ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 31, JULY 2014, 735–742

A Decadal Shift of Summer Surface Air Temperature over Northeast Asia around the Mid-1990s

CHEN Wei*[1,2] and LU Riyu[1]

[1]*State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing* 100029

[2]*Division of Earth Environmental System, Pusan National University, Busan, South Korea*

(Received 23 July 2013; revised 23 October 2013; accepted 29 November 2013)

ABSTRACT

This study identifies a decadal shift of summer surface air temperature (SAT) over Northeast Asia, including southeastern parts of Russia, Mongolia and northern China, around the mid-1990s. The results suggest that the SAT over the Northeast Asia experienced a significant warming after 1994 relative to that before 1993. This decadal shift also extends to northern China, and leads to a warmer summer over Northeast China and North China after the mid-1990s.

The decadal warming over Northeast Asia is found to concur with the enhancement of South China rainfall around the mid-1990s. On the one hand, both the Northeast Asian SAT and South China rainfall exhibit this mid-1990s decadal shift only in summer, but not in other seasons. On the other hand, both the Northeast Asian SAT and South China rainfall exhibit this mid-1990s decadal shift not only in the summer seasonal mean, but also in each month of summer (June, July and August). Furthermore, the decadal warming is found to result from an anticyclonic anomaly over Northeast Asia, which can be interpreted as the response to the increased precipitation over South China, according to previous numerical results. Thus, we conclude that the warming shift of summer Northeast Asian SAT around the mid-1990s was a remote response to the increased precipitation over South China.

Key words: surface air temperature, Northeast Asia, decadal shift, mid-1990s, South China rainfall

Citation: Chen, W., and R. Y. Lu, 2014: A decadal shift of summer surface air temperature over Northeast Asia around the mid-1990s. *Adv. Atmos. Sci.*, **31**(4), 735–742, doi: 10.1007/s00376-013-3154-4.

1. Introduction

The change in summer surface air temperature (SAT) that has occurred in recent decades over Northeast Asia is noted for its remarkable warming trend. Zhu et al. (2012) demonstrated a warming trend of summer SAT over Northeast Asia from 1954 to 2010, and suggested that this warming trend may be explained by global warming. The warming trend of SAT over this region has also occurred in spring (Zhu et al., 2008). Moreover, this robust warming over the continental interior of Asia is further reflected in the annual mean SAT, evident over the past few decades (Hansen et al., 1999, 2006). In particular, the warming of SAT over Northeast Asia is much stronger after the late-1990s (Zhu et al., 2010).

The warming trend has also been observed in China. Wang and Ye (1993) pointed out a pronounced warming of annual mean SAT in northern China. Although the warming trend in many regions over China has significant seasonality, the warming in northern China is robust in every season (Hu et al., 2003; Tang and Zhai, 2005). Qi and Wang (2012) indicated that the warming trend for both seasonal mean and extreme temperature in summer are much more significant after 1990 over China. In addition, the warming can also be measured by the diurnal SAT. The minimum daily temperature has increased over northern China during recent decades (Ren and Zhai, 1998; Liu et al., 2004; Qian and Lin, 2004).

Some previous studies have indicated that the warming over Northeast Asia and northern China has been accompanied by changes in circulation over East Asia. The warming SAT over Northeast Asia is related to a positive geopotential height anomaly (Zhu et al., 2010; Zhu et al., 2012). Additionally, the high frequency of extreme hot weather in northern China is associated with the positive geopotential height anomaly in the middle and upper troposphere (Sun et al., 2011).

The upper-tropospheric circulation over Northeast Asia and East Asia experienced a decadal variation in the mid-1990s. Kwon et al. (2007) suggested that the upper-tropospheric westerly jet over East Asia weakened significantly, with an anticyclonic anomaly over Northeast Asia and a cyclonic anomaly over South China after the mid-1990s, and indicated the shift point was in 1993/94. Kwon et al. (2007) demonstrated that the change of circulation in

* Corresponding author: CHEN Wei
Email: chenwei@mail.iap.ac.cn

the mid-1990s was related to enhanced precipitation over South China, as a barotropic response to the heat forcing of increased precipitation. The reasons for the decadal increase of South China rainfall have been investigated. Kwon et al. (2007) suggested that the enhancement was induced by the increase in the number of typhoons passing through the southeastern part of China. On the other hand, Wu et al. (2010) argued that the increases in SSTs over the Indian Ocean and snow cover on the Tibetan Plateau could be the cause. Some previous studies have suggested that this decadal variation of circulation may lead to changes in extreme high temperature in China (Wei and Chen, 2011; Park et al., 2012)

Previous studies have mainly focused on the warming trend of SAT over Northeast Asia. However, little attention has been paid to the decadal variation of Northeast Asia SAT, which tends to be modulated by natural variability. Actually, a decadal shift can be superimposed on the long-term trend and thus offset or enhance the trend over particular periods. On the other hand, various studies have investigated the decadal variability of SAT over China. Kang et al. (2006) suggested a decadal warming over China after the mid-1970s. In addition, a warming shift of annual SAT over Northeast China took place around the 1980s (Wang and Fang, 2004), and it was more significant in winter and summer (Zhang and Zhang, 2005). Lian et al. (1997) also indicated that the summer SAT in Jilin Province cooled from the 1950s to the 1970s, but has been warming since the 1980s. However, these previous studies, by using data before the year 2000, did not detect the decadal variations in the most recent one or two decades. Recently, Shen et al. (2012) noticed a decadal warming over Northeast China around 1994, but did not attempt to discuss the possible reasons for the warming.

In the present reported study, we identified a decadal shift of summer Northeast Asian SAT around the mid-1990s, and discuss here the possible reasons for this shift. The remainder of the paper is organized as follows. Section 2 introduces the datasets used in the work. The decadal shift of summer Northeast Asian SAT is investigated in section 3. A relationship with the decadal shift of precipitation over South China is discussed in section 4. Section 5 further analyzes the changes of summer SAT over northern China. And finally, conclusions are drawn in section 6.

2. Datasets

The datasets used in the present study included SAT from the Goddard Institute for Space Studies/National Aeronautics and Space Administration (GISS/NASA) global land SAT dataset (Hansen et al., 1999, 2006), precipitation data from the precipitation reconstruction over land (PREC/L) dataset (resolution: $1.0^{\circ} \times 1.0^{\circ}$) (Chen et al., 2002), and the atmospheric circulation variables of geopotential height and horizontal winds from the monthly mean National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) Reanalysis I dataset (Kalnay et al., 1996). In addition, monthly mean SAT of 160 stations, provided by the National Climate Center of the China Meteorological Administration, was used to analyze the changes of SAT in China. The study period was from 1958 to 2010 (53 years). Summer time was defined as June, July and August (JJA). A running t-test with a 10-yr sliding window was applied to test the abrupt point of the decadal shift (similar results were obtained using a 5-yr and 15-yr sliding window, but are not shown in this paper).

3. Decadal shift of the summer SAT over Northeast Asia

Figure 1 shows the differences of the upper-tropospheric geopotential height and zonal wind between the periods of 1994–2010 and 1958–93. The geopotential height anomalies are all positive north of 40°N over Northeast Asia, with a significant center around the Lake Baikal region (Fig. 1a). This suggests that the geopotential height over Northeast Asia is remarkably enhanced after the mid-1990s. The 200-hPa zonal wind shows a negative anomaly along 40°N over East Asia (Fig. 1b), which weakens the climatological subtropical westerly jet. Also, this easterly anomaly and the westerly anomaly over the north of Lake Baikal and Southeast Asia, form an anticyclonic circulation anomaly over Northeast Asia and a cyclonic anomaly over South China, which are features consistent with the findings of Kwon et al. (2007). In short, after the mid-1990s, the circulations are behaving as a strengthened geopotential height over Northeast Asia and a weakened subtropical westerly jet over East Asia.

In addition, the contrast in the geopotential height anomaly between the north and south is more significant if the time period starts from 1979, when the dataset is said to be more reliable. The decadal shift of geopotential height anomalies between 1994–2010 and 1979–93 shows a seesaw pattern with a positive geopotential height anomaly over Northeast Asia and a negative one over southern China (figures not shown). The positive geopotential height anomaly over Northeast Asia exists from the lower to the upper troposphere. This further implies the occurrence of a decadal shift in the mid-1990s for the circulation anomaly.

Corresponding to the changes of large-scale circulation after the mid-1990s, the SAT experiences a significant warming over a wide area, ranging from central to eastern parts of northern Asia, including southeastern Russia, Mongolia, and northern China (Fig. 2a). This decadal shift of warming after the mid-1990s coincides with the intensified geopotential height over Northeast Asia and the weakened East Asian subtropical westerly jet (Fig. 1). On the one hand, the positive height anomaly increases the input of solar radiation and results in a warming over Northeast Asia; while on the other hand, the warming induces a decrease in the meridional air temperature gradient and generates a negative vortex, which leads to a weakened subtropical westerly jet over East Asia and an enhanced geopotential height over Northeast Asia, according to thermal wind theory (Li et al., 2010; Sun et al., 2010; Zhu et al., 2010; Xu et al., 2011).

The most significant warming region over Northeast Asia is marked by a rectangle (40°–50°N, 90°–130°E) in Fig. 2a. The amplitude of the decadal shift for the warming is 1.18°C, measured by the positive SAT anomalies averaged within the rectangle. The time series of the SAT anomaly over this region is shown in Fig. 2b, with an interannual standard deviation of 0.73°C. This indicates that the amplitude of the decadal shift for the summer SAT over Northeast Asia is more remarkable and much larger than the amplitude of interannual variation.

The abrupt point for the decadal shift was further examined by the running t-test with a 10-yr sliding window (Fig. 2c). The most significant point appears in the year 1993, which indicates the decadal shift for the SAT over Northeast Asia occurs in 1993/94. The SAT anomaly varies from −0.37°C during 1951–93 to 0.81°C during 1994–2010 (Table 1). This change of SAT anomaly is significant at the 99% confidence level, with a growth ratio of 3.19 (Table 1; the growth ratio was calculated as the difference between the two periods, divided by the value in the pre-period).

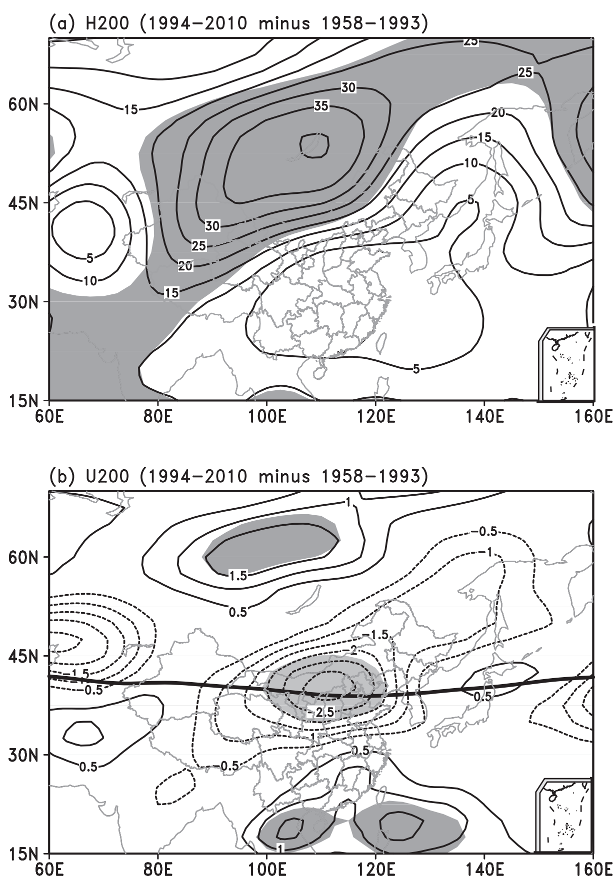

Fig. 1. Composite differences of (a) 200-hPa geopotential height (units: m) and (b) zonal wind (units: m s^{-1}) between the periods of 1994–2010 and 1958–93. Shading indicates the region where the values are significant at the 95% confidence level according to the t-test. The thick solid line in (b) represents the climatological subtropical westerly jet.

Table 1. Values of summer SAT anomaly over Northeast Asia and precipitation anomaly over South China averaged during 1958–93 and 1994–2010. Results are shown for the JJA-mean, and for June, July and August, individually. The growth ratio was calculated as the difference between the two periods divided by the value in the pre-period [(II–I)/abs(I)].

		1958–93 (I)	1994–2010 (II)	Growth ratio
SLB SAT (°C)	JJA	−0.37	0.81	3.19
	June	−0.40	0.88	3.20
	July	−0.42	0.99	3.36
	August	−0.28	0.53	2.89
SCR (mm d^{-1})	JJA	−0.39	0.89	3.28
	June	−0.50	1.05	3.10
	July	−0.35	0.74	3.11
	August	−0.39	0.82	3.10

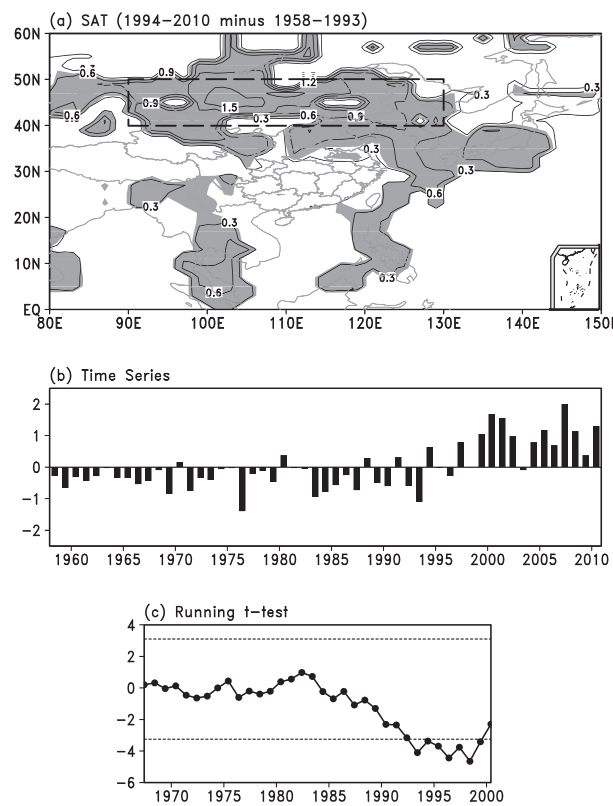

Fig. 2. (a) The same as Fig. 1, but for the SAT anomalies (units: °C). (b) Time series of the SAT anomalies averaged over the region (40°–50°N, 90°–130°E) [the rectangle in (a)]. (c) Running t-test for the time series. Curved and straight dashed lines in (c) represent the t value and the 99% confidence level, respectively.

These circulation and SAT changes around the mid-1990s differ appreciably to those associated with the warming trend. The region with the decadal shift of summer SAT around the mid-1990s is located southward in comparison with the region of the warming trend that might be due to global warming (Zhu et al., 2012). The circulation changes shown in Fig. 1 are also located southward relative to those associated with the warming trend, which are characterized by a positive 200-hPa geopotential height anomaly centered around 60°N, and the strongest easterly wind anomaly over East Asia along 45°N (Zhu et al., 2012). Furthermore, the amplitude of the decadal SAT variation is five times as large as that of the warming trend, according to the rate of 0.22°C (10 yr)$^{-1}$ suggested by Zhu et al. (2012). Thus, the decadal shift of summer SAT over Northeast Asia is different to the warming trend.

4. Relationship with the decadal shift of South China rainfall in the mid-1990s

Figure 3 shows the changes in precipitation anomalies between the post- and pre- mid-1990s. There is a negative precipitation anomaly over Northeast Asia associated with the warming SAT there. The precipitation anomaly averaged over this region (40°–50°N, 90°–130°E) varies from 0.06 mm d^{-1} during 1958–93 to -0.14 mm d^{-1} during 1994–2010. The amplitude for this decadal shift is 0.20 mm d^{-1}, which is 69% of one standard deviation of the interannual variation in precipitation over this region (0.29 mm d^{-1}). The decrease of Northeast Asian precipitation associated with the enhanced geopotential height in turn contributes to the warming SAT locally through increasing downward shortwave radiation (Trenberth and Shea, 2005).

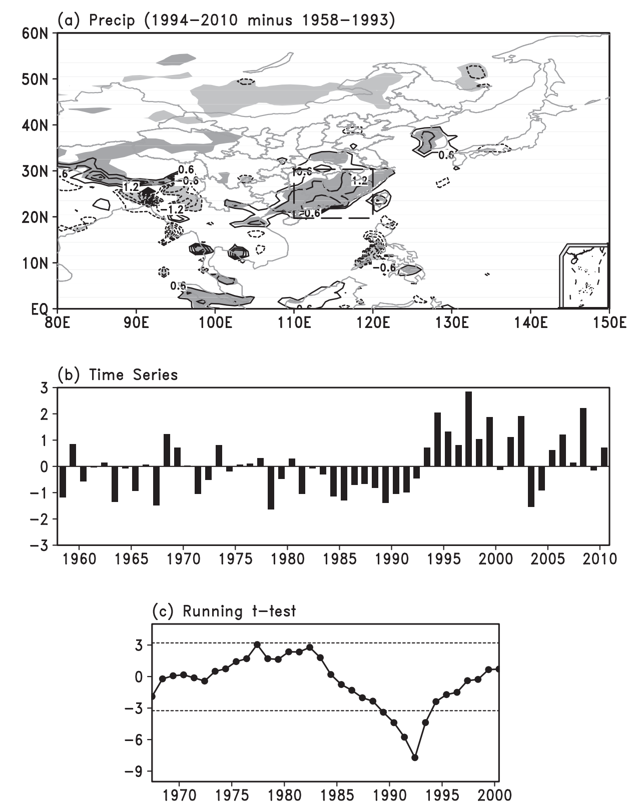

Fig. 3. (a) The same as Fig. 1, but for the precipitation anomalies (units: mm d^{-1}). (b) Time series of the precipitation anomalies averaged over the region (20°–30°N, 110°–120°E) [the rectangle in (a)]. (c) Running *t*-test for the time series.

In addition, there is a positive precipitation anomaly over South China, indicating a remarkable increase of South China rainfall after the mid-1990s, consistent with the results of Kwon et al. (2007). This decadal shift was further investigated via the time series of precipitation anomalies averaged over the region (20°–30°N, 110°–120°E) (Fig. 3b; the region is marked by the rectangle in Fig. 3a). The running *t*-test result suggests that the abrupt year for this decadal shift is also 1993/94.

The remarkable decadal shift of precipitation over South China is characterized as a dry state altering to a wet one. The South China precipitation anomaly, measured by the average over the region (20°–30°N, 110°–120°E), is -0.39 mm d^{-1} in the previous period (Table 1), and there are only four out of 36 years during this period showing clear positive precipitation anomalies, judged by the criterion of 0.3 mm d^{-1}. On the contrary, almost all years during 1994–2010 have positive anomalies over South China, with only two years of appreciably negative anomalies. The precipitation anomaly averaged over the subsequent period is 0.89 mm d^{-1} (Table 1). The growth ratio is 3.28, which is close to the ratio for the decadal shift of summer SAT over Northeast Asia.

The decadal shifts of the summer Northeast Asian SAT and the South China rainfall show an identical changing point of 1993/94 and similar growth ratios. The concurrence of both decadal shifts in the mid-1990s appears only for summer, but not for other seasons (Fig. 4). For the SAT anomaly over Northeast Asia, the 7-yr running mean for these time series implies that the decadal shift in the mid-1990s is only for summer, with the time of the decadal shift tending to appear in the late-1980s for other seasons. On the contrary, for South China precipitation, the decadal shifts are unclear in winter, spring and autumn, while the interannual variability is dominant in these seasons. Actually, the changes in upper-tropospheric circulation between the post- and pre-mid-1990s in DJF, MAM and SON are quite different with those in JJA (figures not shown). The enhancement of geopotential height over Northeast Asia and the weakening of the subtropical East Asian westerly jet around the mid-1990s do not occur in these three seasons. Also, the nonexistence of an inverse circulation anomaly north and south of the westerly jet over East Asia implies a disconnection of the Northeast Asian SAT and South China precipitation in winter, spring and autumn. The concurrence of decadal shifts of both the summer Northeast Asian SAT and South China precipitation around the mid-1990s, as well as the corresponding upper-tropospheric circulation changes, suggests a possible connection between these two remote climate changes, and that such a possible connection is only for summer, rather than other seasons.

The mid-1990s shifts of both the summer Northeast Asian SAT and South China precipitation are apparent not only in the seasonal mean, but also the monthly variations (Fig. 5). Both the Northeast Asian SAT and South China precipitation show clear decadal shifts around the mid-1990s for June, July and August. Both of them exhibit a negative phase during 1958–93 and a positive phase during 1994–2010. The am-

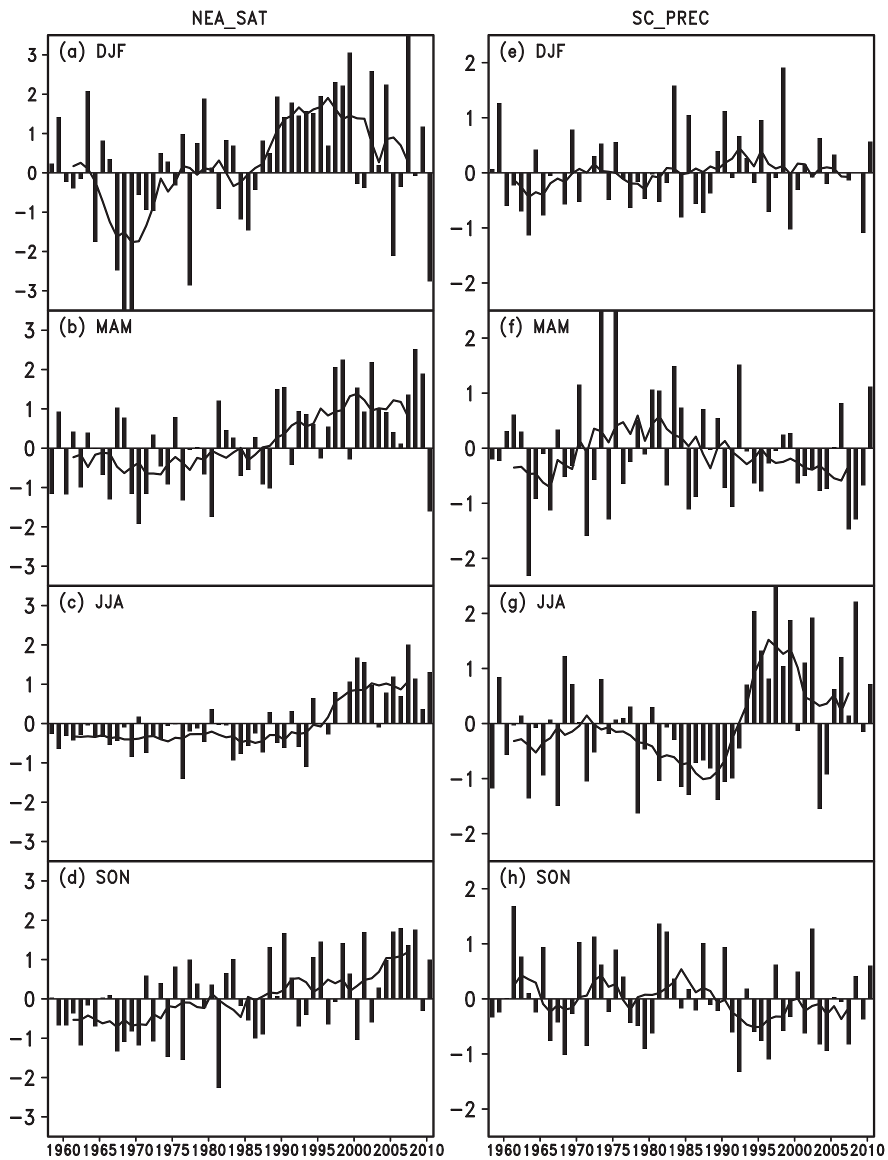

Fig. 4. Time series of the SAT anomaly (units: °C) over Northeast Asia (left panel) and the precipitation anomaly (units: mm d^{-1}) over South China (right panel) in (a, e) DJF, (b, f) MAM, (c, g) JJA, and (d, h) SON. Bars are the original data and the solid lines are the 7-yr running mean.

plitudes of interannual variability in the monthly series (Fig. 5) are generally stronger than those for summer-mean series (Figs. 4c and g), which can be expected by the weak autocorrelations between monthly series.

The mid-1990s decadal shifts in JJA-mean and monthly mean are further illustrated by the anomalies averaged before and after 1993/94 (Table 1). The decadal variation in each month is close to that in the seasonal mean for both the Northeast Asian SAT and South China rainfall. Moreover, the growth ratios in JJA-mean and in each month for the SAT are all similar to those for the precipitation, which implies that the linkages between them exist both in the seasonal and monthly mean. In addition, the connection between the Northeast Asian summer SAT and South China rainfall only appears on the decadal timescale with the correlation coefficient of seasonal mean time series of 0.68 (calculated by using the time series with a 7-yr running mean). This connection is very weak on the interannual timescale, with a correlation coefficient of 0.19 (calculated by using the time series without the 7-yr running mean). This implies that the Northeast Asian summer SAT might be modulated by various factors on the interannual timescale, and the effect of South China rainfall, as one of the factors, could be concealed on this timescale. However, on the decadal timescale, the effects of other factors are much weaker, since their decadal variations are not as clear as the South China rainfall, and thus the effect of South China rainfall might become dominant.

This study suggests a linkage between the Northeast Asian SAT and South China rainfall on the decadal timescale. The decadal connection is demonstrated by the concurrence

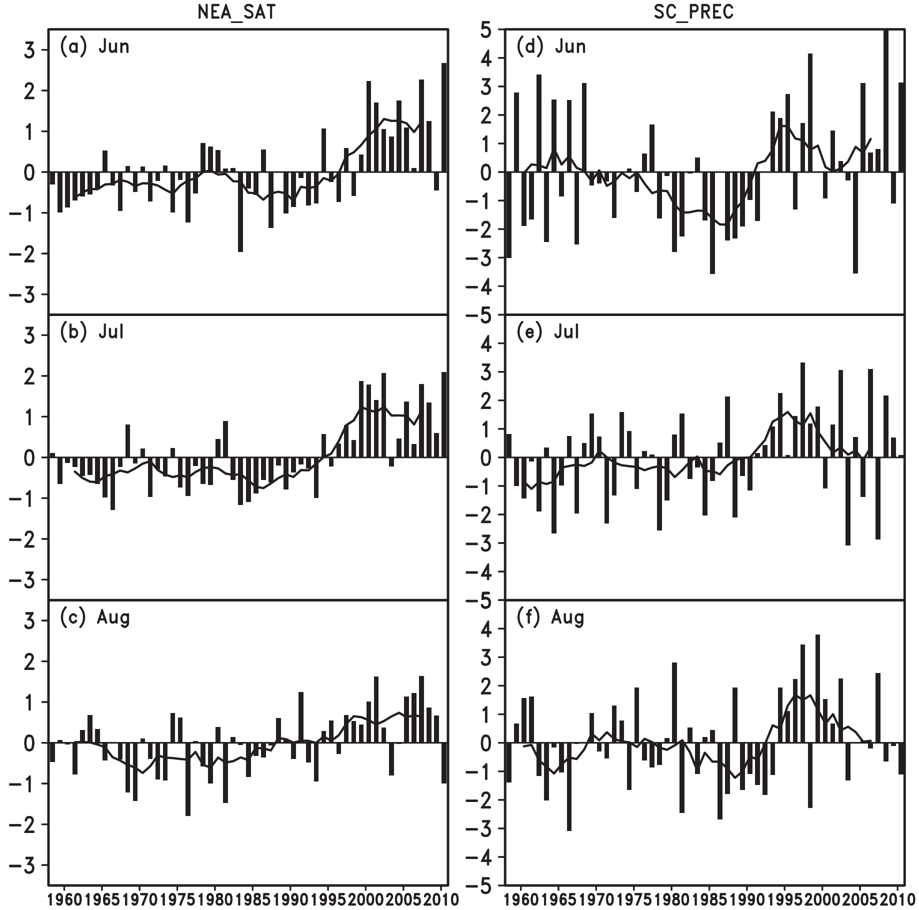

Fig. 5. The same as Fig. 4, but for (a, d) June, (b, e) July, and (c, f) August.

of the decadal shifts of the Northeast Asian SAT, South China precipitation, and the corresponding upper-tropospheric circulation around the mid-1990s. Additionally, both of the decadal shifts are only for summer, but not for other seasons, and both of the decadal shifts are not only in the summer mean, but also in each month of summer (June, July and August). These similarities also indicate the decadal connection. Furthermore, the physical processes for the decadal connection can be understood as follows. After the mid-1990s, the increased South China rainfall leads to a positive geopotential height anomaly over Northeast Asia, according to Kwon et al. (2007). The Northeast Asian positive geopotential height anomaly contributes to the warmer SAT through increasing the solar radiation input and decreasing local precipitation. Thus, we can conclude that the decadal shift of SAT after the mid-1990s was a remote response to the increased precipitation over South China.

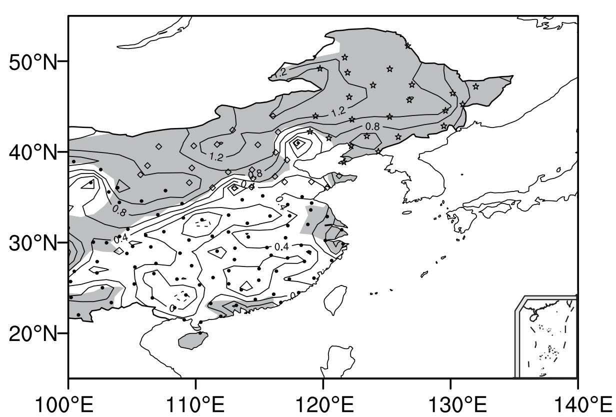

Fig. 6. The same as Fig. 1, but for the SAT anomalies (units: °C) using the 160-station dataset. The asterisk and the rhombus represent the stations over Northeast China and North China, respectively.

5. Decadal shift of summer SAT over northern China

The decadal shift of summer SAT in the mid-1990s extends to the northern part of China (Fig. 6). The significant positive summer SAT anomalies cover Northeast China and North China after the mid-1990s. We defined northern China as the region east of 105°E and north of 36°N in China. Forty-nine stations are located in this region, including in Heilongjiang Province, Jilin Province, Liaoning Province, Inner Mongolia Province, Beijing City, Tianjin City, Ningxia Province, Shanxi Province, the northern part of Shandong Province, and eastern part of Shaanxi Province. Moreover, we divided northern China into Northeast China and North China. Northeast China represents the region east of 118°E and north of 38°N, which contains 26 stations over Heilongjiang Province, Jilin Province, Liaoning Province, and the northeastern part of Inner Mongolia Province. The other 23 stations belong to North China.

The time series of JJA-mean SAT anomalies averaged over these three regions are shown in Fig. 7. Similar to northern China, both Northeast China and North China exhibit a decadal change with lower SAT before the mid-1990s and higher SAT after. The running *t*-test results indicate the time for the abrupt decadal shift is 1993/94 for all three regions, which is consistent with that for the summer Northeast Asian SAT and South China precipitation.

6. Conclusions

In this study, we investigated the decadal variations of summer SAT over Northeast Asia. The summer Northeast Asian SAT was found to display a decadal shift around the mid-1990s, with an abrupt point of change in 1993/94. The Northeast Asian SAT anomalies vary from −0.37°C during 1958–93 to 0.81°C during 1994–2010. This decadal change of SAT anomaly is significant at the 99% confidence level. The robust decadal variation of SAT averaged over the Northeast Asia (1.18°C) is larger than both its interannual standard deviation (0.73°C) and warming trend [0.22°C (10 yr)$^{-1}$ (Zhu et al., 2010)]. The region with decadal shift covers a wide area of Northeast Asia, including the southeastern part of Russia, Mongolia and northern China. In particular, the analysis using the Chinese station dataset further confirmed that the mid-1990s decadal shift of summer SAT also exists in northern China, and a warming summer can be observed over Northeast China and North China after 1994. In addition, precipitation experiences a decadal shift in the mid-1990s over Northeast Asia. The summer Northeast Asian precipitation significantly decreases after the mid-1990s, which is in favor of the warming SAT there through increasing downward shortwave radiation.

The decadal shift of summer SAT over Northeast Asia in the mid-1990s corresponds with the decadal shift of upper-tropospheric circulation, which shows as a positive geopotential height anomaly over Northeast Asia and a weakened subtropical westerly jet over East Asia after the mid-1990s. The enhancement of geopotential height over Northeast Asia leads to the warming of Northeast Asia SAT by increasing the solar radiation input and suppressing local precipitation.

Actually, we found that the mid-1990s decadal shift of summer Northeast Asian SAT is connected with that of South China rainfall. This linkage is demonstrated by the concurrence of the mid-1990s decadal shifts of the Northeast Asian SAT, South China precipitation, and the corresponding upper-tropospheric circulation. Moreover, both the decadal shifts of Northeast Asian SAT and South China rainfall are only for summer, but not for other seasons. Additionally, both the decadal shifts of Northeast Asian SAT and South China rainfall are not only in the summer mean, but also in each month of summer (June, July and August). These similarities indicate a possible connection between the summer Northeast Asian SAT and South China rainfall on the decadal timescale.

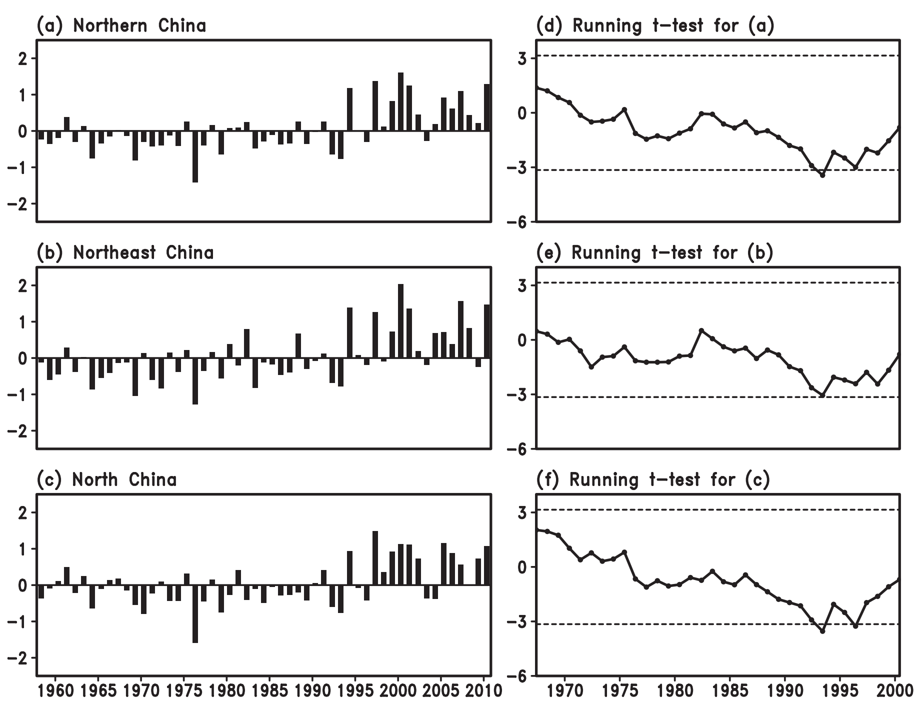

Fig. 7. Time series of the SAT anomalies averaged over (a) northern China (north of 36°N, east of 105°E; 49 stations), (b) Northeast China (north of 38°N, east of 118°E; 26 stations), and (c) North China (remaining 23 stations). The right panels show the running *t*-test for their respective time series in the left panels.

Furthermore, after the mid-1990s, the positive geopotential height anomaly over Northeast Asia can be interpreted as the response to the increased precipitation over South China, according to previous numerical results (Kwon et al., 2007). This enhanced geopotential height contributes to the warmer SAT there. Therefore, based on the present results, we suggest that the warming shift of summer Northeast Asian SAT after the mid-1990s was a remote response to the increased precipitation over South China.

Acknowledgements. The authors acknowledge the two anonymous reviewers for their valuable comments and suggestions. This study was supported by the National Natural Science Foundation of China (Grant No. 41105046), the National Basic Research Program of China (Grant No. 2010CB950403), and the Chinese Academy of Sciences (Grant No. XDA05090000).

REFERENCES

Chen, M. Y., P. P. Xie, J. E. Janowiak, and P. A. Arkin, 2002: Global land precipitation: A 50-yr monthly analysis based on gauge observations. *Journal of Hydrometeorology*, **3**, 249–266, doi: 10.1175/1525–7541.

Hansen, J., R. Ruedy, J. Glascoe, and M. Sato, 1999: GISS analysis of surface temperature change. *J. Geophys. Res.*, **104**, 30 997–31 022.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D. W. Lea, and M. Medina-Elizade, 2006: Global temperature change. *Proceedings of the National Academy of Sciences of the United States of America*, **103**, 14 288–14 293, doi: 10.1073/pnas.0606291103.

Hu, Z.-Z., S. Yang, and R. G. Wu, 2003: Long-term climate variations in China and global warming signals. *J. Geophys. Res.*, **108**(D19), 4614, doi: 10.1029/2003JD003651.

Kalnay, E., and Coauthors, 1996: The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, **77**, 437–471.

Kang, L. H., W. Chen, and K. Wei, 2006: The interdecadal variation of winter temperature in China and its relation to the anomalies in atmospheric general circulation. *Climatic and Environmental Research*, **11**(3), 330–339. (in Chinese)

Kwon, M., J.-G. Jhun, and K.-J. Ha, 2007: Decadal change in East Asian summer monsoon circulation in the mid-1990s. *Geophys. Res. Lett.*, **34**, L21706, doi: 10.1029/2007GL031977.

Li, J. P., Z. W. Wu, Z. H. Jiang, and J. H. He, 2010: Can global warming strengthen the East Asian summer monsoon? *J. Climate*, **23**, 6696–6705.

Lian, Y., G. An, and Q. Wang, 1997: Variations of temperature and precipitation during the last forty years in Jilin province. *Quart. J. Appl. Meteor.*, **8**(2), 197–204. (in Chinese)

Liu, B. H., M. Xu, M. Henderson, Y. Qi, and Y. Q. Li., 2004: Taking China's temperature: Daily range, warming trends, and regional variations, 1955–2000. *J. Climate*, **17**, 4454–4462.

Park, J. K., R. Lu, C. F. Li, and E. B. Kim, 2012: Interannual variation of tropical night frequency in Beijing and associated large-scale circulation background. *Adv. Atmos. Sci.*, **29**(2), 295–306, doi:10.1007/s00376-011-1141-1.

Qi, L., and Y. Q. Wang, 2012: Changes in the observed trends in extreme temperatures over China around 1990. *J. Climate*, **25**, 5208–5222.

Qian, W. H., and X. Lin, 2004: Regional trends in recent temperature indices in China. *Climate Res.*, **27**, 229–134, doi: 10.3354/cr027119.

Ren, F. M., and P. M. Zhai, 1998: Study on changes of China's extreme temperatures during 1951–1990. *Scientia Atmospherica Sinica*, **22**, 217–227. (in Chinese)

Shen, B. Z., Y. Lian, H. Yang, and S. Zhang, 2012: Interdecadal change characteristics of summer temperature in Northeast China. *Scientia Geographica Sinica*, **32**(6), 739–745. (in Chinese)

Sun, Q. Q., H. J. Wang, and W. Yuan, 2011: Decadal variability of the extreme hot event in China and its association with atmospheric circulations. *Climatic and Environmental Research*, **16**, 199–208. (in Chinese)

Sun, Y., Y. H. Ding, and A. G. Dai, 2010: Changing links between South Asian summer monsoon circulation and tropospheric land-sea thermal contrasts under a warming scenario. *Geophys. Res. Lett.*, **37**, L02704, doi: 10.1029/2009GL041662.

Tang, H. Y., and P. M. Zhai, 2005: Consistence and inconsistence of variations in surface air temperatures between eastern and western China during 1951 $\sim$ 2002. *Chinese J. Geophys.*, **48**, 582–592.

Trenberth, K. E., and D. J. Shea, 2005: Relationships between precipitation and surface temperature. *Geophys. Res. Lett.*, **32**, L14703, doi:10.1029/2005GL022760.

Wang, S. W., and D. Z. Ye, 1993: An analysis of global warming during the last one hundred years. *Climate Variability*, D. Z. Ye et al., Eds., China Meteorological Press, 23–32. (in Chinese)

Wang, X. J., and Z. F. Fang, 2004: Surface air temperature in China and its relation to arctic oscillation index. *Plateau Meteorology*, **23**, 80–88. (in Chinese)

Wei, K., and W. Chen, 2011: An abrupt increase in the summer high temperature extreme days across China in the mid-1990s. *Adv. Atmos. Sci*., **28**(5), 1023–1029, doi: 10.1007/s00376-010-0080-6.

Wu, R. G., Z. P. Wen, S. Yang, and Y. Q. Li, 2010: An interdecadal change in southern China summer rainfall around 1992/93. *J. Climate*, **23**, 2389–2403.

Xu, K., C. W. Zhu, and J. H. He, 2011: Impact of the surface air temperature warming around Lake Baikal on trend of summer precipitation in north China in the past 50 years. *Plateau Meteorology*, **30**(2), 309–317. (in Chinese)

Zhang, Y. C., and L. J. Zhang, 2005: Precipitation and temperature probability characteristics in climatic and ecological transition zone of Northeast China in recent 50 years. *Scientia Geographica Sinica*, **25**(5), 561–566. (in Chinese)

Zhu, C., B. Wang, and W. Qian, 2008: Why do dust storms decrease in northern China concurrently with the recent global warming? *Geophys. Res. Lett.*, **35**, L18702, doi: 10.1029/2008GL034886.

Zhu, C. W., B. Wang, W. H. Qian, and B. Zhang, 2012: Recent weakening of northern East Asian summer monsoon: A possible response to global warming. *Geophys. Res. Lett.*, **39**, L09701, doi: 10.1029/2012GL051155.

Zhu, Y. L., H. J. Wang, W. Zhou, and J. H. Ma, 2010: Recent changes in the summer precipitation pattern in East China and the background circulation. *Climate Dyn.*, **36**, 1463–1473, doi: 10.1007/s00382-010-0852-9.