and 50 hPa in June–July, showing significant temperature changes at $-1.6^{\circ}\text{C}/\text{decade}$ and $-1.2^{\circ}\text{C}/\text{decade}$, respectively. The temperature changes in the lower to middle troposphere are opposite to those in the upper troposphere to lower stratosphere. The former shows a weak positive/ascending temperature trend. Two large value centers appeared near 250 hPa in winter and 500 hPa in summer, with the highest temperature rise at $0.6^{\circ}\text{C}/\text{decade}$ and $0.2^{\circ}\text{C}/\text{decade}$, respectively. The ascending temperature trend is relatively weak, compared with the temperature drop in the lower stratosphere and upper troposphere. Figure 1b presents the annual evolution of the air temperature at 50 hPa in summer (June–August), indicating in the lower stratosphere a basically sustained descending trend with significant interannual and interdecadal variations during the period of 1979–2002. The air temperature at 50 hPa dropped by about 3°C in summer from 1979 to 2002.

Based on the satellite MSU monthly mean air temperature data in the lower stratosphere (100–50 hPa) during 1979–2002, Fig. 2 shows the time evo-

lution of the globally averaged temperature anomaly (Fig. 2a) and the temperature anomaly averaged over the plateau region (Fig. 2b). From the satellite data, it is shown that in the lower stratosphere both the global and the plateau mean temperatures have a significant descending trend. However, the rates of the descending are different. The global mean temperature has a linear decreasing rate of $-0.48^{\circ}\text{C}/\text{decade}$, while that over the TP is $-0.74^{\circ}\text{C}/\text{decade}$. For a better comparison, monthly mean air temperature anomalies derived from the sounding data averaged at 100–50 hPa are used to calculate the linear temperature drop during the period of 1979–2002. The results show that the temperature drop rate is $-0.66^{\circ}\text{C}/\text{decade}$, basically in agreement with that indicated by the satellite data, demonstrating that the satellite data is reliable.

To further depict the unique attributes of the air temperature changes over the plateau, the MSU monthly mean air temperature data in the lower stratosphere (100–50 hPa) from 1979 to 2002 are used to calculate the annual and seasonal means of temperature decreasing rates over the plateau and the non-plateau region in the same latitudes (Fig. 3). Figure 3 suggests that the lower stratosphere above the plateau has a larger temperature drop, compared with the non-plateau region in the same latitudes, for both annual and seasonal averages. Meanwhile, with the sounding data, vertical distributions of the linear temperature trends for the plateau and the non-plateau regions are obtained (Fig. 4). From Fig. 4, we can see that the linear temperature trends over the plateau region are different from those over the non-plateau region. Over the plateau, it is a descending (ascending) temperature above (below) 250 hPa. Over the non-plateau region in the same latitudes in the eastern part of China, the descending temperature trend starts from a lower altitude of 280 hPa, below which is a ascending trend. It is also apparent that in the upper troposphere and lower stratosphere above 150 hPa, a larger temperature drop occurs over the plateau. Below 250 hPa, there is a larger temperature rise over the plateau. These indicate that over the plateau there exist not only a larger temperature drop in the upper troposphere to lower

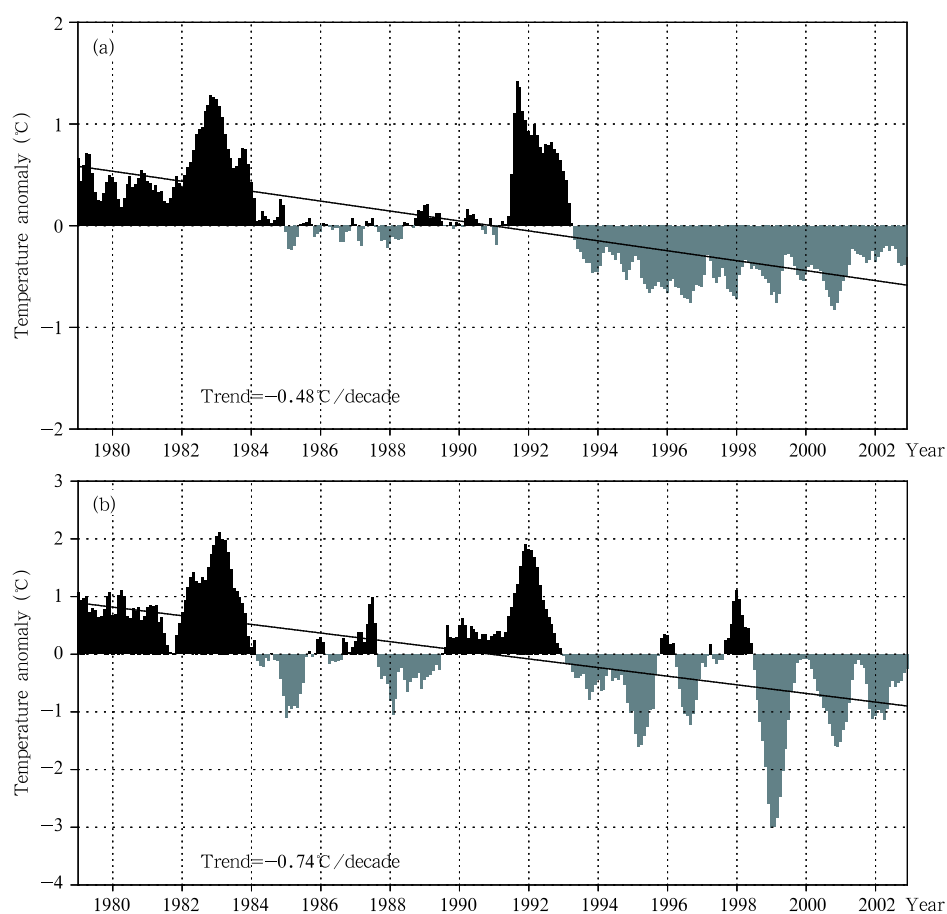


Fig. 2. Monthly MSU temperature anomalies in the lower stratosphere (100–50 hPa) in 1979–2002 and their linear trends (straight lines). (a) Global average. (b) The average over the TP.

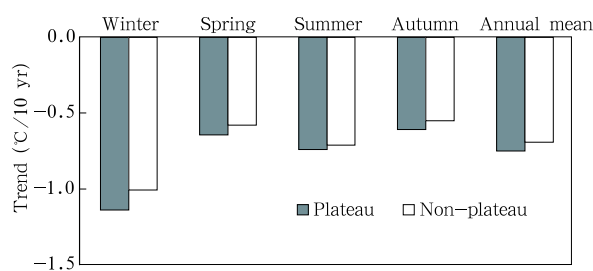


Fig. 3. Linear MSU temperature trends in the lower stratosphere (100–50 hPa) in 1979–2002 for annual and seasonal means over the TP (dark bars) and the non-plateau region (light bars).

stratosphere but also a larger temperature rise in the lower to middle troposphere compared with the non-plateau region in the same latitudes.

4. Trends of total ozone changes

Based on the 24-yr (1979–2002) global monthly

mean total ozone data derived from the TOMS/SBUV, Fig. 5 shows a time-longitude section of climatological monthly mean total ozone averaged between 27.5° and 37.5°N . It is apparent that there

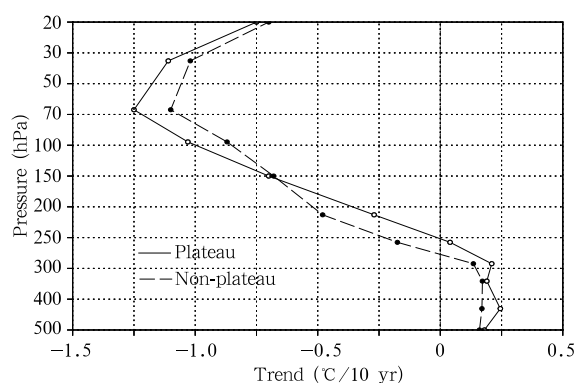


Fig. 4. Linear trends of temperature changes observed from radiosonde stations over the TP (solid line) and the non-plateau region in the same latitudes in eastern China (dashed line; unit: $^{\circ}\text{C}/\text{decade}$).

is remarkably less total ozone across the plateau of 75° – 105° E, compared with the ozone distributions in other regions in the same latitudes. Zhou et al. (1995) analyzed the total ozone data collected by TOMS during the period of 1979–1991, and found that June was marked with a reduced ozone concentration over the plateau. The lower ozone concentration would not end until September. Zou (1996) found the similar ozone valley over the plateau using the same data. In fact, as shown in Fig. 5, the TP's total ozone is featured with considerable seasonal variations, with the maximum value appearing in February–April and the minimum in September–November. Overall, total ozone remains low over the plateau compared with that over other regions in the same latitudes all year long.

Figure 6 presents the time evolution of the monthly mean total ozone, its linear trend, and 23-month running mean over the plateau. The linear

trend of the total ozone shows a notable downturn. Meanwhile, the evolution of total ozone exhibits both interannual and interdecadal variations. Zou (1996) calculated the climatological means for the zonal departure of global total ozone based on the 12-yr TOMS data (1979–1991), and found a downturn trend for the total ozone in all seasons over the plateau. Here, the total ozone data (1979–2002) are used to further examine if such a downturn trend has sustained. Figure 7 shows the change rates of total ozone over the plateau and the non-plateau regions in the same latitudes in different seasons and their annual means. Obviously, in each season the linear trend displays a negative value, indicating that over both the plateau and the non-plateau regions in the same latitudes, the total ozone has been lost. However, a comparison of the magnitudes of the ozone depletion rate shows that the TP experiences a bigger/faster decrease of ozone

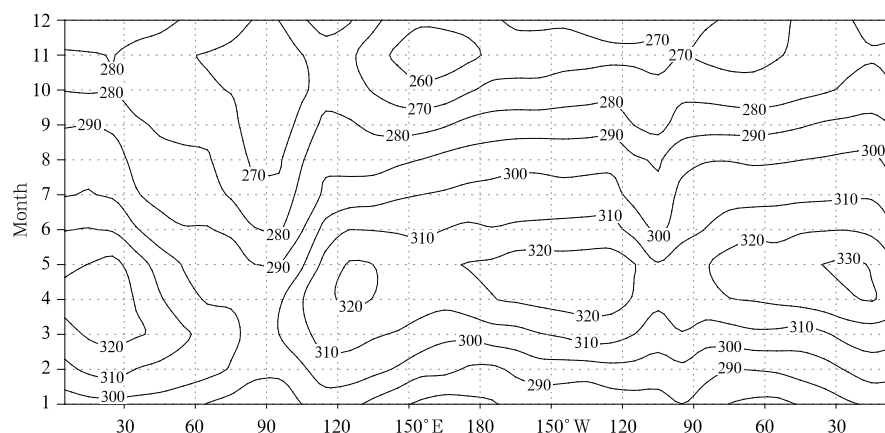


Fig. 5. Time-longitude cross-section of the climatological total ozone averaged along 27.5° – 37.5° N (unit: DU).

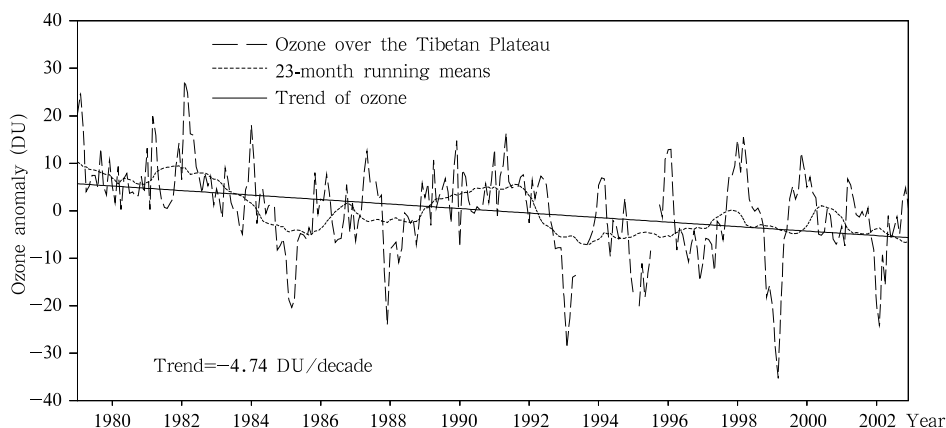


Fig. 6. Monthly total ozone anomaly (dashed line) over the TP, its linear trend (solid line), and 23-month running mean (dotted line).

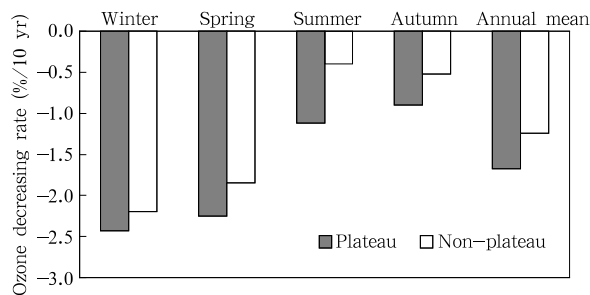


Fig. 7. Linear trend rates for seasonal and annual means of total ozone over the TP and the non-plateau region in the same latitudes (unit: %/decade).

in each season, indicating that over the plateau more ozone has been lost than over the non-plateau region in the same latitudes.

5. A possible role of ozone depletion in air temperature changes

The results so far indicate that over the TP, the trends of air temperature or ozone changes in 1979–2002 are unique and different from those over other parts of the globe. Over the plateau in the upper troposphere to lower stratosphere, a faster air temperature drop is seen. Moreover, in the lower to middle troposphere there exists an air temperature increase that is also larger than the non-plateau regions in the same latitudes in the eastern part of China. Meanwhile, over the plateau the climatological total ozone is appreciably lower than in other regions in the same latitudes throughout the year. The downturn trend of total ozone is featured with a faster speed and a larger magnitude over the TP for all seasons. To understand if there is a connection between the temperature and ozone changes over the plateau, Fig. 8 presents a time-altitude distribution of the correlation coefficient between air temperature and total ozone (Zhou and Zhang, 2005). One can see from Fig. 8 that there is a positive correlation in the upper troposphere and lower stratosphere above 150 hPa, and it is statistically significant (exceeding the 0.05 significance level) all year round at 100–20 hPa. The period of March–June is marked with the highest correlation coefficient greater than 0.8 at 30–50 hPa. In the lower and middle troposphere, a negative correlation exists. During February–June and September–November, there are

significant negative correlations exceeding the 0.05 significance level below 200 hPa. This indicates that the total ozone change over the plateau is closely associated with the TP air temperature changes. The decrease of total ozone goes along with a decrease of air temperature in the upper troposphere to lower stratosphere, and a temperature rise in the lower to middle troposphere.

To further reveal the connection between ozone and temperature changes over the plateau, in Fig. 9 the Morlet wavelet approach (Torrence and Compo, 1998) is used to analyze time evolutions for both the total ozone (Fig. 9a) and the air temperature at 50 hPa (Fig. 9b) in the summer season (June–August). It shows that temperature has a variation identical to ozone, with significant variations appearing on the interannual and interdecadal time scales. The most pronounced periods are the 2–3-yr interannual variation and the 8–13-yr interdecadal variation for both temperature and ozone. These periods appear almost in the same time for both temperature and ozone. The 2–3-yr interannual variation appears in 1982–1992, while the 8–13-yr interdecadal variation appears throughout the entire data time period. This indicates that variations of ozone and temperature over the TP are consistent not only in the long-term interdecadal trend, but also in the interannual variation trend. This further confirms the close relation between ozone and temperature variations across the plateau.

Why is it that the variations of total ozone and air temperature over the TP are consistent? As a matter of fact, the variation of ozone can lead to the air temperature change. There is a possible physical connection between them. In the context of the earth's atmosphere, ozone mainly exists in the stratosphere at 10–50 km. Ozone heats up the stratospheric atmosphere by absorbing shortwave solar radiation as well as long wave radiation of the earth-atmosphere system. The reduced ozone concentration over the TP cuts down the absorption of ultraviolet solar radiation by the plateau's stratosphere, allowing more radiation into the troposphere, which results in a reduced temperature in the upper troposphere to lower stratosphere, and an increased temperature in the lower to

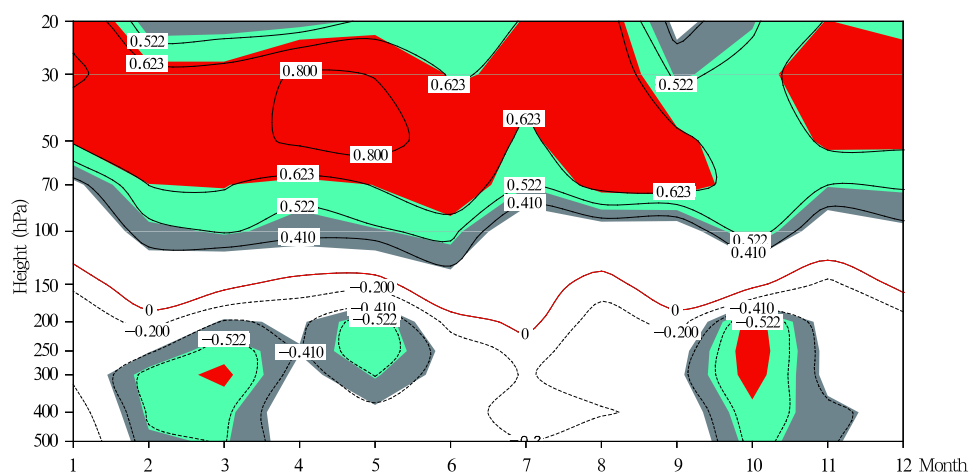


Fig. 8. The time-altitude distribution of the correlation coefficient between total ozone and temperature over the TP. Grey, green, and red shadings indicate areas with correlation coefficients exceeding the 0.05, 0.01 and 0.001 confidence levels, respectively (from Zhou and Zhang, 2005).

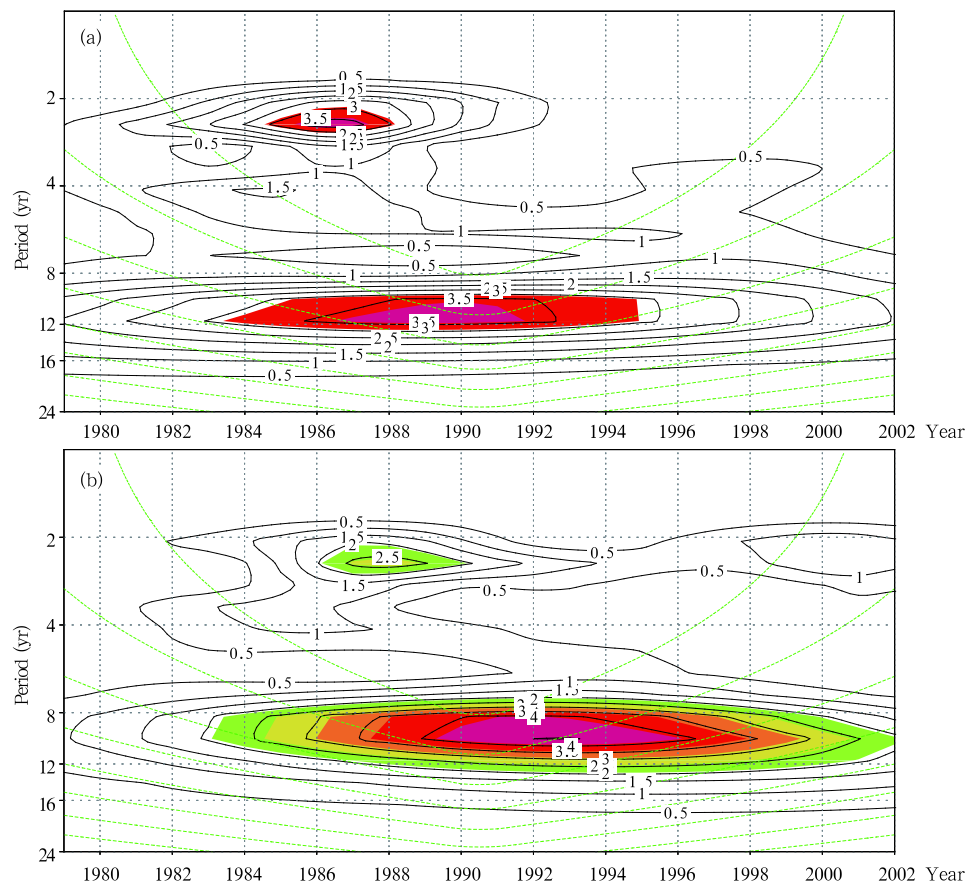


Fig. 9. The Morlet wavelet spectrum for the total ozone (a) and temperature at 50 hPa (b) over the TP in summer (June–August). Shadings represent areas of greater than 90% significance. Dotted lines denote the areas under the edge effects.

middle troposphere over the plateau.

6. Conclusions

In this paper, we analyzed the trends of both air temperature and total ozone changes over the TP and other regions, using the surface and satellite observational data during the period of 1979–2002. It is found that over the plateau, air temperature in the upper troposphere to lower stratosphere decreases, which is in agreement with the global and the areal-mean (other regions in the same latitudes) temperature changes. but it has a larger decreasing rate. The air temperature in the lower to middle troposphere has developed a changing trend opposite to that in the upper troposphere to lower stratosphere over the plateau, namely a weak positive temperature trend, or weak ascending temperatures over time. Additionally, compared with the air temperature change over the non-plateau regions in the same latitudes in the eastern part of China, the linear trend of the air temperature changes over the TP is unique. Over the plateau above (below) 250 hPa, air temperature decreased (increased). Over the non-plateau regions in the same latitudes in the eastern part of China, opposite temperature changes occur at a reduced altitude of 280 hPa. Over the plateau, a larger decreasing rate of air temperature is noticed in the upper troposphere to lower stratosphere above 150 hPa. Below 250 hPa, a larger increasing rate of air temperature over the plateau is observed. These indicate that over the plateau there exist not only stronger temperature decreasing in the upper troposphere to lower stratosphere, but also stronger temperature increasing in the lower to middle troposphere, compared with those in other regions in the same latitudes.

On the other hand, the climatological total ozone in all seasons is less over the TP, with a marked linear downturn trend compared with that in other regions in the same latitudes. Over the plateau, the total ozone amount shows a larger decreasing rate, though a downturn trend is seen over both the plateau and the non-plateau region in the same latitudes. This indicates a stronger ozone depletion over the TP.

There is a close connection between air temper-

ature and total ozone variations over the TP. The correlation is significantly positive in the upper troposphere to lower stratosphere, and significantly negative in the lower to middle troposphere. The decrease of total ozone goes along with a decrease of air temperature in the upper troposphere to lower stratosphere, and an increase of air temperature in the lower to middle troposphere. Over the plateau, total ozone and air temperature are consistent not only on the interdecadal but also interannual time scales.

The difference in total ozone depletion between the TP and other regions in the same latitudes may have caused the air temperature change difference. Since over the TP there is a stronger total ozone depletion, less ultraviolet solar radiation is absorbed by the stratosphere and more enters into the lower and middle troposphere. This can result in a larger temperature decrease in the upper troposphere to lower stratosphere, and a stronger temperature increase in the lower to middle troposphere over the plateau.

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