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Changes in Seasonal Cycle and Extremes in China during the Period 1960–2008

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ABSTRACT

Recent trends in seasonal cycles in China are analyzed, based on a homogenized dataset of daily temperatures at 541 stations during the period 1960–2008. Several indices are defined for describing the key features of a seasonal cycle, including local winter/summer (LW/LS) periods and local spring/autumn phase (LSP/LAP). The Ensemble Empirical Mode Decomposition method is applied to determine the indices for each year. The LW period was found to have shortened by 2–6 d (10 yr)$^{-1}$, mainly due to an earlier end to winter conditions, with the LW mean temperature having increased by 0.2°C–0.4°C (10 yr)$^{-1}$, over almost all of China. Records of the most severe climate extremes changed less than more typical winter conditions did. The LS period was found to have lengthened by 2–4 d (10 yr)$^{-1}$, due to progressively earlier onsets and delayed end dates of the locally defined hot period. The LS mean temperature increased by 0.1°C–0.2°C (10 yr)$^{-1}$ in most of China, except for a region in southern China centered on the mid-lower reaches of the Yangtze River. In contrast to the winter cases, the warming trend in summer was more prominent in the most extreme records than in those of more typical summer conditions. The LSP was found to have advanced significantly by about 2 d (10 yr)$^{-1}$ in most of China. Changes in the autumn phase were less prominent. Relatively rapid changes happened in the 1980s for most of the regional mean indices dealing with winter and in the 1990s for those dealing with summer.

Key words: seasonal cycle, temperature extremes, season length, climate change indices

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1. Introduction

One of the most influential features of climate in China is the prominent seasonal cycle (SC). Typically, this involves severely cold conditions during the East Asian winter monsoon season, extremely hot conditions during summer, with transitional spring and autumn periods between. This cycle influences basic ecosystem functions, agricultural practices, and many other environmental and social characteristics in the region (Liu et al., 2008b). According to IPCC (2007), the average global surface temperature increased by about 0.7°C during the last century, with an enhanced warming rate lasting the latter half of the century. A recent study based on homogenized observations indicated that in China, the annual mean temperature has risen significantly almost everywhere during the period 1960–2008, with a countrywide mean warming rate of 0.27°C (10 yr)$^{-1}$ (Li and Yan, 2009). It is interesting to investigate how the SC has changed under this warming trend in China.

There are two basic aspects when considering

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changes to the SC. The first is the strength of the SC, which can be roughly expressed by the contrast in temperatures between the two season extremes, i.e. winter and summer. Many studies have pointed out a weakening of the SC under the recent warming trend, with warming found to be more prominent in winter than in summer (e.g. Yan et al., 2001). Changes in the strength of the SC can further be demonstrated by contrasting seasonal temperature extremes, as implied in Yan and Yang (2000), who found that the lowest annual temperature (mean of the 10 lowest records) increased by up to 10°C during the last half of the century, while the trend in the highest annual temperature series was not quite so noticeable in China.

The other aspect that can be considered is the phase of the SC. For instance, one can study changes to the growing season length (GSL), which exerts an influence upon the ecosystem and is considered as a useful index for monitoring climate change (Robeson, 2002; Chen et al., 2005; Linderholm, 2006; Christidis et al., 2007; Song et al., 2010). Similarly, the frost-free season (FFS) based on a threshold of 0°C is also often used as a feature of the seasonal cycle (Cooter and LeDuc, 1995; Kunkel et al., 2004; Liu et al., 2008a). There is no doubt that the GSL and FFS have tended to extend under the trend of global warming, and phase changes around spring and autumn are critical. Qian et al. (2009) proposed a method to adaptively determine the timing of the climatic spring onset (CSO) and studied the trend in the series of the CSO date (Qian et al., 2009, 2010b). However, for a more comprehensive understanding of SC phase changes, it is beneficial to study as well the changes in some phase points in both the transitional seasons. As suggested in many studies, climatic changes can be quite different for different seasons (e.g. Wei et al., 2003).

Zhang (1934) proposed 10°C and 22°C, in terms of pentad-mean temperature, as the thresholds for winter and summer in China, respectively. Spring and autumn were defined as falling between the dates at which these thresholds are passed. Miao and Wang (2007) applied these definitions and found that in most of China, the summer period has extended and the winter period has shrunk in recent decades. However, a given threshold is not applicable for all regions. Thresholds established from local seasonal cycles of daily temperature records are needed for comparing reasonably the changes in local seasonal cycles. A locally defined hot/cold duration is used to represent local summer (LS)/winter (LW) in the present paper. Similarly, a locally defined date of climatic spring phase (LSP) and autumn phase (LAP) are analyzed for each station. Details are explained in section 2.

Another fundamental problem arises from the fact that the timings of CSO defined using different methods in previous studies could differ quite considerably (Walther and Linderholm, 2006). The same is true of other threshold-related dates, e.g. the FFS above the 0°C threshold, as weather variability often leads to multiple choices of dates matching the given threshold. This difficulty can be overcome, as illustrated in Qian et al. (2009; 2010b), by using the Ensemble Empirical Mode Decomposition (EEMD) method, a recently developed tool for nonlinear and nonstationary time series analysis (Huang and Wu, 2008; Wu et al., 2008b; Wu and Huang, 2009).

The present paper aims to demonstrate changes in the SC in China based on an updated homogenized daily mean surface air temperature dataset. The methods and data used are explained briefly in section 2. The results are illustrated in section 3. Finally, conclusions are summarized with a discussion in section 4.

2. Data and methods

Daily mean surface air temperature (SAT) series at 541 stations in China during 1960–2008, chosen from a homogenized dataset developed by Li and Yan (2009) using the Multiple Analysis of Series for Homogenization (MASH) method (Szentimrey, 1999; 2008), were applied in this study.

Several terms are used for quantifying changes in the SC based on locally determined thresholds for each station, including the local summer (LS) and winter (LW) periods and the locally defined date of the climatic spring phase (LSP) and autumn phase (LAP).

The local summer/winter temperature threshold (ST/WT) was defined, for each station, as the average of the temperature on the beginning date and the end date of the hottest (coldest) continuous-90-day period in the climatological annual cycle over the period 1971–2000. For each year, the period with the daily SAT records continuously beyond ST (below WT) was defined as the local summer (winter). The extremities of the seasonal cycle, length, beginning and end dates of the LS/LW and their changes could then be deduced. Different from the conventional concept of summer/winter, the LS/LW represents a locally hottest/coldest period in a year for a given site, hence allowing how long a locally extreme summer/winter condition persists in each year to be expressed.

For the transitional seasons, spring/autumn, the focus here is on any phase shift of the SC around the spring/autumn equinox (around 21 March/23 September). The local climatic spring/autumn phase (LS P/LAP) was defined for each year as an indicator of changes in the phase. The temperature threshold for LSP/LAP was defined as the average temperature of 19–23 March/21–25 September over the period 1971–2000. Then, the date of LSP/LAP of each year could be determined when the SAT surpassed the threshold.

However, the raw daily SAT series may have multiple intersections with a given threshold due to synoptic fluctuations, and that cannot be overcome, even if a 30-day moving average is applied to the raw data in some cases (Qian et al., 2009). To solve this problem, as suggested by Qian et al. (2009; 2010b), an annual cycle and longer timescale component (ALC) extracted using the Ensemble Empirical Mode Decomposition (EEMD) method can be applied to adaptively and uniquely determine the abovementioned indices. Details of the EEMD method are documented in previous publications (e.g. Huang et al., 1998; Huang and Wu, 2008; Wu and Huang, 2009). Procedures to obtain the ALC can be found in Qian et al. (2009).

The highest/lowest n-day-average temperature was calculated for each year to further express the extremities of the SC at each station, with n varying from one to a large number, in order to understand the uncertainty or significance of changes in the seasonal extremes. The Mann-Kendall test was applied to assess the significance of trends (Sneyers, 1999) and a moving-t-test (with the length of subsequence n=10) applied to identify the fastest change (referred to hereafter as a change point) in a climate index series.

3. Results

3.1 *Geographical patterns of SC thresholds*

First, let us describe an example to illustrate how the terms LS, LW, LSP and LAP are relevant in a seasonal cycle. With EEMD, a daily SAT series is decomposed into a high-frequency component (HF) representing weather-intraseasonal fluctuations and an ALC involving the annual cycle and longer-term variations. Figure 1 displays the ALC and the original Beijing SAT series for the years 2001 and 2002, together with the HF component. The thresholds for defining the LS, LW, LSP and LAP have clear intersections with the ALC; hence, the beginning/end dates of the LS and LW and the dates of the LSP and LAP can be uniquely determined. In order to eliminate the minor influence of data end effect on the EEMD components, the results of the first and the last year are omitted (Qian et al., 2010a). The subsequent analysis, therefore, is for the period 1961–2007.

Figure 2 shows the thresholds for defining the LS, LW, LSP and LAP in China. The local summer threshold varies from below 10°C in part of the Qinghai-Tibetan Plateau (20°–40°N, 73°–102°W) to above 25°C in southern China. The local winter

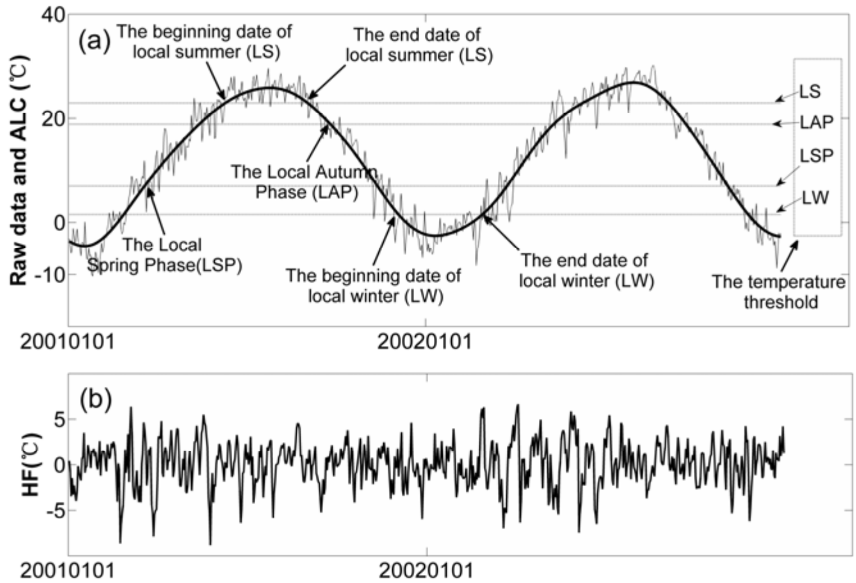

Fig. 1. The original daily temperature series [thin line in (a)] and its ALC component (thick line in (a), representing the annual cycle and longer-term variations), compared with the HF component [(b), representing weather-intraseasonal fluctuations] for Beijing during 2001–2002 (730 days). The dashed lines in (a) indicate the temperature thresholds for determining the LS, LW, LSP, and LAP.

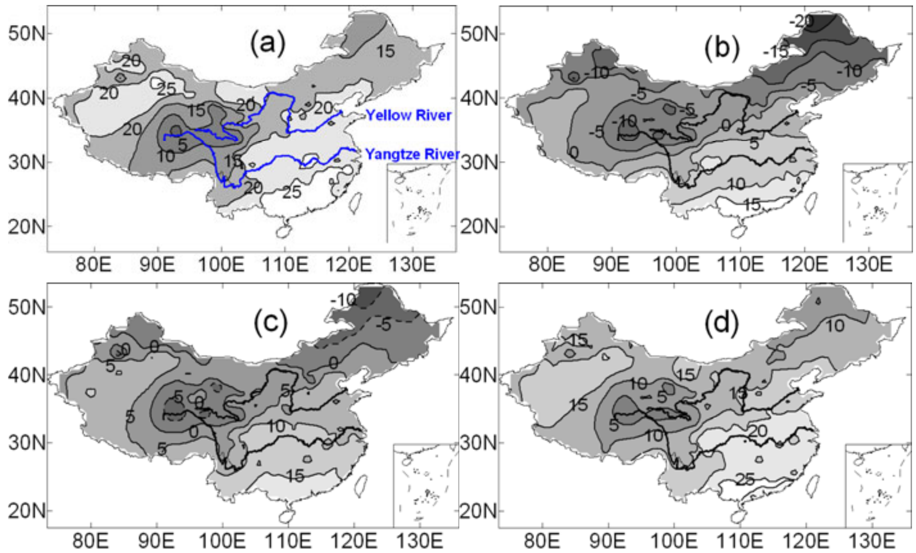

Fig. 2. Geographical patterns of the temperature thresholds for the (a) LS, (b) LW, (c) LSP, and (d) LAP in China, units: °C.

threshold ranges from below 15°C in northeastern China to above 15°C in southern China. It is clear that there is not a universal threshold (e.g. 10°C for winter or 20°C for summer) for defining a particular season over the whole region. This demonstrates the need for LS/LW concepts to quantify changes in local seasonal cycles.

Similarly, different from the "spring onset" used in many previous studies, the LSP is used here as an index to quantify a local transitional climate phase point (date) from a cold to warm season. According to Fig. 2, the temperature threshold for this date varies from below −5°C in northernmost parts of China and part of the Qinghai-Tibetan Plateau to above 15°C in southern China. The threshold temperature for the LAP, representing the transitional phase point to local autumn, ranges from below 10°C in the Qinghai-Tibetan Plateau to above 20°C in southeastern China.

3.2 *Trends in local summer (**LS**) and winter (**LW**)*

Figure 3 shows the trend in the beginning and end dates and the lengths of LS and LW. It is clear that the hottest summer period has been lengthening through an advancing beginning date and a delaying end date over most of China during the past few decades. The lengthening rate of the LS in most areas is about 2–4 d $(10\ \mathrm{yr})^{-1}$, the exception being for a region centered around the mid-lower reaches of the Yangtze River (Fig. 3a) where a minor linear trend, insignificant with a rate between 0 and 2 d $(10\ \mathrm{yr})^{-1}$, exists. The advancing trend of the beginning date of the LS is about −1 to −2 d $(10\ \mathrm{yr})^{-1}$, significant at many sites. A minor trend occurs in the lower reaches of the Yellow River, southern Tibet, and Southwest China. A delaying trend of the end date of the LS occurs in northeastern and northwestern China and the southern Qinghai-Tibetan Plateau, significant with a rate of about 1–3 d $(10\ \mathrm{yr})^{-1}$. An opposite but minor trend down to −1 d $(10\ \mathrm{yr})^{-1}$ occurs around the middle reaches of the Yangtze River.

In contrast, the coldest winter period has been shortening significantly almost everywhere during the same period, with a rate of −2 to −6 d $(10\ \mathrm{yr})^{-1}$. Clearly, the climate trend for winter is more prominent than that for summer. Figure 3 shows that the shortening of the LW is due mainly to an advancing trend of the end date of the LW, with a rate of −2 to −4 d $(10\ \mathrm{yr})^{-1}$, significant at most sites, except for part of southwestern China. A significant delaying trend of the beginning date of the LW occurs only in the Qinghai-Tibetan Plateau and southern China, with a rate of about 2–3 d $(10\ \mathrm{yr})^{-1}$.

The mean temperature of the hottest (coldest) continuous-90-day period was calculated, as a measure of the extremity of the seasonal cycle. Figure 4 shows the linear trends of these seasonal mean temperatures during the past half century. The warming trend of the winter is significant almost everywhere, with a rate of about 0.2°C–0.4°C $(10\ \mathrm{yr})^{-1}$. The LS temperature has also increased in most of China, with a rate of about 0.1°C–0.2°C $(10\ \mathrm{yr})^{-1}$, but the region around the middle reaches of the Yangtze River bearing a negative (though minor and hardly significant) trend remains notable.

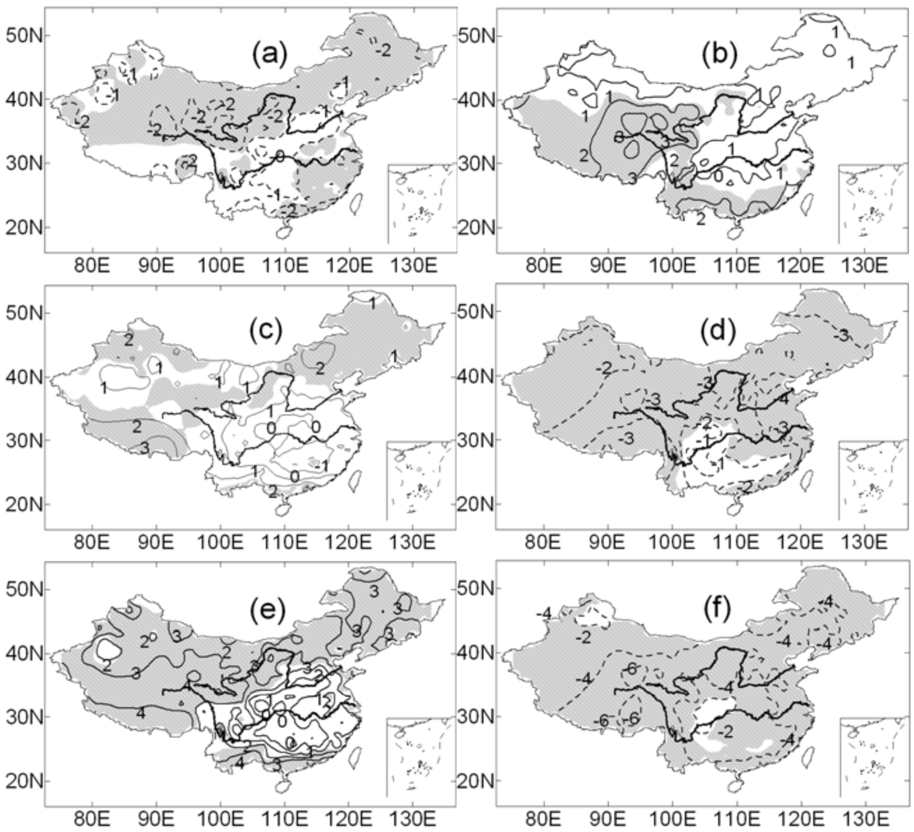

Fig. 3. Linear trend of the beginning dates, end dates, and lengths of the LS [(a), (c) and (e), respectively] and those of the LW [(b), (d), and (f), respectively] during 1961–2007. Units: d (10 yr)$^{-1}$. Shading represents a significant trend based on the Mann-Kendall test (α <0.05). The Yangtze and Yellow Rivers are marked with bold lines.

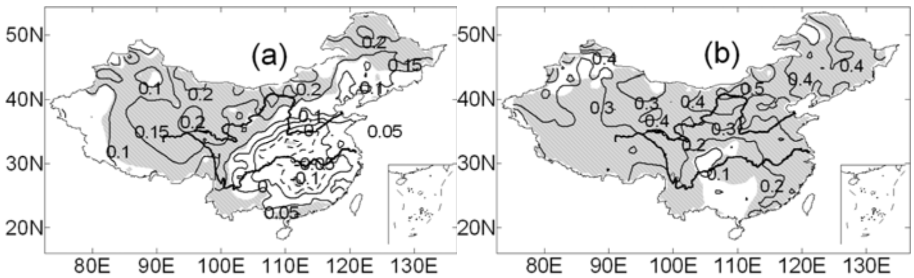

Fig. 4. Linear trend of mean temperatures of the hottest (a) and coldest (b) continuous-90-day period during 1961–2007, units: °C (10 yr)$^{-1}$.

3.3 *Comparisons of trends in the LS and LW among* 4 *regions*

Still focusing on large-scale regional features of changes in the SC, we divided China into four regions, using 35°N and 102°E as the boundaries: Northeast (NE), Northwest (NW), Southeast (SE), and Southwest (SW) China. It is of course possible to use more sophisticated categorizations of climate regions, but it was felt that doing so would not lead to any substantial improvement in our understanding as far as the subject of the present paper is concerned. Regional mean series were used for further analyses of variations in the SC.

It is well known that there was a sharp increase in global temperature around 1980 (Yan and Zeng, 1995). Wei et al. (2003) pointed out that in China the interdecadal change in annual mean temperature was not remarkable until 1990. It is interesting, therefore, to see whether there were any rapid changes in the sea-

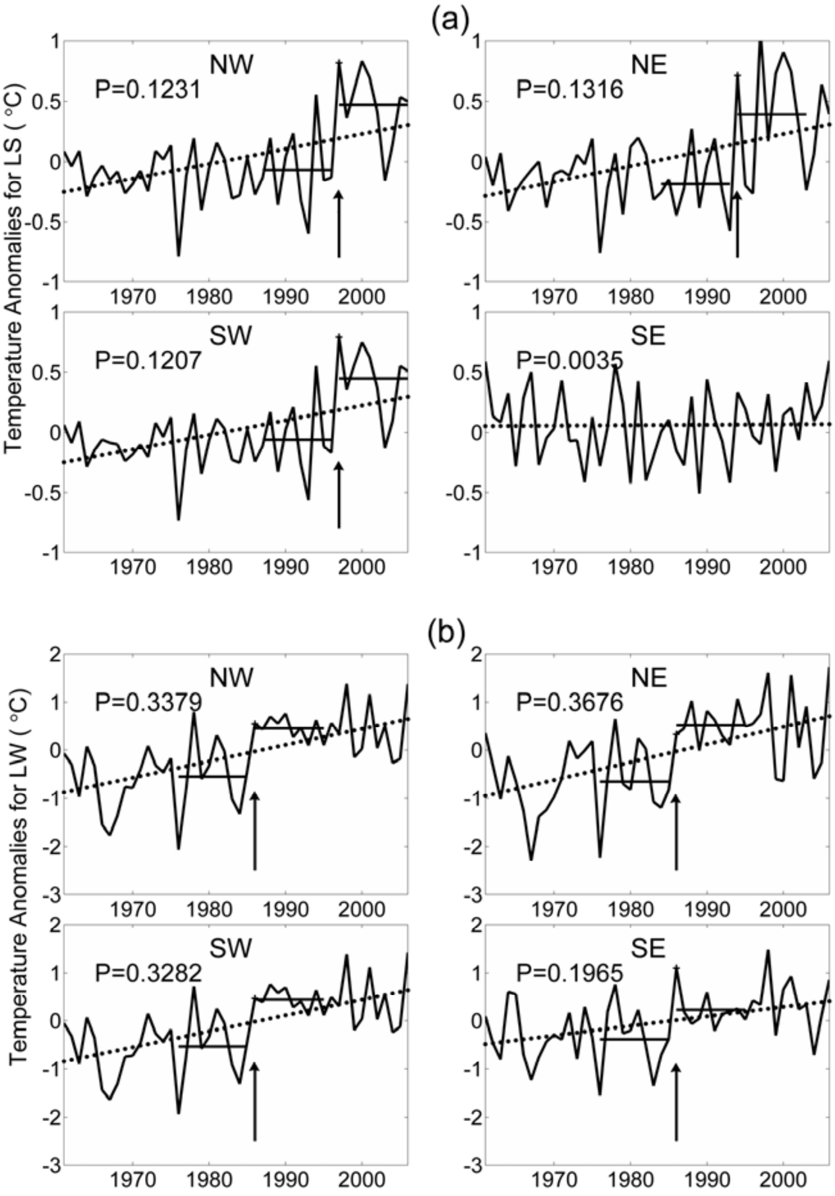

Fig. 5. Regional mean seasonal temperature anomalies (with respect to the 30-year mean SAT from 1971–2000) for the (a) LS and (b) LW. The dotted line indicates a linear trend with a rate of P [°C (10 yr)$^{-1}$]. The arrow indicates the most significant change of the mean level, if there is one, under a moving-t-test (α <0.05). The horizontal line represents the 10-year average before or after the change point.

sonal indices during recent decades.

Figure 5 shows that the LS temperature increased significantly during the period analyzed in NW, NE, and SW China, with a rate of about 0.12°C (10 yr)$^{-1}$. There was a minor trend in SE China, consistent with the geographical pattern described in the previous subsection. The warming of the LW was more prominent, with a rate of 0.34°C, 0.37°C, 0.33°C, and 0.20°C per decade in NW, NE, SW and SE China, respectively.

A warming change point occurred in the 1990s (1994 and 1997, according to a moving-t-test with a significance level of 0.05) for summer, except in the SE region. For winter, a warming change point occurred in the 1980s, more prominent than that for summer (Fig. 5).

Figure 6c shows that the LS was lengthening significantly during the period analyzed by about 2.8 d (10 yr)$^{-1}$ in NW, NE, and SW China, due to an advanc-

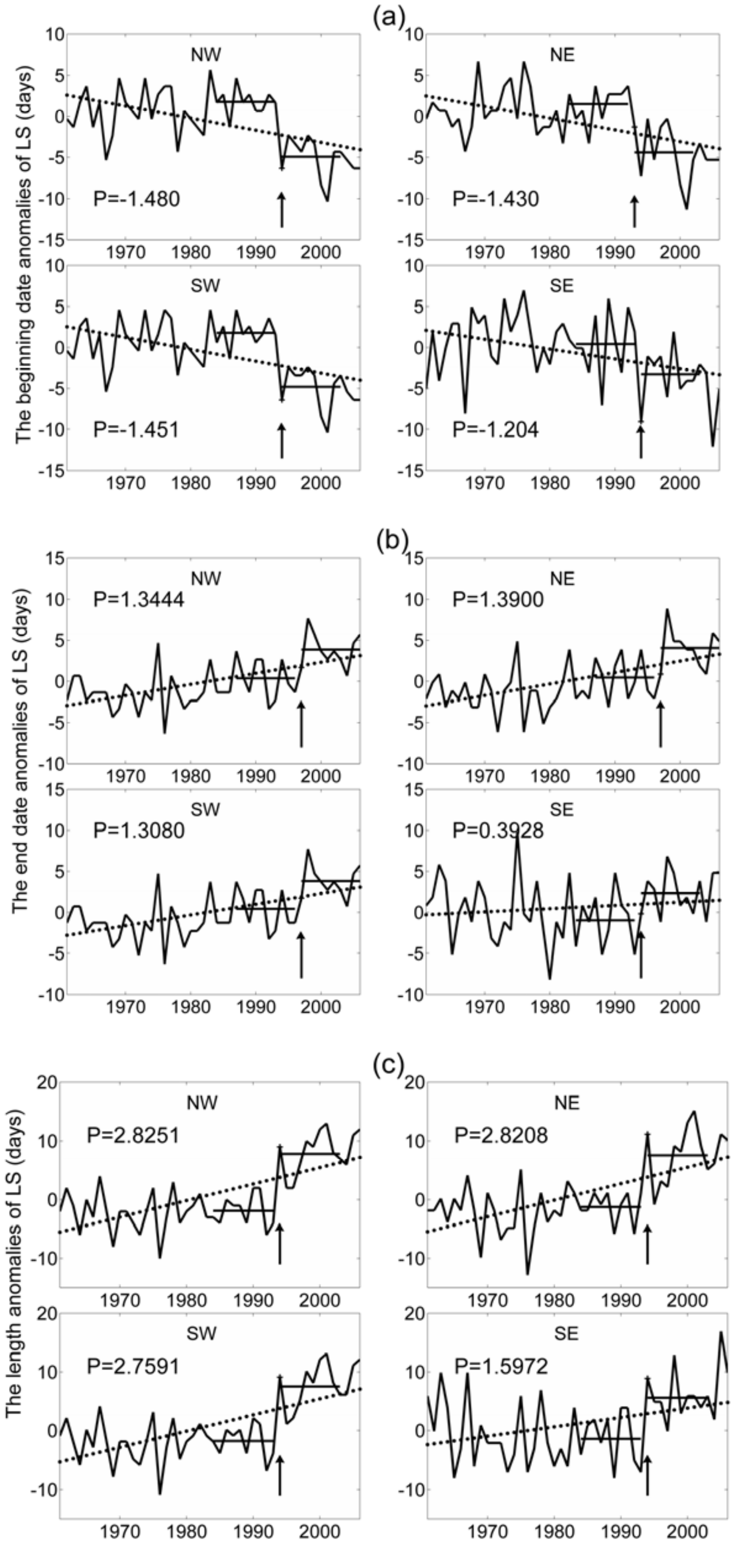

Fig. 6. Same as Fig. 5, but for (a) the beginning dates, (b) end dates, and (c) lengths of the LS. Units: number of days before (−) or after (+) the climatological mean date. Units for the linear trend: d (10 yr)$^{-1}$.

ing beginning date [Fig. 6a, rate of about −1.5 d (10 yr)$^{-1}$] and a delaying end date [Fig. 6b, rate of about 1.3 d (10 yr)$^{-1}$]. A lengthening trend of the summer period also occurred in the SE region, but with a minor rate of 1.6 d (10 yr)$^{-1}$, due mainly to an advancing beginning date [rate of −1.2 d (10 yr)$^{-1}$]. Figure 6 also shows that a sharp change happened in the 1990s in most cases, though the change in SE China was not as significant as in the other regions.

Figure 7c shows that the length of the LW was shortening at a rate of −3.8 d (10 yr)$^{-1}$ in NW, −4.0 d (10 yr)$^{-1}$ in NE, −3.7 d (10 yr)$^{-1}$ in SW, and −3.6 d (10 yr)$^{-1}$ in SE China, due mainly to an advancing end date [Fig. 7b, rate of −2.7 d, −3.2 d, −2.7 d, and −2.5 per decade, respectively]. A change point occurred in the 1980s, apart from in the SE region where the change point happened in the 1990s. However, the beginning date of the winter period did not appear to be of a delaying change point for NW, SE, and SW China (Fig. 7a). It is believed that this asymmetry in climate changes around the winter season might be associated with snowmelt feedback, which tends to be influential by the end of the winter season (Groisman et al., 1994; Cayan et al., 2001).

In short, recent large-scale warming has led to an extended summer period, both by an advancing beginning and a delaying end to the hot period across most of China. It has also led to a shortened winter period, due mainly to an earlier end to the cold period. A sharp change point in the seasonal indices dealing with winter appears to have happened in the 1980s, and another dealing with summer in the 1990s.

3.4 *Trends in extreme-n-day-mean temperatures*

To further understand climatic changes in the extremes of the SC, we used raw SAT series for the four regions to calculate extreme-n-day-mean temperatures in each year (n=1, 2, 3 . . . 90), in order to investigate how a stable trend pattern in extremes emerges.

Figure 8 shows trends in the hottest/coldest extremes with varying n values from one day to an entire season (90 d). For summer extremes, there is a general tendency that the larger the n value, the smaller the warming trend, ignoring the variation at the lower end of the n value spectrum. This suggests that the recent warming trend for summer was due more to increases in the few highest daily temperature records than to changes in general summer temperature. This implies that the probability of extremely hot days in summer has enhanced, while more typical summer conditions have been subject to relatively less changes.

For winter extremes, however, the warming trend tends to enhance when n changes from small to a considerably larger number, i.e. 18 for NW and SE China, 33 for NE China, and even larger than 90 for SW China. This is consistent with the fact that cold surges have reduced significantly in China during the last half a century (Zhai et al., 2008; Ding et al., 2009), while some extremely cold events still occasionally take place [e.g. the unprecedented frozen rain events in southern China during early 2008 (Zhou et al., 2009b)].

3.5 *Trends in the local spring and autumn phases*

Figure 9 shows that in most of China, the LSP advanced significantly during the period analyzed, with a rate of −1 to −3 d (10 yr)$^{-1}$, except for some small parts of northwestern China, the middle reaches of the Yangtze River, and southwestern China. A significant delaying trend of the LAP prevailed to the north of 35°N, with a rate of 1–1.5 d (10 yr)$^{-1}$, while a minor trend occurred in the south, with a rate of 0–1 d (10 yr)$^{-1}$. It is notable that the SC phase changed more prominently around the spring than autumn, consistent with the abovementioned finding that the winter period shortened due mainly to an earlier end date.

For a more explicit expression, we calculated the LSP/LAP dates for the four regions defined in the previous subsection. As Fig. 10a shows, the LSP was advancing significantly during the period analyzed, with a rate of −1.7 d (10 yr)$^{-1}$ in NW, −2.0 d (10 yr)$^{-1}$ in NE, −1.6 d (10 yr)$^{-1}$ in SW, and −1.6 d (10 yr)$^{-1}$ in SE China. Estimates of the linear trends in the LSP dates given here are comparable to the results of Qian et al. (2010b), who used a different definition of CSO for northern China and reported a 1.67 d (10 yr)$^{-1}$ advancement during 1955–2003. Two sharp advancing change points were found for the late 1980s (NE China) and for the 1990s (NW, SW, and SE China) (Fig. 10a).

As shown in Fig. 10b, the LAP was delaying significantly in NW, NE and SW China during the period analyzed, with a rate of about 1.3 d (10 yr)$^{-1}$, and there was a change point in the late 1980s (NE China) and 1990s (NW and SW China). For the SE region, the delaying trend of LAP was minor [about 0.8 d (10 yr)$^{-1}$], with a change point in the mid 1990s.

To further express changes in the spring/autumn phases, we calculated the linear trend in the series of the mean temperature around the spring equinox (SET, average temperature 19–23 March) and autumn equinox (AET, average temperature 21–25 September).

As shown in Fig. 11, the SET was increasing all over the country during the period analyzed, and by up to 0.7°C (10 yr)$^{-1}$ in northeastern China. Minor trends exist in southern China, at about 0°C–0.2°C

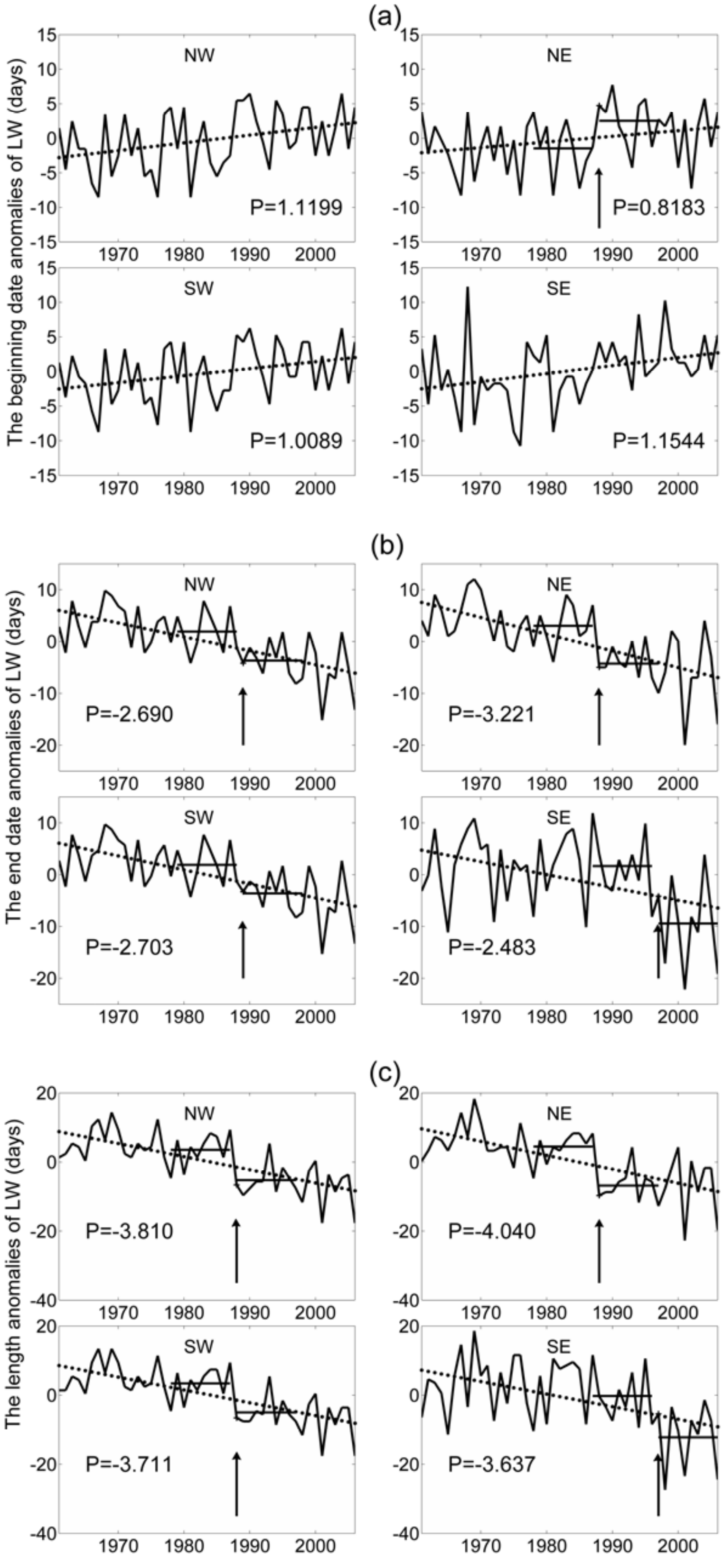

Fig. 7. Same as Fig. 6, but for the beginning dates (a), end dates (b), and lengths (c) of the LW.

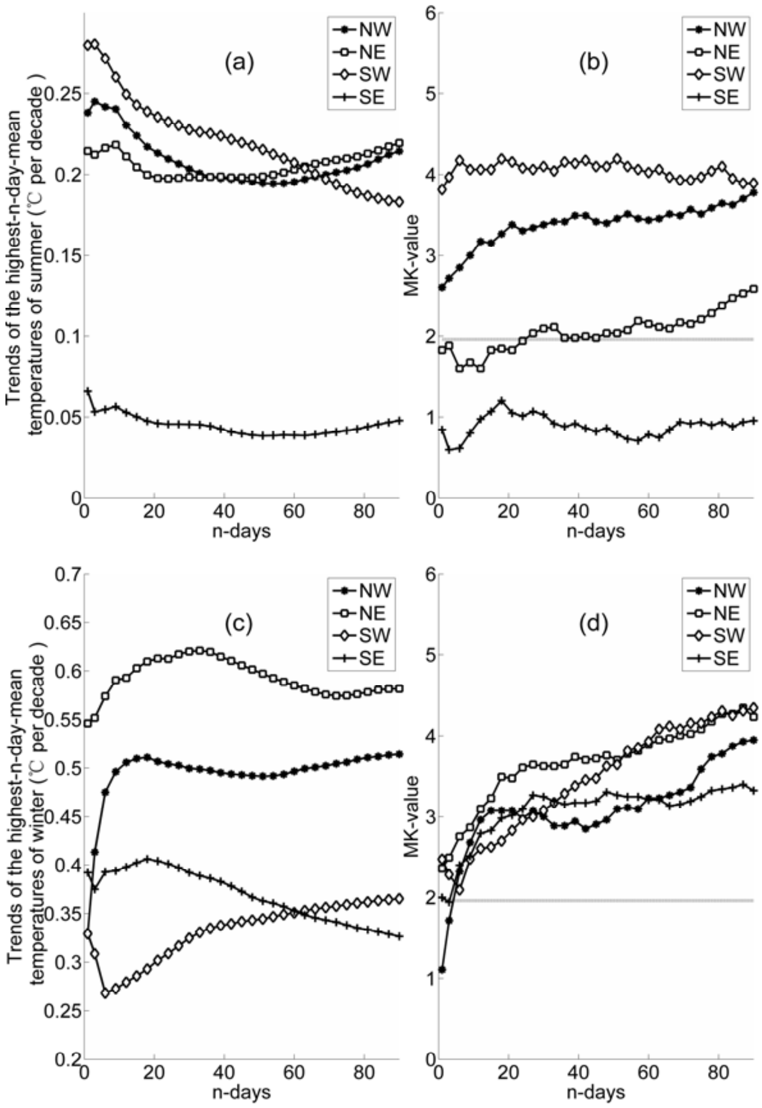

Fig. 8. Trend of the highest-n-day-mean temperatures of summer and the corresponding Mann-Kendall test statistics [(a) and (b)] and those of the lowest-n-day-mean temperatures of winter [(c) and (d)] during 1961–2007 for the four regions. The horizontal dashed line crossing with the Mann-Kendall test curves indicates the threshold for a significant trend (α <0.05). n= 1, 2, 3, . . . 90.

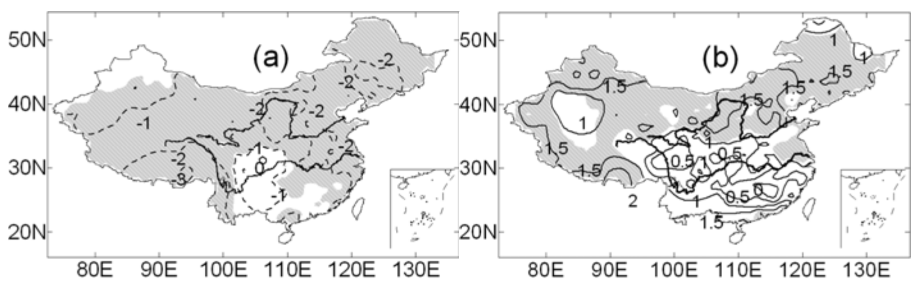

Fig. 9. Trend in the dates of the (a) LSP and (b) LAP during 1961–2007, units: d (10 yr)$^{-1}$.

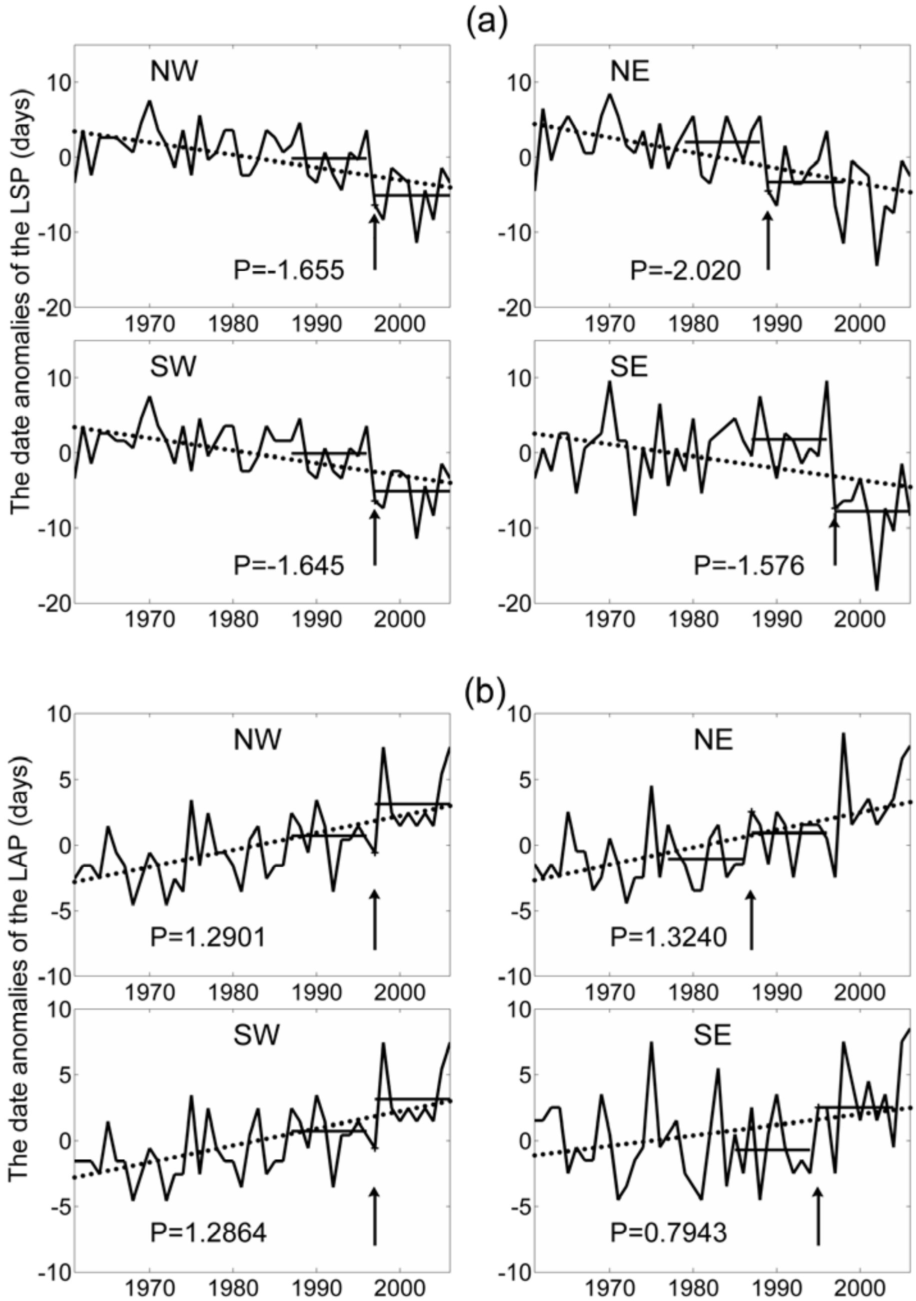

Fig. 10. Same as Fig. 6 but for the dates of the (a) LSP and (b) LAP.

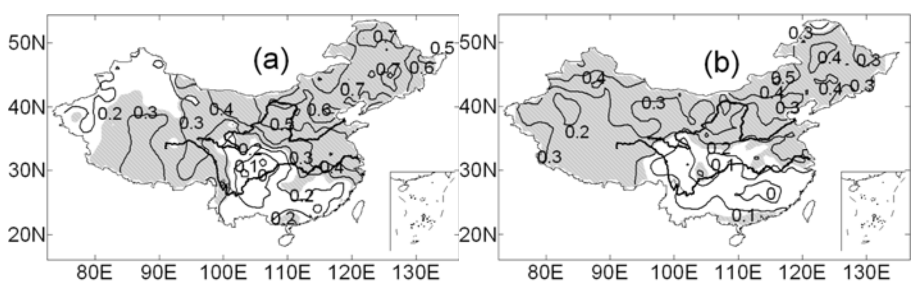

Fig. 11. Trend of the SET (a) and AET (b) during 1961–2007, units: °C (10 yr)$^{-1}$.

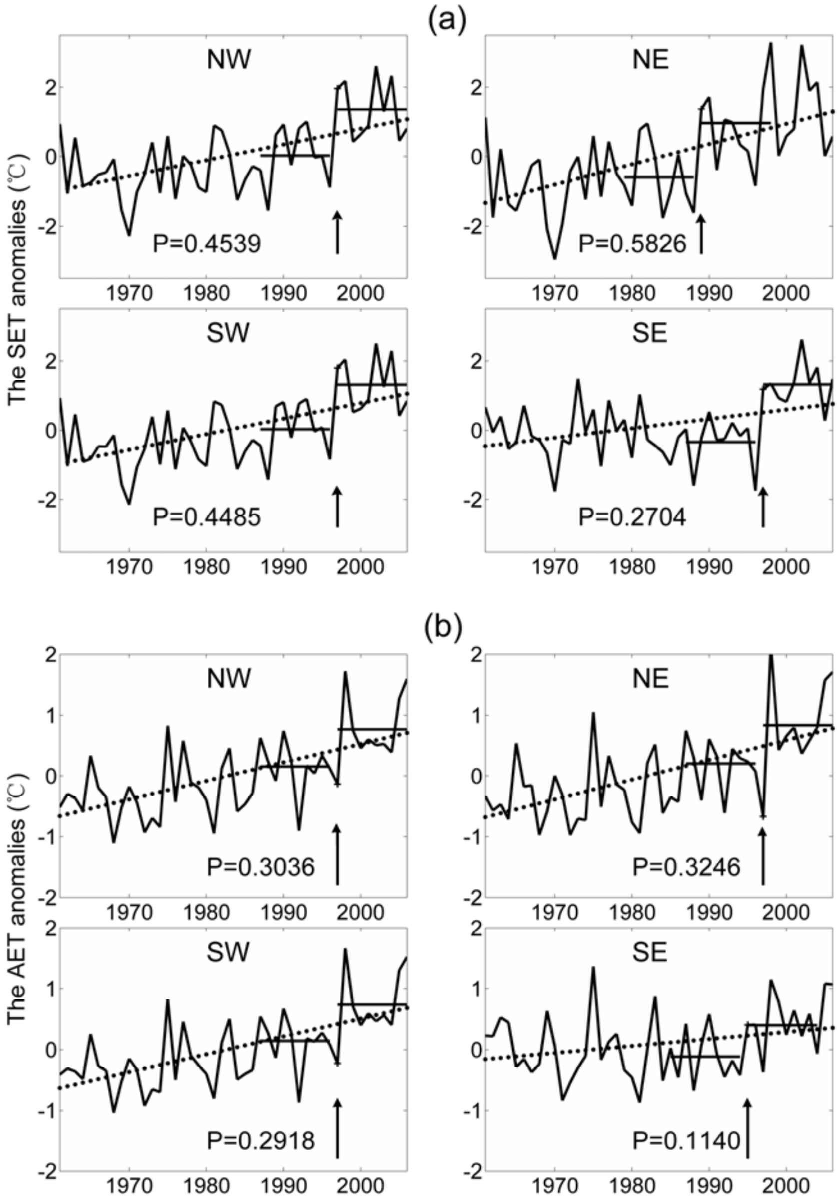

Fig. 12. Same as Fig. 5 but for regional (a) SET and (b) AET series, 1961–2007.

(10 yr)$^{-1}$. The AET was also increasing across most of China, by up to 0.4°C (10 yr)$^{-1}$ in the northeast. Minor trends exist in southern China, at about 0°C–0.1°C (10 yr)$^{-1}$.

All the four regional SET and AET series exhibit a positive trend (Fig. 12). The significant increasing rates of SET are 0.45°C (10 yr)$^{-1}$ for NW China, 0.58°C (10 yr)$^{-1}$ for NE China, 0.45°C (10 yr)$^{-1}$ for SW China, and 0.27°C (10 yr)$^{-1}$ for SE China, with a sharp change point in the late 1980s (NE China) and mid 1990s (NW, SW, SE) (Fig. 12a). Those for AET are 0.30°C (10 yr)$^{-1}$ for NW China, 0.32°C (10 yr)$^{-1}$ for NE China, and 0.29°C (10 yr)$^{-1}$ for SW China, with a change point around 1997 (Fig. 12b). The linear trend of AET for SE is minor, but with a warming change point in the 1990s.

4. Summary

This paper has provided an overview of recent climate trends in seasonal cycles in China based on a homogenized dataset of daily temperature observations at 541 stations during 1960–2008. Several indices were defined for describing the key features of a seasonal cycle based on climatology of the period 1971–2000, including local winter/summer (LW/LS), representing extreme phases, and local spring/autumn phases (LSP/LAP), representing transitional phase points.

The EEMD method was applied to the daily temperature series in order to help determine the indices for each year. The results were not inconsistent with conventional studies, e.g. those dividing a year into four seasons of equal length, and have thus brought fresh insight into recent climatic trends in SCs in China, especially in terms of seasonal extremes and transitional phases. The main conclusions drawn from the study are as follows.

(1) The winter period has been shortening by 2–6 d (10 yr)$^{-1}$, due mainly to an earlier end to cold conditions; meanwhile, the winter mean temperature level has been increasing by 0.2°C–0.4°C (10 yr)$^{-1}$ over almost all of China since 1960. A climatic (warming) change point occurred in the 1980s for most of the regional mean winter indices. Although more general winter severity has lessened significantly, the most extreme records appear to have been remained more constant.

(2) The summer has been lengthening by 2–4 d (10 yr)$^{-1}$, due to an advanced beginning and a delayed end date to the locally defined hot period; meanwhile, the summer mean temperature has been increasing by 0.1°C–0.2°C (10 yr)$^{-1}$ across most of China. A climatic (warming) change point occurred in the 1990s for most of the regional mean summer indices, compared to the 1980s for the winter indices. An exception was for a region in southern China, centered around the mid-lower reaches of the Yangtze River, where summer condition do not appear to have warmed up. Also different from the winter cases, the warming trend in summer tended to be more prominent for the most extreme records, rather than more general summer temperatures.

(3) The local spring phase tended to advance significantly by about 2 d (10 yr)$^{-1}$ across most of China, with a mean temperature around the spring equinox increasing by up to 0.7°C (10 yr)$^{-1}$ in northeastern China. Changes in the autumn phase appeared less prominent. The local autumn phase delayed progressively by about 1 d (10 yr)$^{-1}$ and the temperature around the autumn equinox increased by less than 0.4°C (10 yr)$^{-1}$ across most of China during the period analyzed. There was also a change point in the regional mean indices of the transitional phases, either in the late 1980s or the 1990s.

It is worthwhile noting that the locally defined seasonal indices in the present paper allow for quantitative assessment of climate changes in the SC, especially in terms of seasonal extremes and transitional phases. Many different definitions of the seasons and transitional phase points (e.g. spring onset based on an ecological viewpoint) can be made, but should not alter the climatic trend results discussed in the present paper. It is also important to note that the sharp signal changes in the late 1980s and the 1990s detected in the regional seasonal indices appeared to lag to those large-scale ones in the late 1970s (Trenberth, 1990; Wang et al., 2006; Yu and Zhou, 2007; Zhou et al., 2008; Zhou et al., 2009a), but were possibly associated with large-scale climate changes in and around the region too, since similar signals were found in, for example, the decadal shift of summer or winter climate over East China (Chan and Zhou, 2005; Zhou et al., 2006; Zhou and Chan, 2007; Zhang et al., 2008; Wang et al., 2009; 2010), temperature in China (Qian et al., 2010a), precipitation in North China and atmospheric circulation in East Asia (Tu et al., 2010), and ocean currents in the northwestern Pacific, the Indian Ocean, and South China Sea (Li et al., 2006; Zhou and Chan, 2007; Wang et al., 2006, 2007; Wu et al., 2008a. Yuan et al., 2008a, b; Cheng et al., 2008; Li et al., 2010). Mechanisms linking the different changes in SCs in China and larger-scale climate changes deserve further study.

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