ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 29, NO. 2, 2012, 274–284

The Impact of Warm Pool SST and General Circulation on Increased Temperature over the Tibetan Plateau

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(Received 28 March 2011; revised 16 September 2011)

ABSTRACT

In this paper, the possible reason of Tibetan Plateau (TP) temperature increasing was investigated. An increase in $T_{\rm min}$ (minimum temperature) plays a robust role in increased TP temperature, which is strongly related to SST over the warm pool of the western Pacific Ocean, the subtropical westerly jet stream (SWJ), and the tropical easterly upper jet stream (TEJ), and the 200-hPa zonal wind in East Asia. Composite analysis of the effects of SST, SWJ, and TEJ on pre- and post-abrupt changes in $T_{\rm a}$ (annual temperature) and $T_{\rm min}$ over the TP shows remarkable differences in SST, SWJ, and TEJ. A lag correlation between $T_{\rm a}/T_{\rm min}$, SST, and SWJ/TEJ shows that changes in SST occur ahead of changes in $T_{\rm a}/T_{\rm min}$ by approximately one to three seasons. Partial correlations between $T_{\rm a}/T_{\rm min}$, SST, and SWJ/TEJ show that the effect of SWJ on $T_{\rm a}/T_{\rm min}$ is more significant than the effect of SST. Furthermore, simulations with a community atmospheric model (CAM3.0) were performed, showing a remarkable increase in $T_{\rm a}$ over the TP when the SST increased by 0.5°C. The main increase in $T_{\rm a}$ and $T_{\rm min}$ in the TP can be attributed to changes in SWJ. A possible mechanism is that changes in SST force the TEJ to weaken, move south, and lead to increased SWJ and movement of SWJ northward. Finally, changes in the intensity and location of the SWJ cause an increase in $T_{\rm a}/T_{\rm min}$. It appears that TP warming is governed primarily by coherent TEJ and SWJ variations that act as the atmospheric bridges to remote SSTs in warm-pool forcing.

Key words: TP temperature, subtropical westerly jet, tropical easterly jet, warm pool

Citation: Wang, C. H., L. Yu, and B. Huang, 2012: The impact of warm pool SST and general circulation on increased temperature over the Tibetan Plateau. *Adv. Atmos. Sci.*, **29**(2), 274–284, doi: 10.1007/s00376-011-1034-3.

1. Introduction

The Tibetan Plateau (TP) is a special geographical area that plays an important role in global climate and East Asian atmospheric circulation through orographic and thermal force mechanisms (Ye et al., 1957; Ye and Zhang, 1974; Ye and Gao, 1979; Ye and Wu, 1998; Wang et al., 2003; Wang et al., 2011a). Simulation experiments reveal that the different topography distribution remarkably affects the strength southwesterly winds over South Asia (Xu et al., 2010). In the past few decades, with global warming, the annual temperature ($T_{\rm a}$) significantly increased over the TP (Karl et al., 1993; David et al., 1997; Feng et al., 1998; Wei et al., 2003; Oku et al., 2006).

The TP climate change and its mechanism have received more attention in recent years. Some research has suggested that TP climate change would be affected by changes in SST of the Pacific Ocean. Huang et al. (2003) suggested that the inter-annual variation of the East Asian summer monsoon is closely associated with the thermal states of the western Pacific warm pool and the convective activities around the Philippines, the different states of the ENSO cycle, and the thermal effects of Tibetan Plateau. Shaman and Tziperman (2005) investigated the relationship

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between ENSO events and TP snow depth and speculated that winter ENSO conditions in the central Pacific may produce stationary barotropic Rossby waves in the troposphere with a northeastward group velocity, anomalous increases in upper tropospheric potential vorticity, and increased winter snowfall over the TP. Zhao et al. (2009) suggested that the summer of the South Asian High (SAH) above the TP appears to play a modulatory role in tropical North Pacific large-scale ocean–atmosphere interactions and serves to transmit ENSO signals.

Some issues regarding the relationship between TP temperature and Pacific SST in the East Asian climate system are not clear. Feng et al. (1998) showed that the TP is a sensitive area and trigger area of climate change in East Asia. Nan et al. (2009) investigated the relationship between spring tropospheric temperature over the TP and SST over the equatorial Pacific. They suggested that when the TP temperature is low in spring, positive SST anomalies appear over the tropical central-eastern Pacific in spring and summer and that when TP temperature is high, negative SST anomalies appear. The relationship is explained by the Asian-Pacific Oscillation (APO) and the ocean–atmosphere interaction over the tropical Pacific. This research suggests that, on a seasonal scale, TP temperature changes occur ahead of or at the same time as Pacific SST anomalies. Meanwhile, Pacific SSTs in different regions were used for prediction; results suggested that regional temperature and precipitation anomalies responded to Pacific SST anomalies. Gong and Wang (1999) investigated the correlation between SST in different Pacific areas and temperature in extratropical and tropical areas. The results showed that tropical temperature anomalies lag by one season, and extratropical temperature anomalies lag by two to three seasons. Dong et al. (2004) found that $T_{\rm a}$ along the TP railway was low during El Niño and high during La Niña. Liu and Li (2009) suggested that a connection exists between SST anomalies in the east equatorial Pacific in the winter and temperature ($T_{\rm a}$) during the following summer in the TP.

The relationship between SST over the Pacific and $T_{\rm a}$ in the TP has drawn more interest in recent years. However, some questions remain. How fast does TP $T_{\rm a}$ increase in relation to global warming? Does a lag or lead phase exist between TP temperature and Pacific SST anomalies? What is the linkage underlying the relationship between SST and TP temperature changes?

To answer these questions, we conducted a detailed analysis of the features of TP maximum temperature ($T_{\rm max}$) and minimum temperature ($T_{\rm min}$) changes, atmospheric general circulation, the warming pool, and equatorial central-eastern Pacific SST anomalies. The remainder of this paper is organized into the following sections. In the next section, we describe the datasets and analysis methods. In section 3, we examine the evolution of TP $T_{\rm max}$ and $T_{\rm min}$ during the past 46 years. In section 4, we analyze the relationship of TP $T_{\rm max}$ and $T_{\rm min}$ with SST and atmospheric circulation in East Asia. In section 5, we further investigate the impact of SST and atmospheric circulation on the Asian-Pacific sector, simulated using a climate model of TP $T_{\rm max}$ and $T_{\rm min}$ changes. A summary and discussion are provided in section 6.

2. Data and methods

The continuous daily temperature data from 1961 to 2006 from 30 observation stations (Fig. 1) over the TP above 3000 m above sea level (a.s.l.) were used to calculate the range of temperature difference. To ensure the quality of the data, a comparison of the observation data and gridded Climatic Re-

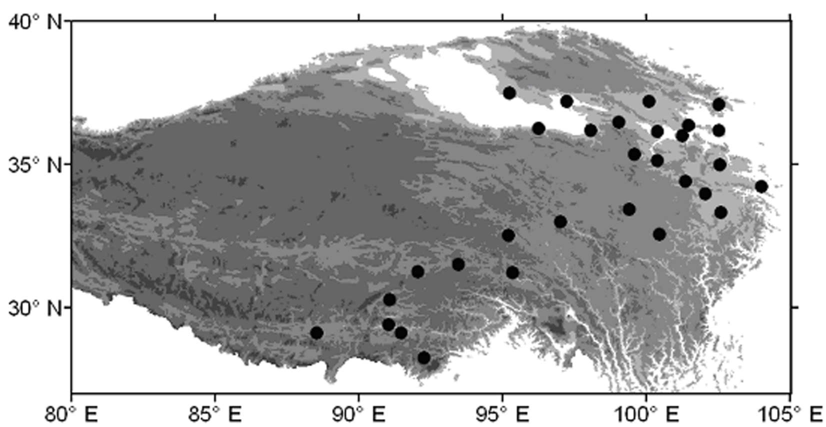

Fig. 1. Distribution of observation stations in the research domain.

search Unit (CRU) data (Jones and Moberg, 2003) was made. The results show that a significant correlation exists between both datasets at the 99% confidence level (1961–2006). Daily wind at 200-hPa was derived from NCEP/NCAR data (1961–2006, 2.5°×2.5° grid; Kalnay et al., 1996). The monthly global SST data were derived from NOAA (1961–2006, 2.0°×2.0° grid; Smith and Reynolds, 1998). The abrupt changes in T_a and T_{min} were detected using the Mann-Kendall (M-K) method and Moving Student t-test (MTT).

3. Characteristics of temperature changes over the TP during the past 50 years

To analyze the changes in temperature in the TP, T_a, T_{min}, T_{max}, and diurnal temperature range (DTR) (Table 1), trends were calculated using linear regression. The results showed a trend in annual T_a of 0.27°C (10 yr)$^{-1}$ during 1961–2006. The T_{min} trend was 0.32°C (10 yr)$^{-1}$, and the slight trend for T_{max} was 0.09°C (10 yr)$^{-1}$ were far less than those of T_{min} and T_a. Spring T_{max} changes were minimal during the past 50 years, whereas T_{min} and T_{max} showed significant asymmetrical changes. T_{min} appears to be the main factor for increased T_a in the TP, whereas T_{min} increased mainly in the winter and spring. The asymmetrical change between T_{min} and T_{max} led to a decline in DTR [0.23°C (10 yr)$^{-1}$]. The DTR decrease also mainly appeared in winter [0.36°C (10 yr)$^{-1}$] and spring [0.37°C (10 yr)$^{-1}$].

The above results coincide with previous investigations in the Northern Hemisphere. T_{min} increased 0.2°C (10 yr)$^{-1}$, and DTR decreased 0.14°C (10 yr)$^{-1}$ during 1951–1990 (Karl et al., 1993). T_a, T_{max}, and T_{min} increased 0.12°C (10 yr)$^{-1}$, 0.01°C (10 yr)$^{-1}$, and 0.29°C (10 yr)$^{-1}$, respectively. DTR decreased 0.08°C (10 yr)$^{-1}$ during 1996–2002 (Oku et al., 2006). These results show that T_{min} increased faster than T_{max}, which caused significant asymmetrical changes in the TP, consistent with other studies (David et al., 1997).

Although T_a in the TP showed a positive trend over the entire period of observation, a considerable amount of fluctuation and variation occurred. Figure 2 illustrates the evolution of T_a, T_{min}, T_{max}, and DTR. A notable feature is that T_a and T_{min} increased significantly in the mid-1980s. T_{max} increased and DTR decreased significantly in the mid-1970s. We first determined whether abrupt changes in T_{min}, T_a, and DTR occurred. The temperature jumps depend on time scales because of the different temporal periods of the data and different numbers of stations used in the analysis. Table 2 shows the abrupt changes in T_{min}, T_a, and DTR revealed by M-K and MTT.

As shown in Table 2, abrupt changes in T_a and T_{min} occurred around 1986. These results are consistent with previous studies (Ma and Li, 2003; Kang et al., 2006; Ding and Zhang, 2008). Remarkable changes in both T_a and T_{min} occurred around the jump point, which was statistically significant at the 95% confidence level, revealed by M-K and MTT. However, no significant change in T_{max} was found. Similarly, on the seasonal scale, the abrupt changes were inconsistent between variables. These seasonal differences in T_{min}, T_a, and DTR require further study.

The above analysis showed differences in the changes in T_a, T_{min}, T_{max}, and DTR over the TP under the background of global warming. T_a and T_{min} evidently increased faster than T_{max}, and DTR decreased significantly because of the asymmetrical changes in T_{min} and T_{max}. Another significant feature is that abrupt changes in T_a and T_{min} occurred around 1986, but no significant abrupt change was found for T_{max}. In general, T_{min} usually appears at night, with no shortwave radiation effects. Some studies attributed these effects to greenhouse gases GHGs, which may be responsible for asymmetrical changes in T_{min} and T_{max} and the consequent decrease in DTR (Duan et al., 2006). However, the study also showed that the amount of GHGs emissions was very small over the TP (Bai et al., 2006). Aside from the impact of GHGs on the TP, the mean SST is considered an important regulator of global and regional climate changes (Bjerknes, 1969; Ratcliffe and Murray, 1970; Horel and Wallace, 1981; Namias et al., 1988; Kiladis and Diaz, 1989; Glantz et al., 1991; Halpert and Ropelewski, 1992).

In the following section, we report our investigation of the role of SST in the Pacific and Indian oceans in

Table 1. Variability of annual temperature (T_a) minimum temperature (T_{min}), maximum temperature (T_{max}), and diurnal temperature range (DTR) over the TP [°C (10 yr)$^{-1}$].

	Trend					
	Annual	Spring	Summer	Autumn	Winter	Time segment
T_{min}	0.32	0.37	0.18	0.32	0.38	1961–2000
T_{max}	0.09	−0.00	0.12	0.17	0.04	1961–2000
T_a	0.27	0.18	0.19	0.28	0.43	1961–2006
DTR	−0.23	−0.37	−0.06	−0.15	−0.36	1961–2000

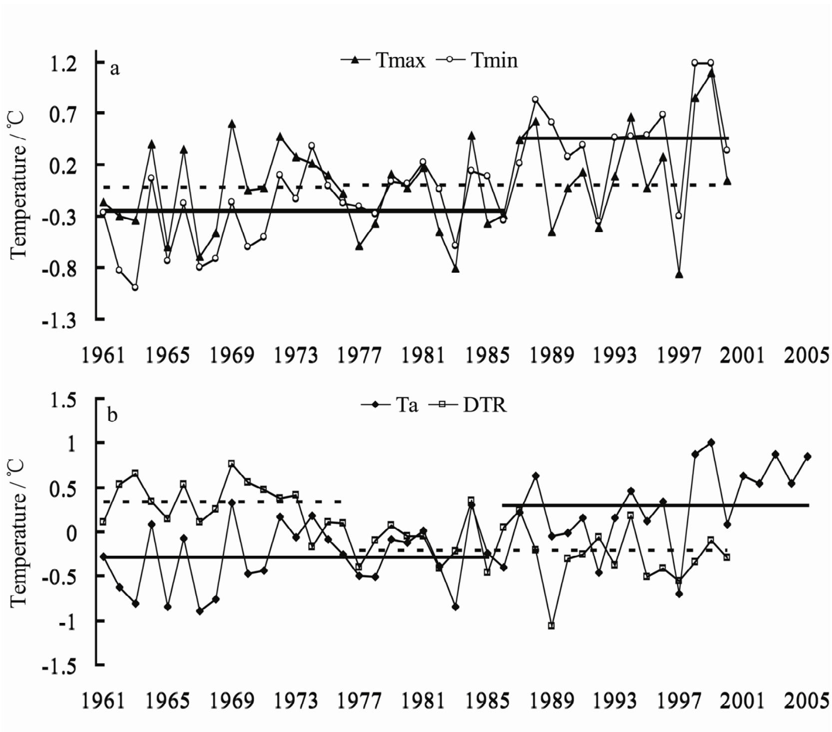

Fig. 2. Evolution of anomalies of $T_{\max}$, $T_{\min}$. (a) Solid lines and dotted lines indicate the average for $T_{\min}$ and $T_{\max}$, T_{a}, and (b) DTR over the TP. Solid lines and dotted lines indicate the average for T_{a} and DTR.

Table 2. Abrupt changes in minimum temperature ($T_{\min}$), annual temperature (T_{a}), and diurnal temperature range (DTR) over the TP, detected using the Mann-Kendall (M-K) method and Student t-test.

	Spring	Summer	Autumn	Winter	Annual
$T_{\min}$	1983	1986	1986	1971	1986
T_{a}	1990	1986	1986	1987	1986
DTR	1976	1965	1977	1974	1976

the trends of increased annual T_{a} and $T_{\min}$ in the TP, as a robust factor. In addition, the contribution of the East Asian atmospheric circulation to increases of the TP T_{a} and $T_{\min}$ were analyzed. Due to the $T_{\min}$ increase is remarkable and a significant factor in the increase in T_{a} in the TP. The present study focused on the roles played by SST and East Asian atmospheric circulation on changes in $T_{\min}$ over the TP.

4. Characteristics of the correlation between TP temperature and SST and atmospheric circulation

4.1 *Correlational characteristics between $T_{\min}$, T_{a}, and SST and atmospheric circulation*

To analyze the relationships between TP temperature, SST, and atmospheric circulation, the correlations of $T_{\min}$ and T_{a} with SST and 200-hPa zonal winds were calculated (Fig. 3). The teleconnection patterns showed significant positive correlations (significant level P=0.01) of $T_{\min}$ and T_{a} with SST (Figs. 3a, b) on the southeast China coast, the warm pool of the western Pacific coast, and the Bay of Bengal. Additionally, a significant positive correlation was found between $T_{\min}$, T_{a}, and 200-hPa zonal winds (Fig. 3c) in the northern area of the TP, whereas a negative correlation (Fig. 3d) was found in the southern area. These results corresponded well to the location of the subtropical westerly jet stream (SWJ) and the tropical easterly upper jet stream (TEJ).

Figure 3 also shows four significant correlation areas. We further analyzed the relationships between TP T_{a}, $T_{\min}$, and SST and western Pacific and general East Asian circulation. We defined correlation area A (5°S–20°N, 110°–130°E) between T_{a}, $T_{\min}$, and SST,

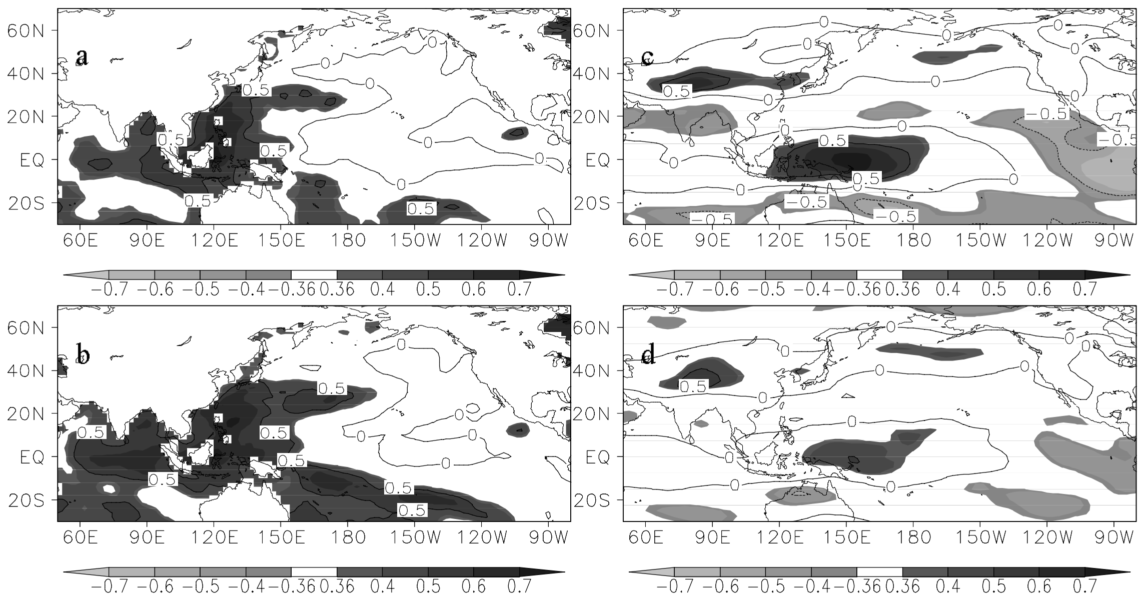

Fig. 3. Distribution of the correlation between SST and $T_{\rm min}$ (a), $T_{\rm a}$ (b), 200-hPa zonal wind and $T_{\rm min}$ (c), $T_{\rm a}$ (d). The shaded areas indicate significance at the 99% confidence level.

and we also defined three significant correlation areas between $T_{\rm min}$, $T_{\rm a}$, and 200 hPa zonal wind (Fig. 4): area B (10°S–10°N, 132°–172°E), area C (32°–40°N, 75°–95°E), and area D (14°–23°N, 75°–95°E).

Area A is related to warm SST in the warm pool of the Pacific Ocean (Figs. 3c, d), whereas areas B and C represent two different locations of the 200-hPa SWJ and TEJ. A close correlation was found between areas B, C, and D and 200-hPa zonal winds. A significant correlation ($r_{\rm B,C}$) was found between areas B and C ($r_{\rm B,C}$=0.55, P=0.01). A distinct correlation was found between the SWJ in the northern TP and the warm pool SST in the Pacific Ocean. We also found that, although areas B and D are in the same easterly wind system, areas B and D are possibly influenced by different oceans (i.e., area B is located in the Pacific Ocean and area D is located in the Indian Ocean). However, the correlation between 200-hPa zonal wind and areas B and D was not significant ($r_{\rm B,D}$=0.28, P=0.01). This reflects the complexity of subtropical westerly wind and tropical easterly wind.

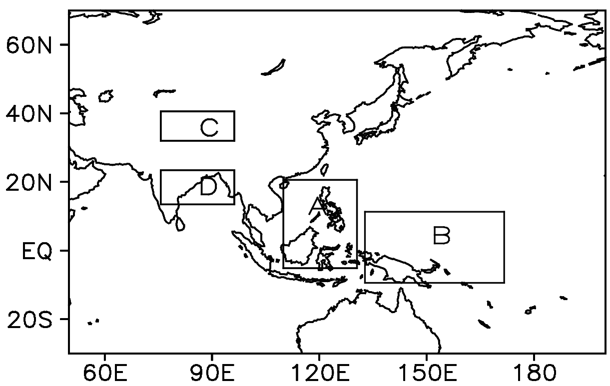

Fig. 4. Significant correlation areas of between $T_{\rm min}$, $T_{\rm a}$, and SST and 200-hPa zonal wind in area A (5°S–20°N, 110°–130°E), area B (10°S–10°N, 132°–172°E), area C (32°–40°N, 75°–95°E), and area D (14°–23°N, 75°–95°E).

4.2 *Differences in SST and atmospheric circulation pre- and post-abrupt changes*

We analyzed the relationships among SST, westerly/easterly winds, and temperature changes. The differences in 200-hPa zonal wind and SST before and after the $T_{\rm a}$ abrupt change in the TP in 1986 was calculated (Fig. 5). The difference in SST (Fig. 5a) was significant over the equatorial Pacific Ocean and the warm pool of the Pacific Ocean (P =0.01), and a significant correlation area was found among $T_{\rm min}$ and SST and 200-hPa zonal wind. The significant area of the 200-hPa westerly zonal wind was relatively small, but the change in easterly zonal wind was not significant in the southern TP.

The above analyses show significant correlations between TP warming and adjustments in general atmospheric circulation in the middle-upper troposphere in the warm SST pool of the Pacific Ocean. Increases in $T_{\rm a}$ and $T_{\rm min}$ over the TP obviously related to the strength of the westerly winds over the northern TP, the decrease in easterly winds over the southern TP, and the increase in SST in the warm pool of the western Pacific.

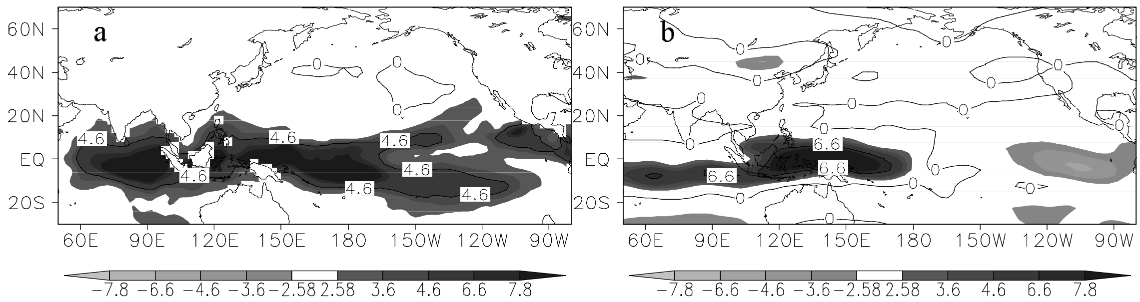

Fig. 5. Differences of SST and zonal wind at 200 hPa between pre- and post-abrupt changes in 1986: (a) indicates SST, (b) indicates zonal wind at 200 hPa. The shaded areas indicate significance at the 99% confidence level of Student t-test.

One remaining issue is the linkage between TP warming and SWJ and atmosphere circulation over the warm pool of the western Pacific.

5. Contribution of SST relative to westerly/easterly zonal winds in TP warming

5.1 *Correlating features between* $T_{\rm min}$ *and* $T_{\rm a}$ *in the TP and SST and* 200-hPa *zonal wind*

Generally, SST has longer persistence. We analyzed the sustainability of the correlation of $T_{\rm min}$ and $T_{\rm a}$ with SST and 200-hPa zonal wind. Figures 6a and 6b show a lag correlation of $T_{\rm min}$ and $T_{\rm a}$ with SST (area A) and 200-hPa zonal wind (areas B, C, and D). The results show a significant positive correlation (P = 0.01) among $T_{\rm min}$, $T_{\rm a}$, and SST and 200-hPa zonal wind (areas B and C) during the same period. The correlation between SST and 200-hPa zonal wind (areas B and C) led to $T_{\rm min}$ approximately four seasons later, which is significant at the 0.05 level. These results indicate that the late TP $T_{\rm min}$ increases were likely influenced by the early SST warm pool in the Pacific Ocean and profound easterly winds over the equatorial Pacific. $T_{\rm min}$ also lagged TEJ over the equatorial Pacific and northern Xinjiang province by approximately four seasons. These results suggest that the increase in $T_{\rm min}$ might be linked with the SST warm pool, easterly wind over the warm pool of the

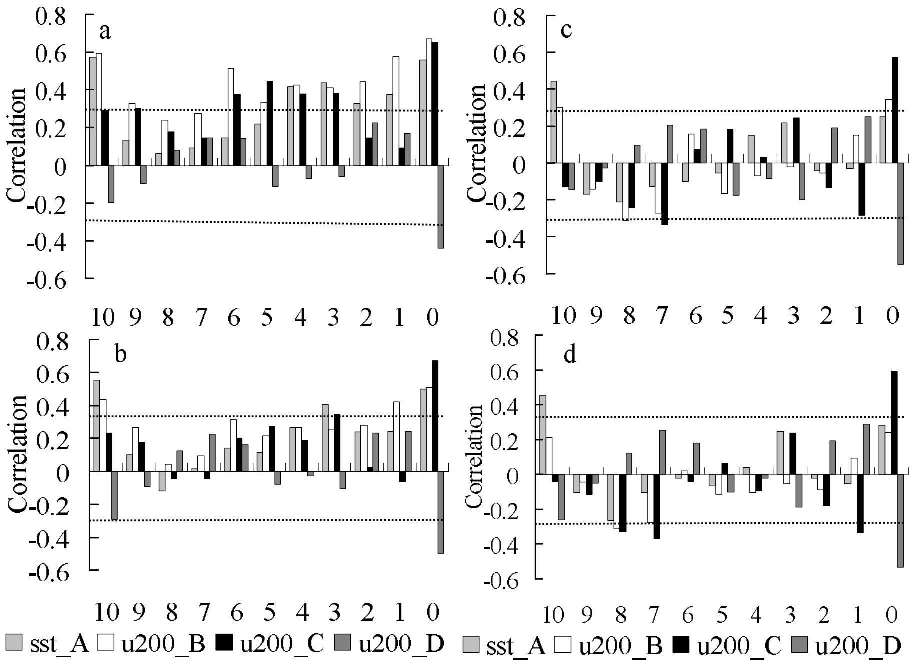

Fig. 6. Distribution of correlations between (a) $T_{\rm min}$ and SST, (b) correlation between $T_{\rm a}$ and SST, (c) correlation between detrended $T_{\rm min}$ and detrended 200 hPa zonal wind, (d) correlation between detrended $T_{\rm a}$ and detrended 200-hPa zonal wind. The dashed lines indicate significance at the 95% confidence level.

Pacific Ocean, and westerly stream in the middle latitude (Xinjiang province) four seasons later. However, although the relationships between $T_{\min}$ and 200-hPa zonal wind in areas D and C were strong, the lag correlations between $T_{\min}$ and 200-hPa zonal wind in both C and D were not significant. This may be interpreted as the shorter persistence of zonal wind. We also found a correlation between $T_{\min}$ in the TP and zonal wind in area C three to six seasons later, but we lack a reasonable explanation for this. The correlation between T_{a} and SST and 200-hPa zonal wind (areas B and C) was not significant when SST and 200-hPa zonal wind led T_{a} (Fig. 6b). T_{a} depends on both $T_{\min}$ and $T_{\max}$, and the difference in the correlations of $T_{\min}$ and T_{a} with SST and zonal wind suggest that $T_{\min}$ is likely more sensitive to external forces.

Furthermore, we investigated whether the relationships of TP T_{a} and $T_{\min}$ with SST and 200-hPa zonal wind are essential and whether they are influenced by the same external forces. Correlations of TP T_{a} and $T_{\min}$ with SST (area A) and 200-hPa zonal wind (areas B, C, and D) after detrending were calculated. Figure 6c and d show that a significant correlation existed only between $T_{\min}$ and T_{a} and westerly (or easterly) wind in areas B, C, and D during the same period. The correlation between $T_{\min}$, T_{a}, and SST (area A) was not significant. These results indicate that the change in TP $T_{\min}$ directly resulted from the westerly wind system. Figure 6d also shows the same results for T_{a} and the relationship between $T_{\min}$ and T_{a} and SST in area A produced by external forces.

To separate the relative contribution of SST (area A) and zonal wind (areas B, C, and D) in the increasing trend in TP $T_{\min}$ and T_{a}, partial correlations between $T_{\min}$, T_{a}, and SST (area A) and zonal wind (areas B, C, and D) were calculated (Figs. 7a, b) using Eq. (1)

$$r_{y1.234} = \frac{r_{y1.23} - r_{y4.23} r_{14.23}}{\sqrt{1 - r_{14.23}^2}\sqrt{1 - r_{y4.23}^2}} \quad (1)$$

where $r_{y1.234}$ is the partial correlation between y and x_1 that excludes x_2, x_3, and x_4, and $r_{y1.23}$ $(r_{y4.23}/r_{14.23})$ is the partial correlation between $y(y/x_1)$ and $x_1(x_4/x_4)$ that excludes x_2 and x_3.

Figure 7 shows that westerly wind (area C) and easterly wind (area B) were more important than SST (area A) and easterly wind (area D) in the increasing trend in TP $T_{\min}$ (Fig. 7a). Westerly wind (area C) was more important than the others in the increasing trend in TP T_{a}. Furthermore, westerly wind (area C) was significantly more important than the others in the increasing trend in TP T_{a} and $T_{\min}$ after detrending ($T_{\min}$, T_{a}, SST, and 200-hPa zonal wind) (Fig. 7b).

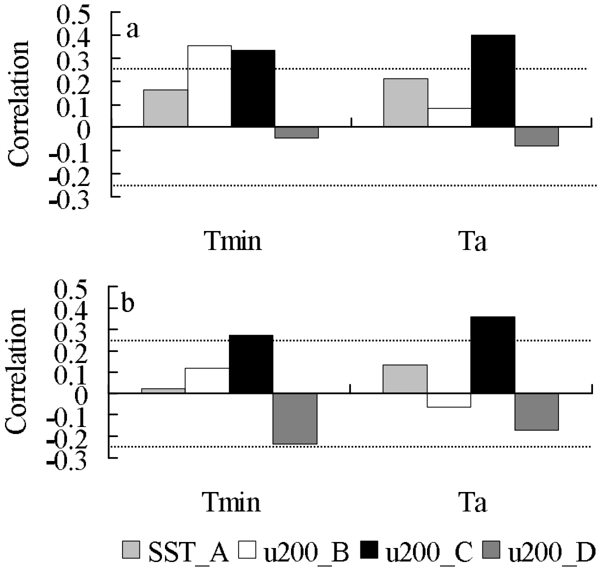

Fig. 7. (a) Partial correlations between $T_{\min}$, T_{a}, and SST and 200 hPa zonal wind. (b) Similar to (a), but for all the variables detrended. The dashed lines indicate significance at the 90% confidence level.

Similarly, $r_{\mathrm{B,C}} = 0.41$ (P =0.01) and $r_{\mathrm{B,D}} = 0.32$ (P =0.05) after detrending, which are significant statistical results. The changes in westerly and easterly winds in the middle-upper troposphere were interrelated with the same westerly wind systems, but different trend changes were found. Additionally, areas B and D are different regions of tropical easterly winds. Area C is in the westerly wind. Therefore, the location and strength of easterly winds in areas B and C are affected by each other, but the easterly wind in area D and westerly wind in area C more likely connected with the thermodynamics of the TP and excite each other.

Similarly, we calculated the correlations of $T_{\min}$ (detrended) with SST (undetrended) and 200-hPa zonal wind (undetrended). The results show a significant correlation (P =0.05) between $T_{\min}$ and 200-hPa zonal wind (areas C and D), the correlation are 0.52 and -0.55 separately, whereas the correlations of $T_{\min}$ with SST (area A) and 200-hPa zonal wind (area B) are not significant. The change in TP T_{a} may well have been directly influenced by westerly wind systems. Conversely, the correlation of $T_{\min}$ with SST (detrended) and 200-hPa zonal wind (areas B, C, and D; detrended) is not significant. These results suggest that the increasing trend in TP $T_{\min}$ was directly controlled by SWJ and TEJ above the northern and southern TP. Moreover, the increasing trend in TP $T_{\min}$, SST, and 200-hPa zonal winds were influenced by the same external forces.

This analysis shows that $T_{\min}$ related to 200-hPa

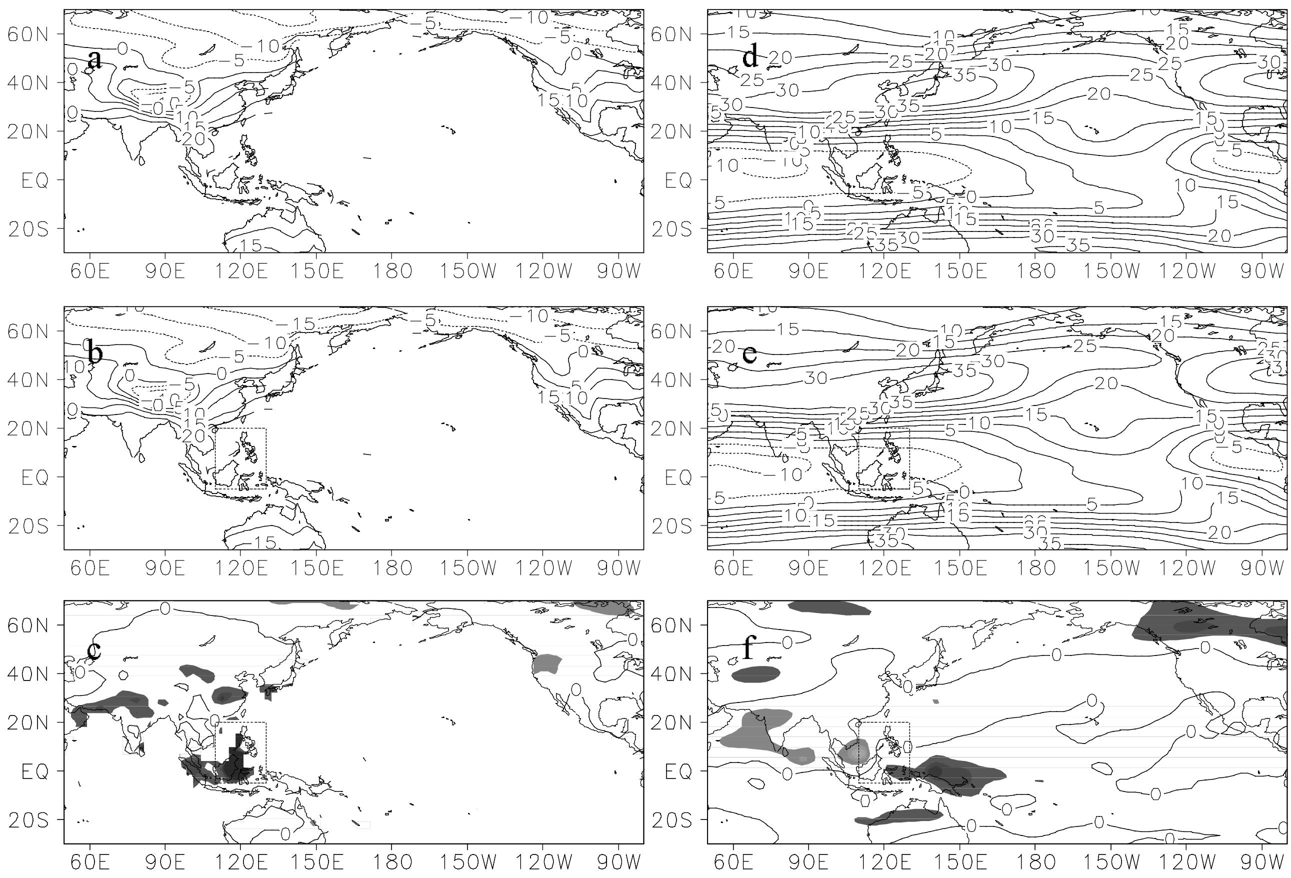

Fig. 8. Distribution of $T_{\min}$ in (a) control experiment (CE) and (B) sensitive experiment (SE), Distribution of 200 hPa zonal wind in (d) CE and in (e) SE. Differences of (c) $T_{\min}$ and (f) 200 hPa zonal wind between SE and CE. The shaded areas indicate significance at the 95% confidence level.

zonal wind (areas B, C, and D) and SST (area A), but this connection was subjected to the same external forces. TP warming may be influenced by SST, but SST impacts the strength and location changes of the easterly wind over the Pacific Ocean, leading to the TEJ location and intensity changes over the southern TP. Furthermore, TEJ excites changes in SWJ, and the strength and location of SWJ impacts the changes in $T_{\rm a}/T_{\min}$ in the TP. These results indicate that TP climate change is directly influenced by easterly wind, SWJ, and TEJ over both the southern and northern TP. The further physical links between these components (SWJ, TEJ, SST in warm pool and TP warming) are complex and deserve further investigation.

5.2 *Numerical experiments*

To further validate our analysis, we designed two group tests with CAM3.0. The control experiment (CE) was without changes in the modeling. The sensitivity test (SE) used +0.5°C (1 standard variance) SST in area A. The simulations were run for 20 years; however, only data obtained in the last 10 years were analyzed.

Figure 8 shows the changes in $T_{\min}$ in CE (Fig. 8a) and SE (Fig. 8b). The difference between the SE and the CE was significant (*t*-test) (Fig. 8c). The results showed significant warming (P =0.05) in the TP hinterland when SST increased in area A. The increase in TP $T_{\rm a}$ was significantly influenced by SST in the western Pacific. The 200-hPa zonal wind was either strengthened or weakened in areas B, C, and D. Although the temperature changes in distinct areas do not match well to statistics, the model reproduced impacts of SST in warm pool on TP temperature changes. These results are consistent with the results described in section 4; showing that the increase in warm pool SST played an important role in the increase in TP $T_{\rm a}$ and the changes in westerly and easterly winds. Due to a community atmosphere model (CAM) coupled with a slab ocean model (SOM), the sensitivity experiments of impacts of TP warming on SST could not be performed. Hence, the actual physical links between TP temperature change and SST (such as APO phenomena) are complex and deserve further investigation.

6. Discussion and conclusion

Adaptations to external forces are one essential characteristic of the climate system. The TP enlarges the effects of climate change because of its special terrain, which plays a special role in climate change in East Asia. Under the background of global warming, the contribution of increased GHS to increased global T_a has been confirmed by numerous studies (e.g., Surabi et al., 2002; Malte et al., 2009). On the regional scale, the response to global warming requires further study, and the increases in TP T_a and T_{min} are representative. This study also showed that SWJ in East Asian and warm pool SST play different roles in the increases in TP T_a and T_{min}. The following findings are a summary of this study.

(1) In TP warming, T_{min} increased most remarkably. Asymmetrical changes in T_{min} and T_{max} occurred, which caused the decrease in DTR. Thus, the increase in T_{min} was the main cause for TP warming. Around 1986, significant abrupt changes in T_{min} and T_a occurred in the TP. Significant differences were found in the intensity and location of the SWJ and the TEJ in the East Asian general circulation, warm pool SST in the Pacific Ocean, and easterly wind over the equatorial central Pacific. These factors are closely related to the increasing trends in TP T_a and T_{min}.

(2) Warm pool SST in the Pacific Ocean was a robust factor in the increasing trend in T_{min}. Lu (2001) point out that the difference in circulation between strong and weak convection over the western Pacific warm pool significantly associate with westward extension of the western Pacific subtropical high, which dominates summer precipitation of China and also relates to easterly anomalies over the warm pool. The results of the numerical experiments in this study reveal that the increase in warm pool SST caused the changes in SWJ and TEJ. However, the impact of warm pool SST on the increases in T_{min} over the TP was not direct. The results demonstrate that warm pool SST caused the changes in the intensity and location of tropical easterly wind over the warm pool. The changes in tropical easterly wind, in turn, caused the changes in SWJ at the entrance of the SWJ (i.e., at the ridges of northern Xinjiang; 500 hPa) and TEJ over the Indian region (i.e., the southern TP). Finally, SWJ and TEJ led to the increase in TP T_{min}. In TP temperature change, SWJ and TEJ act as the atmospheric bridges to remote SST forcing; this mechanism is similar to the relation of SST and precipitation anomalies of the Yangtze River valley of China (Wang et al., 2011b; Liang et al., 1997, 1998, 2001).

(3) Warm-pool SST has increased by 0.28°C in the past 100 years (Zhang et al., 2009). Our results show that SST (area A) increased by 0.42°C during 1961–2006. A significant correlation was found between TP T_{min} ahead ($<$ 5 seasons) of SST increases in the warm pool, but the correlation was not significant when the trends in T_{min} and SST were removed. By combining the results of the numerical experiments and data analysis, we can speculate that external forces (including GHGs and the conveyor belt of ocean current) elicit changes in warm-pool SST, leading to further increases in TP T_{min}. The mechanisms underlying this linkage, including whether it involves GHGs, require further study.

Acknowledgements. The authors wish to express their gratitude to Prof. Deliang Chen for meticulous proofreading of the manuscript and kind suggestion for language polishing. We thank the Climate Diagnostic Center/NOAA for providing the NCEP-NCAR reanalysis data, the University of East Anglia for providing the CRU data on their websites. We also thank NCAR for providing the CAM3 model on its website and the Gansu supercomputer center of China. The research was supported by the National Basic Research Program of China (Grant No. 2007CB411506), National Natural Science Foundation of China (Grant Nos. 4107108 and 40875050).

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