Interdecadal variability in the thermal difference between western and eastern China and its association with rainfall anomalies

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Abstract

This study investigated the spring thermal difference between western and eastern China and its association with the rainfall anomalies using station and reanalysis data from 1960 to 2006. The spring thermal difference between western and eastern China underwent an obvious interdecadal shift around 1979. The thermal difference between western and eastern China was small during 1960–1978, which strengthened the southwesterly wind anomalies in line with the thermal wind. This enhanced the East Asian summer monsoon. In addition, the increase in rainfall over North China and decrease in rainfall over the Yangtze River were associated with the strong East Asian summer monsoon. However, during 1979–2006, the thermal difference between western and eastern China was large, which strengthened the northeasterly wind anomalies in line with the thermal wind. This supports the notion of weakened East Asian summer monsoon associated with the decrease in rainfall over North China and increase in rainfall over the Yangtze River.

Keywords: thermal difference; interdecadal variability; rainfall

1. Introduction

The East Asian summer monsoon is an important subsystem of the global climate system. The monsoon is related to changes in the land–sea thermal contrast. Previous studies mainly focused on the ocean thermal change and land surface processes to study the East Asian summer monsoon. In the ocean thermal change, many have studied the thermal effect of the Western Pacific warm pool and El Niño-Southern Oscillation (ENSO) cycle. East Asian summer monsoon anomalies were associated with the thermal variability of the Pacific Sea Surface Temperature (SST) anomalies (e.g. Huang et al., 1999; Chang et al., 2000a, 2000b; Wang, 2001; Wu and Wang, 2002; Zhou and Huang, 2003; Zhou and Chan, 2007; Ding et al., 2008). In addition, the thermal state of the warm pool and its overhead convective activities play an important role in the interannual variation of the East Asian summer monsoon (Huang and Li, 1987; Nitta, 1987; Huang and Sun, 1992). In terms of land surface processes, the effect of land–air interaction on the East Asian summer monsoon has been studied extensively (e.g. Webster, 1983; Yeh et al., 1984; Meehl, 1994; Douville and Royer, 1996; Yang and Xu, 1994; Yang and Lau, 1998; Xu et al., 2006; Wu and Kirtman, 2007; Zhou and Huang, 2010). Many studies also pointed out that the Qinghai Plateau has a huge heating effect on atmospheric and thermal anomalies, and strongly affects the East Asian summer monsoon (e.g. Ye and Gao, 1979; Li et al., 2003; Zhao and Qian, 2007). More recently, the effect of the thermal state of the arid and semiarid Northwest China on the East Asia climate change was studied. One of the regions with the strongest surface sensible heat flux is in Northwest China, which is called a warm underlying surface, whose variability may impact local and remote climate (Zhou and Huang, 2008, 2010; Zhou et al., 2009). Moreover, Gao et al. (2008) numerically simulated the thermal anomaly in Northwest China that affects the local and surrounding atmospheric circulation anomalies. Many ecosystems with different surface characteristics, e.g. Gobi desert and the humid monsoon regions, characterize China. Northwest China is an arid and semiarid region with strong solar radiation, sparse vegetation, and strong surface sensible heat flux. In contrast, eastern China is a monsoon region with high precipitation and weak surface sensible heat flux. Based on station data, Qu et al. (2011) and Wen et al. (2014) concluded that the surface air temperatures, precipitation, and temperature differences were not the same between eastern and western China. Zhou and Huang (2014) pointed out the significant difference in surface sensible and latent heat fluxes between western and eastern China using the ERA-40 reanalysis datasets. The surface radiation fluxes were also found to have the same characteristics based on CMIP5 data (Zhou and Du, 2016). It is well established that the monsoon is mainly caused by the...
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Figure 1. The locations of the 218 stations for $T_s$ and $T_a$, including western China stations (red), eastern China stations (blue), and other stations (black).

Figure 2. Time series of spring $T_s - T_a$ anomaly in western China (unit: °C) (a) and in eastern China (unit: °C) (b). (c) Time series of $\Delta(T_s - T_a)$ anomaly in spring (unit: °C). The solid curve shows the 7-year running mean. Values are the averages of the measurements from the stations in western and eastern China. The climatological mean of $T_s$ and $T_a$ in various months averaged for 1971–2000 is taken as their normal, respectively. (d) The forward and backward statistic rank series (solid and dashed curves) in the Mann–Kendall test of the spring $\Delta(T_s - T_a)$. The solid straight lines indicate the 0.05 confidence level of the Mann–Kendall test.

Figure 3. Distributions of the summer (JJA) rainfall (unit: mm) averaged for 1960–1978 (a), and 1979–2006 (b). The climatological monthly mean is based on the period 1971–2000. The solid and dashed lines indicate positive and negative values, respectively. Shaded regions denote positive anomalies in (a) and (b).

thermal contrast between land and sea. The thermal differences between the arid areas of Northwest China and the humid monsoon regions of eastern China inevitably contribute to the local and remote atmospheric circulation. Moreover, the temperature difference was related to the rainfall and circulation anomalies in China (Zhou and Huang, 2006; Zhou, 2015).

2. Datasets

This study used daily observations of the land surface temperature ($T_s$) and the surface air temperature ($T_a$) at 218 stations in China from 1960 to 2006. Monthly rainfall data for 1960–2006 were collected at 160 stations. The above data were provided by the Chinese Meteorological Data Center. The monthly mean wind, temperature, omega, height, sea level pressure (SLP), and special humidity were derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis for 1960–2006.

3. Results

3.1. Interdecadal variability of the spring thermal difference between western and eastern China

The sensible heat flux was predominantly determined from the difference between the surface temperature
Figure 4. Distributions of the summer (JJA) water vapor flux (integration of 1000–100 hPa) anomalies (unit: kg m$^{-1}$ s$^{-1}$) (a), water vapor flux (integration 1000–100 hPa) convergence anomalies (unit: g m$^{-2}$ s$^{-1}$) (c), and omega anomalies at 700 hPa (unit: Pa s$^{-1}$) (e) averaged for 1960–1978. The (b), (d), and (f) are same as (a), (c), and (e), but for averaged for 1979–2006. The climatological monthly mean is based on the period 1971–2000. The solid and dashed lines indicate positive and negative values, respectively. The shaded regions indicate the 0.05 significance level according to the Student’s t-test.

(56x79)andsurfaceairtemperature($T_s$)difference, $T_s-T_a$ (Fan et al., 2004; Zhou, 2009). Thus, we used this land–air temperature difference to study the thermal difference between western and eastern China and its association with the East Asian summer monsoon. Previous studies show there was an obvious difference in $T_s-T_a$ between western and eastern China (Wen et al., 2014; Zhou and Wen, 2016). According to station location from Figure 1, the region average in $T_s-T_a$ of western and eastern China was calculated, respectively. Figure 2 shows the mean $T_s-T_a$ anomalies in western and eastern China in spring. The $T_s-T_a$ anomalies were mostly negative in western China before the late 1970s and largely positive after the late 1970s (Figure 2(a)). However, for eastern China (Figure 2(b)), the $T_s-T_a$ anomalies were mostly positive before the late 1970s but largely negative after the late 1970s. The data suggest that the spring thermal state in eastern and western China underwent an opposite interdecadal shift around the late 1970s. Moreover, $\Delta(T_s-T_a)$ was used to represent the thermal difference between western and eastern China, where $\Delta(T_s-T_a) = (T_s-T_a)_{\text{west}} - (T_s-T_a)_{\text{east}}$.

Figure 2(c) shows that the $\Delta(T_s-T_a)$ anomalies were mainly low before the late 1970s but mostly high thereafter. $\Delta(T_s-T_a)$ also suggests an interdecadal increase around late 1970s. The 7-year running mean (curve) in Figure 2(c) point to the interdecadal shift. The Mann–Kendall (M–K) test was used to analyze the shift in $\Delta(T_s-T_a)$. The two statistical rank series of the test are shown in Figure 2(d), which cross the year 1979 above the 95% confidence level. This suggests that the interdecadal shift of $\Delta(T_s-T_a)$ took place around 1979 and supports the appearance of the interdecadal shift around 1979. Consequently, the thermal difference between western and eastern China was stronger in 1979–2006 than 1960–1978.

3.2. Interdecadal variability of rainfall in China

The temperature difference was related to the rainfall anomalies in China (Zhou and Huang, 2006; Zhou, 2015). To investigate the association of the thermal difference anomaly with the summer rainfall variability in China, summer rainfall anomalies, water vapor flux and moisture, and vertical velocity were examined before and after 1979.

During 1960–1978, positive rainfall anomalies appeared over North China and negative anomalies appeared over the Yangtze River (Figure 3(a)).
these anomalies were related to the East Asian summer monsoon circulation. The southwestward anomalous water vapor fluxes along the coast of eastern China substantially enhanced the moisture supply to North China from the South China Sea. This consequently increased the summer rainfall over North China (Figure 4(a)). Moreover, the increase in the rainfall was associated with water vapor flux convergence and ascending motion over North China. On the other hand, the decrease in the rainfall was associated with water vapor flux divergence and sinking motion over the Yangtze River (Figure 4(c) and (e)). However, during 1979–2006, negative rainfall anomalies also appeared over North China and positive anomalies appeared over the Yangtze River (Figure 3(b)). This was related to the weakening of the East Asian summer monsoon and the dominant northeasterly anomalies over East Asia. The northeastward anomalous water vapor fluxes were not contributed to transport into North China (Figure 4(b)), which were helpful for a decrease in rainfall over North China. Moreover, tropospheric moisture divergence and sinking motion occurred over North China (Figure 4(d) and (f)), whereas tropospheric moisture convergence and ascending motion were observed over the Yangtze River (Figure 4(d) and (f)). The latter contributed to increased rainfall in the region.

To understand the relationship between spring thermal difference between western and eastern China and the East Asian summer monsoon, the summer wind at 850 hPa, temperature at 700 hPa, and SLP were analyzed. Figure 5 shows regression of summer wind at 850 hPa (unit: m s\(^{-1}\)), temperature at 700 hPa (unit: °C), and sea level pressure (SLP) (unit: Pa) with respect to the normalized spring thermal difference for the period of 1960–2006. From Figure 5(a), an anticyclonic circulation anomaly appeared over Mongolia. And the anomalous northeasterly winds occurred over eastern China. This may be related to the negative temperature anomalies appeared over Mongolia, which corresponded to positive land–air temperature difference between eastern and western China (Figure 5(b)). The negative temperature anomalies corresponded to an increased in SLP (Figure 5(c)). This enhanced in pressure difference contributed to an increase the northeasterly wind anomalies in East Asia, and a decrease in the East Asian summer monsoon.

### 3.3. Interdecadal variability of the atmospheric circulation

The summer rainfall anomalies in China and atmospheric circulation anomalies are closely related. In the previous section, the data suggested that the thermal difference underwent an interdecadal shift around 1979. Moreover, the thermal differences were closely related with the East Asian summer monsoon. To understand the thermal difference between western and eastern China and its association with the interdecadal variability in East Asian summer monsoon circulation anomalies, the summer 850 hPa wind, SLP, 700 hPa temperature, and geopotential height anomalies at 500 hPa were analyzed before and after 1979.

During 1960–1978 (Figure 6(a)), cyclonic circulation anomalies appeared over Mongolia. To the east flank of this anomalous cyclone were anomalous southwest-erly winds over eastern China. These anomalous winds extended from South to North China, which helped to strengthen the East Asian summer monsoon circulation. From the above analysis, the thermal difference between eastern and western China was found to be relatively small in this period. Based on the thermal wind, the small thermal difference between western and eastern China contributed to strengthening of southwesterly wind in eastern China, which were helpful for strengthening in East Asian summer monsoon. However, during 1979–2006 (Figure 6(b)), anticyclonic circulation anomalies appeared over Mongolia. Moreover, the anomalous northeasterly winds weakened the East Asian summer monsoon circulation. The large thermal difference between western and eastern China was in 1979–2006. Therefore, according to thermal wind, it indicated that large thermal difference between western and eastern China contributed to strengthening of
Figure 6. Distributions of the summer (JJA) wind anomalies at 850 hPa (unit: m s\(^{-1}\)) (a), temperature anomalies at 700 hPa (unit: °C) (c), SLP anomalies (unit: Pa) (e), and geopotential height anomalies (unit: gpm) at 500 hPa (g) averaged for 1960–1978. The (b), (d), (f), and (h) are same as (a), (c), (e), and (g), but for averaged for 1979–2006. The climatological monthly mean is based on the period 1971–2000. The solid and dashed lines indicate positive and negative values, respectively. The shaded regions indicate the 0.05 significance level according to the Student’s t-test.

Northeasterly winds, which were helpful for weakening in East Asian summer monsoon. The East Asian summer monsoon anomalies are consistent with previous studies that concluded interdecadal weakening for the East Asian summer monsoon in the late 1970s (e.g. Huang et al., 1999; Chang et al., 2000a, 2000b; Wang, 2001; Wu and Wang, 2002; Zhou and Huang, 2003; Ding et al., 2008).

To analyze in more detail, the effect of the thermal difference between western and eastern China on the East Asian summer monsoon, the temperature, SLP, and geopotential height were examined. During 1960–1978, at 700 hPa, large positive temperature anomalies appeared over Mongolia (Figure 6(c)). The positive temperature anomalies decreased the SLP (Figure 6(e)) and geopotential height anomalies.
This enhanced the cyclonic circulation anomalies over Mongolia and increased the southwesterly wind anomalies in East Asia. However, during 1979–2006, negative temperature anomalies appeared over Mongolia (Figure 6(d)). The negative temperature anomalies increased the SLP (Figure 6(f)) and geopotential height anomalies (Figure 6(h)). This enhanced the anticyclonic circulation anomalies over Mongolia and increased the northeasterly wind anomalies in East Asia.

4. Summary and discussion

This study identified the interdecadal variability of the spring thermal difference between western and eastern China and its association with the rainfall anomalies using station and reanalysis data for 1960–2006. The spring $\Delta(T_a - T_w)$ was used to represent the thermal difference between western and eastern China. During 1960–1978, large positive temperature anomalies appeared over Mongolia. The positive temperature anomalies contributed to a decrease in pressure in this region, which contribute to an enhanced in cyclonic circulation anomalies over Mongolia. To the east flank of this anomalous cyclone were anomalous southwesterly winds over eastern China, which helped to strengthen the East Asian summer monsoon circulation. The rainfall increase over North China was associated with water vapor flux convergence and ascending motion, whereas the decrease in rainfall over the Yangtze River was associated with water vapor flux divergence and sinking motion. However, during 1979–2006, negative temperature anomalies appeared over Mongolia. The negative temperature anomalies increased the pressure and the anticyclonic circulation anomalies over Mongolia. To the east flank of this anomalous anticyclone were anomalous northeasterly winds over eastern China, which were helpful for a weakening in the East Asian summer monsoon circulation. The results suggest tropospheric moisture divergence and sinking motion over North China and tropospheric moisture convergence and ascending motion over Yangtze River that contributed to increased rainfall in this region.

The interdecadal variability of the East Asian summer monsoon was affected by land surface processes and ocean thermodynamics. There are other factors, such as thermal field over the Tibetan Plateau, the snow cover, the Pacific SST, and the middle and high latitudes (e.g. Yang and Lau, 1998; Huang et al., 1999; Chang et al., 2000a, 2000b; Wang, 2001; Wu and Wang, 2002; Zhou and Huang, 2003; Ding et al., 2008), which may affect the atmospheric circulation over East Asia and the rainfall anomalies in China.

It is well known that climate shifts are characterized by changes in the background state of the Pacific Ocean and the ENSO dynamics. The interdecadal variabilities before and after the late-1970s for SST-forced teleconnection are found in many regions (Hare and Mantua, 2000; Karspeck and Cane, 2002; Hartmann and Wendler, 2005; Rodriguez-Fonseca et al., 2011).

Because of the limited data, it cannot be determined whether the change in previous studies as well as in this study is permanent or reversible. In view of the impact of global warming on the tropical sea surface and land surface temperature, it is likely that the East Asian summer monsoon will change in the future owing to global warming.

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References

Chang CP, Zhang Y, Li T. 2000a. Interannual and interdecadal variations of the East Asian summer monsoon and the tropical Pacific SSTs. Part I: Roles of the subtropical ridge. Journal of Climate 13: 4310–4325.

Chang CP, Zhang Y, Li T. 2000b. Interannual and interdecadal variations of the East Asian summer monsoon and tropical Pacific SSTs. Part II: meridional structure of the monsoon. Journal of Climate 13: 4326–4340.

Ding Y, Wang Z, Sun Y. 2008. Inter-decadal variability of the summer precipitation in East China and its association with decreasing Asian summer monsoon. Part I: observed evidences. International Journal of Climatology 28(9): 1139–1161, doi: 10.1002/joc.1615.

Douville H, Royer JF. 1996. Sensitivity of the Asian summer monsoon to an anomalous Eurasian snow cover within the Meteo-France GCM. Climate Dynamics 12: 449–466.

Fan LJ, Wei ZG, Dong WJ. 2004. The characteristic of temporal and spatial distribution of the differences between ground and air temperature in the Arid Region of Northwest China. Plateau Meteorology 3: 360–367.

Gao R, Dong WJ, Wei ZG. 2008. Numerical simulation of the impact of abnormality of sensible heat flux in Northwest Arid Zone on precipitation in China. Plateau Meteorology 27(2): 320–324.

Hare SR, Mantua NJ. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. Progress in Oceanography 47: 103–145.

Hartmann B, Wendler G. 2005. The significance of the 1976 Pacific climate shift in the climatology of Alaska. Journal of Climate 18: 4824–4839, doi: 10.1175/JCLI3532.1.

Huang RH, Li WJ. 1987. Influence of the heat source anomaly over the tropical western Pacific on the subtropical high over East Asia. Proceedings of the International Conference on the General Circulation of East Asia, Chengdu, 40–51.

Huang RH, Sun FY. 1992. Impact of the tropical western Pacific on the East Asian summer monsoon. Journal of the Meteorological Society of Japan 70: 243–256.

Huang RH, Xu YH, Zhou LT. 1999. The interdecadal variation of summer precipitations in China and the drought trend in North China. Plateau Meteorology 18(4): 465–476.

Karspeck AR, Cane MA. 2002. Tropical Pacific 1976–77 climate shift in a linear, wind – driven model. Journal of Physical Oceanography 32: 2350–2360, doi: 10.1175/1520-0485(2002)032<2350:TOPICS>2.0.CO;2.

Li DL, Wei L, Li WJ, Lv LZ, Zhong HL, Ji GL. 2003. The effect of surface sensible heat flux of the Qinghai-Xizang Plateau on general circulation over the Northern Hemisphere and climatic anomaly of China. Climatic and Environmental Research 8(1): 60–70.

Meehl GA. 1994. Influence of the land surface in the Asian summer monsoon: external condition versus internal feedbacks. Journal of Climate 8: 358–375.

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Nitta TS. 1987. Convective activities in the tropical western Pacific and their impact on the Northern Hemisphere summer circulation. *Journal of the Meteorological Society of Japan* **64**: 373–390.

Qu Y, Gao X, Chen W, Hui X, Zhou C. 2011. Comparison of surface air temperatures and precipitation in Eastern and Western China during 1951–2003. *Plateau Meteorology* **27**(3): 524–529.

Rodriguez-Fonseca B, Janicot S, Mohino E, Losada T, Bader J, Caminade C, Chauvin F, Fontaine B, García-Serrano J, Gervois S, Joly M, Polo I, Ruti P, Roucou P, Voldoire A. 2011. Interannual and decadal SST – forced responses of the West African monsoon. *Atmospheric Science Letters* **12**: 67–74, doi: 10.1002/asl.308.

Wang HJ. 2001. The weakening of the Asian monsoon circulation after the end of 1970’s. *Advances in Atmospheric Sciences* **18**: 378–386.

Webster PJ. 1983. Mechanisms of monsoon low-frequency variability: surface hydrological effects. *Journal of the Atmospheric Sciences* **40**: 2110–2124.

Wen LM, Zhou LT, Huang RH, Fan GZ. 2014. Characteristics of interdecadal variability in the difference between surface temperature and surface air temperature in Southeast and Northwest China (in Chinese). *Climatic and Environmental Research* **19**(5): 636–648.

Wu RG, Kirtman BP. 2007. Observed relationship of spring and summer East Asian rainfall with winter and spring Eurasian snow. *Journal of Climate* **20**: 1258–1304.

Wu R, Wang B. 2002. A contrast of the east Asian summer monsoon – ENSO relationship between 1962–77 and 1978–93. *Journal of Climate* **15**: 3266–3279, doi: 10.1175/1520-0442.

Xu M, Chang CP, Fu C, Qi Y, Robock A, Robinson D, Zhang H. 2006. Steady decline of East Asian monsoon winds, 1969–2000: evidence from direct ground measurements of wind speed. *Journal of Geophysical Research* **111**: D24111, doi: 10.1019/2006JD007337.

Yang S, Lau KM. 1998. Influences of sea surface temperature and ground wetness on Asian summer monsoon. *Journal of Climate* **11**: 3230–3246.

Zhao Y, Qian YF. 2007. Relationships between the surface thermal anomalies in the Tibetan Plateau and the rainfall in the Jianghuai Area in summer. *Chinese Journal of Atmospheric Sciences* **31**(1): 145–156.

Zhou LT. 2015. Difference in the interdecadal variability of spring and summer sensible heat fluxes over Northwest China. *Atmospheric and Oceanic Science Letters* **2**(2): 119–123.

Zhou LT. 2009. Influence of land–air temperature difference on spring rainfall anomalies over North China and its feedback mechanism. *International Journal of Climatology* **35**: 2676–2681, doi: 10.1002/joc.4126.

Zhou W, Chan JCL. 2007. ENSO and South China Sea summer monsoon onset. *International Journal of Climatology* **27**: 157–167, doi: 10.1002/joc.1380.

Zhou LT, Du ZC. 2016. Regional differences in the surface energy budget over China: an evaluation of a selection of CMIP5 models. *Theoretical and Applied Climatology* **25**: 241–266, doi: 10.1007/s00704-015-1407-0.

Zhou LT, Huang RH. 2003. Research on the characteristics of interdecadal variability of summer climate in China and its possible cause. *Climatic and Environmental Research* **8**: 274–290.

Zhou LT, Huang RH. 2006. Characteristics of interdecadal variability of the difference between surface temperature and surface air-temperature(Ta-Ta) in spring in arid and semi-arid region of Northwest China and its impact on summer precipitation in North China. *Climatic and Environmental Research* **11**: 1–13.

Zhong LT, Huang RH. 2008. Interdecadal variability of sensible heat in arid and semi-arid regions of Northwest China and its relation to summer precipitation in China. *Chinese Journal of Atmospheric Sciences* **32**(6): 1276–1288.

Zhou LT, Huang RH. 2010. The interdecadal variability of summer rainfall in Northwest China and its possible causes. *International Journal of Climatology* **30**: 549–557.

Zhou LT, Huang RH. 2014. Regional differences in surface sensible and latent heat fluxes in China. *Theoretical and Applied Climatology* **116**: 625–637, doi: 10.1007/s00704-013-0975-0.

Zhou LT, Wen LM. 2016. Characteristics of temporal and spatial variation in land-air temperature differences in China and its association with summer rainfall. *Climatic and Environmental Research*, doi: 10.3878/j.issn.1006-9585.2016.15196 (in press).

Zhou CC, Gao XQ, Chen W, Hui XY, Li J. 2009. The impact of sensible heat flux anomaly over Central Asia on temperature and precipitation in Northwest China. *Plateau Meteorology* **28**(2): 395–401.