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Trends in Temperature Extremes in Association with Weather-Intraseasonal Fluctuations in Eastern China

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ABSTRACT

Trends in the frequencies of four temperature extremes (the occurrence of warm days, cold days, warm nights and cold nights) with respect to a modulated annual cycle (MAC), and those associated exclusively with weather-intraseasonal fluctuations (WIF) in eastern China were investigated based on an updated homogenized daily maximum and minimum temperature dataset for 1960–2008. The Ensemble Empirical Mode Decomposition (EEMD) method was used to isolate the WIF, MAC, and longer-term components from the temperature series. The annual, winter and summer occurrences of warm (cold) nights were found to have increased (decreased) significantly almost everywhere, while those of warm (cold) days have increased (decreased) in northern China (north of 40°N). However, the four temperature extremes associated exclusively with WIF for winter have decreased almost everywhere, while those for summer have decreased in the north but increased in the south. These characteristics agree with changes in the amplitude of WIF. In particular, winter WIF of maximum temperature tended to weaken almost everywhere, especially in eastern coastal areas (by 10%–20%); summer WIF tended to intensify in southern China by 10%–20%. It is notable that in northern China, the occurrence of warm days has increased, even where that associated with WIF has decreased significantly. This suggests that the recent increasing frequency of warm extremes is due to a considerable rise in the mean temperature level, which surpasses the effect of the weakening weather fluctuations in northern China.

Key words: climate extremes, EEMD, weather-intraseasonal fluctuations, modulated annual cycle, global warming

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1. Introduction

The impact of global warming on human society and ecosystems is realized greatly via changes in locally unusual weather phenomena, or so-called climate extremes. For instance, a record-breaking heat wave event in Europe in summer 2003 resulted in widespread droughts, crop losses, and more than 22 000 heat-related deaths across Europe (Christoph and Gerd, 2004; Levinson and Waple, 2004). At the other end of the spectrum, a persistent freezing event in southern China during early 2008 caused economic

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losses amounting to 151.65 billion Yuan (Tao and Wei, 2008). Yan et al. (2001) suggested that weather variability (timescales of five days up to two months) explains about 80% of the total variance of the daily anomaly series and any trend in this band of variability is, therefore, likely to be a good indication of changes in real climate extremes. Recent changes in climate extremes have been documented based on worldwide observations (e.g. Karl and Easterling, 1999; Zhang et al., 2000; Manton et al., 2001; Peterson et al., 2001; Yan et al., 2002; Klein Tank and Können, 2003; Zhang et al., 2005a; Klein et al., 2006; Alexander et al., 2006). Temperature extremes in China have also been widely studied (e.g. Yan and Yang, 2000; Zhai and Pan, 2003; Ma et al., 2003; Qian and Lin, 2004; Qian and Zhang, 2007; Gong et al., 2009; Wan et al., 2009; Ding et al., 2009; Li et al., 2009; Hu et al., 2009). However, few, if any, previous studies have reported changes of temperature extremes in association with weather variability and its role in changes of overall temperature extremes. Although previous studies have reported that, in agreement with warming trends, the number of warm nights and warm days in many land areas sampled during recent decades have increased, while cold nights and cold days have decreased (IPCC, 2007), it remains unclear how those changes in temperature extremes are related to a warming trend or changes in weather variability.

Based on an analysis of several long-term daily temperature series, Yan et al. (2001) found that weather variability tended to be weaker at northern mid-high-latitude sites during warm decades than during cold decades, except for warm months at some lower-latitude sites. According to that result, fewer warm extremes can be expected during a warmer period at mid-high-latitudes unless the warming extent surpasses the effect of weakening weather fluctuations. To quantify what has been observed during the last few decades with regard to this point, it is necessary to define properly the extremes in association with weather variability.

In previous studies, climate extremes have usually been defined with respect to a climatological mean annual cycle (CAC) over a "standard reference" period, e.g. 1961–1990 (Jones et al., 1999), or the whole period studied (Yan et al., 2002). Different references may lead to different definitions of climate anomalies, and thus different frequencies of climate extremes. Having considered variations in annual cycles, Wu et al. (2008) proposed that a physically better reference for studying climate anomalies is the amplitude-frequency modulated annual cycle (MAC), obtained adaptively by using the Ensemble Empirical Mode Decomposition (EEMD) method (Wu and Huang, 2009; Huang and Wu, 2008), which is an adaptive and temporally local data analysis tool. Qian et al. (2010) further analyzed some spatiotemporal characteristics of multi-timescale variability of mean temperature in China from daily datasets based on MAC. The EEMD method enables proper identification of the roles of changes in weather variability, annual cycle and longer-term climate variations on trends in climate extremes.

The aim of the present paper is to investigate linear trends in the relative temperature extremes associated exclusively with weather-intraseasonal fluctuations and, with the combination of weather-intraseasonal fluctuations and longer-term variations with respect to a modulated annual cycle (w.r.t. MAC hereafter) in China in recent decades, to provide some insight into how changes in temperature extremes are related to a warming trend or changes in weather variability. The study was based on an updated homogenized daily maximum and minimum temperature dataset for the period 1960–2008, which is more suitable for large-scale climate change analysis than the original dataset, as most of the unnatural local biases (e.g. due to site changes and changes in observation protocols) have been adjusted (Li and Yan, 2009). The EEMD method was applied to isolate a weather-intraseasonal fluctuations component, a MAC component, and a longer-term variations component from daily temperature series at each station. Further descriptions of the data and methods used are given below, in section 2. The results are then presented in section 3, with conclusions and a discussion summarized in section 4.

2. Data and methods

Since inhomogeneity may considerably influence the results of climate change analyses, an updated homogenized daily maximum and minimum temperature dataset for China for the period 1960–2008 (Li and Yan, 2009) was used in this study. Eastern China (east of 110°E) was chosen as the target region, mainly because observations are scarce in western China. For convenience when analyzing the data, the record for 29 February in a leap year was excluded and that for 28 February was replaced by the average of the original 28 February and 29 February records, thus leaving 365 daily values for every year. This modification of the data may have caused some loss of precision in terms of judging extremes for some local cases, but should not have altered the main results presented and described below, especially the geographical patterns of long-term trends in the indices of temperature extremes.

The EEMD method was used to decompose a daily temperature series at each station to obtain the weather-intraseasonal fluctuations (WIF, over timescales of several days to months), MAC, and longer-term variations (LV, representing interannual to longer timescale variations) components. EEMD improves upon the Empirical Mode Decomposition (EMD) method (Huang et al., 1998; Huang and Shen, 2005; Wu et al., 2007; Huang and Wu, 2008), which is an adaptive data analysis method to decompose any complicated data series into a finite and often small number of amplitude-frequency modulated oscillatory components. The basics and effectiveness of this method applied to geophysical data analyses have been documented in many recent papers (e.g. Huang and Wu, 2008; Wu et al., 2008; Wu and Huang, 2009; Qian et al., 2009, 2010, 2011). In particular, the capability and advantage of EEMD in extracting the annual cycle component, which is of strong amplitude-frequency modulation, have been demonstrated well through analyzing synthetic data, monthly sea surface temperature data, and observed daily temperature records (Wu et al., 2008; Qian et al., 2011). The procedures for using EEMD to obtain the WIF, MAC, and LV components from a daily temperature series detailed in Qian et al. (2010) were followed in the present study. The added noise in the EEMD program for analyzing the daily maximum and minimum temperature series in eastern China had a standard deviation of 0.3 for most cases. Considering the minor data end effect within one cycle at each end of the series as far as the MAC component is concerned (Qian et al., 2010), the first and last year of the decomposed results were excluded in the present study, leaving 1961–2007 as the period of analysis. In order to give the reader a visual impression, the daily minimum temperature series at Beijing and its three major timescale components from applying the EEMD method are used as an example and displayed in Fig. 1.

Four indices of percentile-based relative temperature extremes at each station are to be analyzed in this paper: the occurrence of unusually warm days (TX90p), cold days (TX10p), warm nights (TN90p), and cold nights (TN10p) (Alexander et al., 2006). These indices can be calculated by counting the number of extreme days in a year or season, for which the daily observations exceed a time-of-year-dependent percentile threshold. The 10th and 90th percentile thresholds are estimated based on sample temperature anomalies of five consecutive days centered on the day of interest for the reference period 1961–1990 (Jones et al., 1999; Folland et al., 1999; Frich et al., 2002), whereas the anomalies are relative to the CAC of the reference period. In order to investigate the impact of amplitude-frequency modulation of the annual cycle on changes in temperature extremes, the extremes

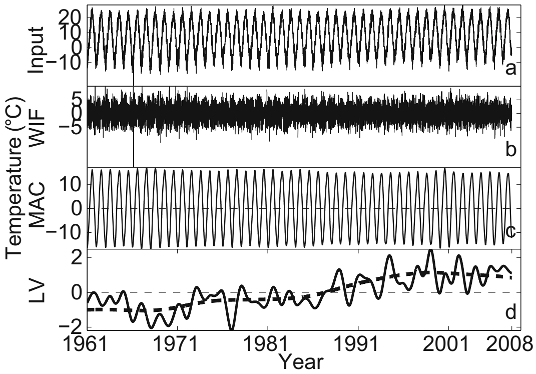

Fig. 1. A diagram of decomposing a daily temperature series using the EEMD method: (a) is the raw series of homogenized daily minimum temperature data for the period 1961–2007 at Beijing (Input); (b), (c) and (d) are its WIF, MAC, and LV components, respectively. In panel (d), the dotted line indicates the interdecadal trend. Variables displayed in panels (c) and (d) are departures from the 1961–2007 mean.

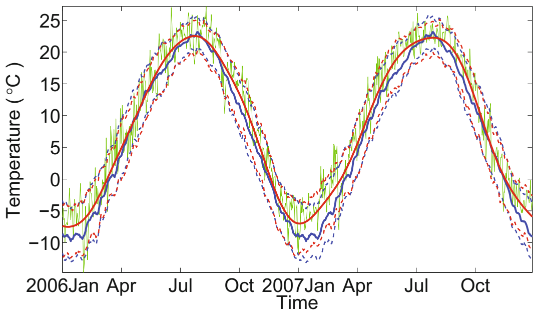

Fig. 2. Annual cycle (thick solid lines) and percentiles (dotted lines) for determining relative temperature extremes based on daily minimum temperature ($T_{\min}$) series at Beijing from 1 January 2006 to 31 December 2007. 10th and 90th percentiles are used. The green line indicates the raw daily $T_{\min}$ series, red is based on MAC, while blue is based on CAC.

and thresholds defined with respect to MAC were calculated. Figure 2 shows an example of the CAC for 1961–1990 as well as the MACs of minimum temperature for Beijing and the 90th/10th percentile thresholds, together with the raw data from 1 January 2006 to 31 December 2007. The four indices were also calculated using the WIF component (Fig. 1b), to reveal the influences of changes in WIF on extremes.

Changes in the upper envelope of WIF of both maximum and minimum temperatures at all the stations in the region studied were analyzed through an index defined as follows:

$$R = \frac{b_{\rm t} \times N}{m_{\rm a}}\,, \tag{1}$$

Table 1. Mann-Kendall test results for linear trends in the four kinds of relative temperature extremes with respect to conventional annual cycle (C) and the modulated annual cycle (M) and associated exclusively with weather-intraseasonal fluctuations (W). Significant trends (α <0.05) are in bold.

	Annual			Winter			Summer		
M-K Significance	C	M	W	C	M	W	C	M	W
warm days	**3.86**	**2.96**	1.1	**2.16**	0.65	0.65	1.82	**2.41**	1.29
cold days	**−2.98**	**−2.67**	−0.45	**−2.24**	**−2.19**	**−2.64**	−1.38	**−2.03**	−0.47
warm nights	**4.94**	**4.91**	**−3.26**	**4.78**	**2.85**	**−3.85**	**3.12**	**4.26**	−1.31
cold nights	**−6.48**	**−6.23**	**−3.4**	**−5.71**	**−5.18**	**−3.87**	**−3.73**	**−5.6**	0.67

where b_t is the linear trend coefficient for the annual, summer or winter mean upper envelope of WIF at each station; N is the length of series (e.g. for annual and summer N is 47, while for winter it is 46); and m_a is the corresponding average upper envelope of WIF at each station during 1961–2007. Here, the upper envelope was estimated via a cubic spline fitting to the local maxima of the daily WIF series. Thus, this index "R" represents the percentage of changes in the amplitude of WIF for 1961–2007, with sign "+" ("−") indicating an increasing (decreasing) amplitude of WIF.

For the combination series of WIF and LV, the effects of changes in LV on changes in the upper and lower envelopes of the combination series are different. In this study, changes in the upper envelope, which is associated with warm events, of the combination series were of greater concern and calculated through a cubic spline fitting to the local maxima of the combination series.

The linear trend of an index series was calculated and the significance assessed using the Mann-Kendall test (α=0.05). To establish the geographical distribution of the linear trends, the "griddata" function in MATLAB 4 was applied for interpolation.

3. Results

3.1 *A case study for Beijing*

This case study was chosen to illustrate the roles of the WIF, MAC, and LV components in estimating temperature extremes and the corresponding trends. Figure 3 shows the annual, winter and summer frequencies of the four kinds of relative temperature extremes with respect to CAC (w.r.t. CAC hereafter) at Beijing for the period 1961–2007 and the corresponding linear trends. It is clear that warm days and warm nights are increasing, while cold days and cold nights are decreasing, and these trends were found to exist in all the annual, winter and summer cases. The trends in the four index series are significant for the annual and winter cases, and for summer, the trends in occurrences of warm nights and cold nights are significant (Table 1).

However, the trends in the extremes associated exclusively with WIF are quite different from those w.r.t. CAC, even with different signs in some cases, e.g. for warm nights (Fig. 3c). It is notable that the annual and winter warm and cold nights and the winter cold days associated with WIF (Table 1) are decreasing significantly, implying weakening weather fluctuations.

The impressive discrepancy between the results w.r.t. CAC and those associated exclusively with WIF could arise from the effect of changes in MAC (e.g. Fig. 1c) or that of changes in the LV component (e.g. Fig. 1d). When modulation of the annual cycle is taken into account by excluding the MAC (e.g. Fig. 1c) instead of the CAC before calculating the indices, the four index series w.r.t. MAC exhibit trends similar to those w.r.t. CAC, although there are differences in rates of trends, especially for the winter and summer cases. This result suggests that modulation of the annual cycle does not necessarily lead to substantial differences in estimating climate trends in annual temperature extremes. However, for individual years, the impact of modulation in the annual cycle can be large. For example, for winter 2006/2007, there are fewer (11) unusually warm nights w.r.t. MAC than those w.r.t. CAC (19) (Fig. 3c2). The same is true for most years after 2000, leading to a smaller rate of trend in the series of warm nights w.r.t. MAC than w.r.t. CAC. For summer, trends in the occurrences of warm days and cold days w.r.t MAC are significant, whereas those w.r.t. CAC are not. In general, the standard deviations of the four indices w.r.t. MAC are larger than those w.r.t. CAC. These differences are basically due to a prominent warming trend at Beijing during the period 1961–2007, especially after the mid-1980s (Fig. 1d) and for cold seasons. Consequently, the CAC for 1961–1990 inevitably underestimates the temperature level in cold seasons in recent years (noting the winter of 2006/2007 in Fig. 2). Such underestimation should affect the 10th and 90th percentile thresholds, and hence affect the calculation of the indices of extremes to some extent. In contrast, the MACs fit the temperature variations appealingly

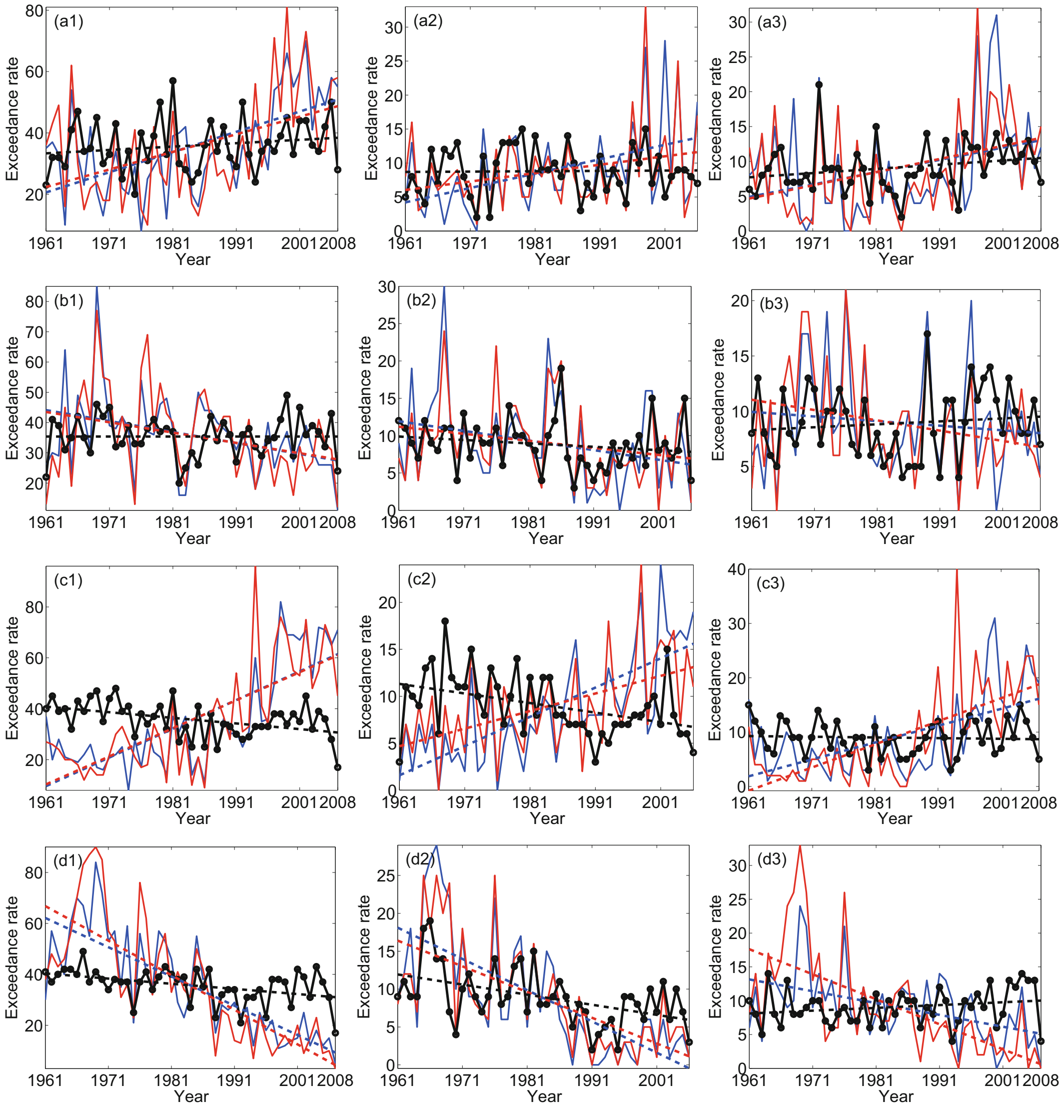

Fig. 3. Frequencies (solid lines) and corresponding linear trends (dashed lines) of relative temperature extremes associated with different components for the period of 1961–2007 at Beijing: (a) warm days (TX90p); (b) cold days (TX10p); (c) warm nights (TN90p); and (d) cold nights (TN10p). The left, middle and right columns represent annual, winter and summer, respectively. Blue, red and black lines represent relative extremes with respect to CAC (1961–1990 climatology), MAC, and that associated exclusively with WIF, respectively. In all panels, units for the y-coordinates are days.

well (Fig. 2). Some other problems of applying CAC, e.g. artificial discontinuities at the beginning and end of the base period used for calculating the percentiles, have been discussed by Zhang et al. (2005b). These problems could be lessened by using the MAC reference.

Having inferred that the effect of modulation of the annual cycle does not induce large differences in the trend estimation of temperature extremes for the Beijing case, we hypothesize that the mentioned discrepancy between the results w.r.t CAC and those associated exclusively with WIF should arise mainly from the effect of LV, i.e. long-term warming. To test this notion, linear trends in the upper envelope of WIF, as well as those in the combination of WIF and LV, for both the maximum and minimum temperatures were examined (Fig. 4). As stated in section 2, for WIF, changes in its upper envelope represent changes in its amplitude. The annual, winter and summer mean upper envelope of the combination series of WIF and LV for the maximum temperature are increasing (Fig. 4b), with a magnitude of change of about 5%, significant for the annual and summer cases (Table 2), while there are no obvious trends in the amplitudes of WIF

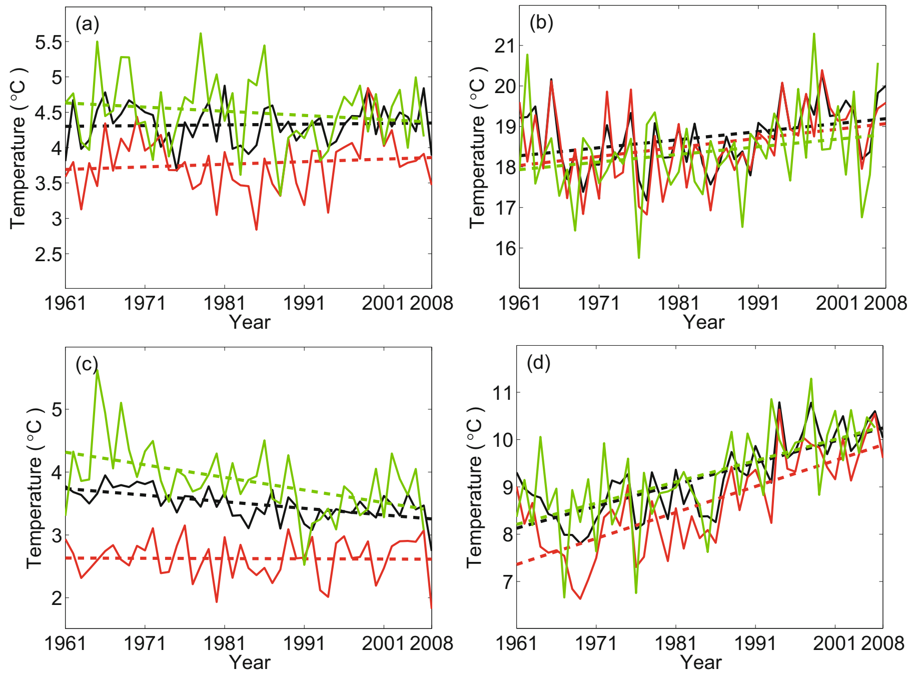

Fig. 4. Linear trends in the amplitude of WIF [(a) and (c)] and in the upper envelope of the combination of WIF and LV [(b) and (d)] for maximum [(a) and (b)] and minimum [(c) and (d)] temperatures at Beijing. In all panels, black, green, and red lines represent the annual mean, winter and summer cases, respectively.

Table 2. Mann-Kendall test results for linear trends in the amplitudes of WIF and in the upper envelope of the combination of WIF and LV (i.e. w.r.t. MAC) for both maximum and minimum temperatures at Beijing, together with the percentages (numbers in parentheses) of changes in those upper envelopes. Significant trends (α <0.05) are in bold.

	Annual		Winter		Summer	
	WIF	w.r.t. MAC	WIF	w.r.t. MAC	WIF	w.r.t. MAC
$T_{\max}$	0.14 (1.1%)	**2.6 (5.0%)**	−0.80 (6.1%)	1.58 (4.8%)	0.60 (4.6%)	**2.45 (5.7%)**
$T_{\min}$	**−4.03 (14.1%)**	**5.57 (23.6%)**	**−3.25 (24.4%)**	**4.42 (22.9%)**	0.50 (0.7%)	**5.38 (30.0%)**

(Fig. 4a). For the minimum temperature, while the annual and winter mean amplitudes of WIF are significantly decreasing, with a magnitude of 14% and 24%, respectively (Fig. 4c and Table 2), the annual and winter mean upper envelope in the combination series of WIF and LV are significantly increasing by about 23% (Fig. 4d). There is little trend in the summer mean amplitude of WIF (Fig. 1d), hence the magnitude of increase in the summer mean upper envelope of the combination series reaches 30%, larger than the annual and winter cases. These contrasts suggest that the extent of long-term warming at Beijing surpasses the effect of changes in the weather fluctuations on the warm extremes.

3.2 *Geographic distribution of trends in temperature extremes w.r.t. MAC*

In order to facilitate a comparison with temperature extremes associated exclusively with WIF, those associated with the combination of WIF and LV are examined first. Figure 5a1 shows that the annual occurrence of warm days w.r.t. MAC is increasing in northern China and along the southeastern coast, with a significant trend in most of North China, northern Northeast China, and the coastal areas of Southeast China (mainly a part of Guangdong Province). The annual occurrence of warm days w.r.t. MAC tends to decrease in central China (mainly the provinces of Henan, Jiangxi and Hunan), but without a significant trend. This spatial distribution is similar to that of warm days w.r.t. CAC (e.g. Qian and Lin, 2004). The winter occurrence of warm days w.r.t. MAC tends to increase in northern China, but with few sites showing a significant trend (Fig. 5a2), and decrease in general in the south, with sites showing a significant trend being scattered in the provinces of Henan, Anhui, Jiangxi, Hunan and Guangxi. The summer occurrence of warm days w.r.t. MAC is increasing at most sites,

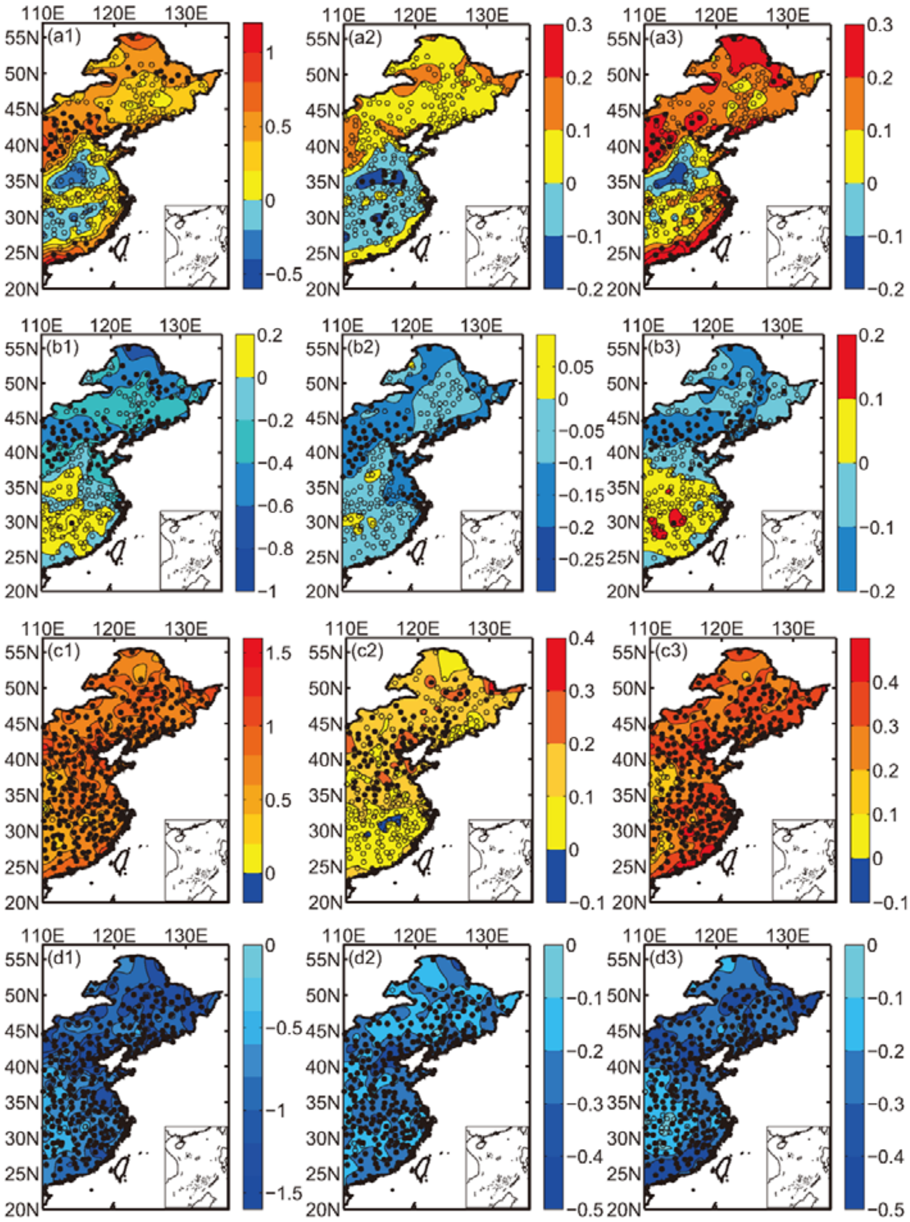

Fig. 5. Geographic distribution of linear trends in temperature extremes w.r.t. MAC for 1961–2007 in eastern China. Panels (a), (b), (c) and (d) represent warm days, cold days, warm nights, and cold nights, respectively. The left, middle and right columns represent the annual, winter and summer cases, respectively. Solid dots indicate a significant trend (α <0.05) and circles indicate an insignificant trend. Units: d $(yr)^{-1}$.

except in parts of central China (mainly in Henan Province) (Fig. 5a3). A significant increasing trend mainly in North China and Guangdong Province is evident. This spatial distribution is also similar to that of hot days in summer w.r.t. CAC (e.g. Ding et al., 2009).

The distributions of trends in the annual and summer occurrence of cold days w.r.t. MAC are similar, decreasing in the north whereas increasing generally in the south (Figs. 5b1 and 5b3). Significant decreasing trends occur mainly in North China and southern Northeast China. The distribution of trends in the winter occurrence of cold days w.r.t. MAC is in general decreasing consistently over all eastern China, with significant decreasing trends occurring in Shandong and Jiangsu, in addition to North China and

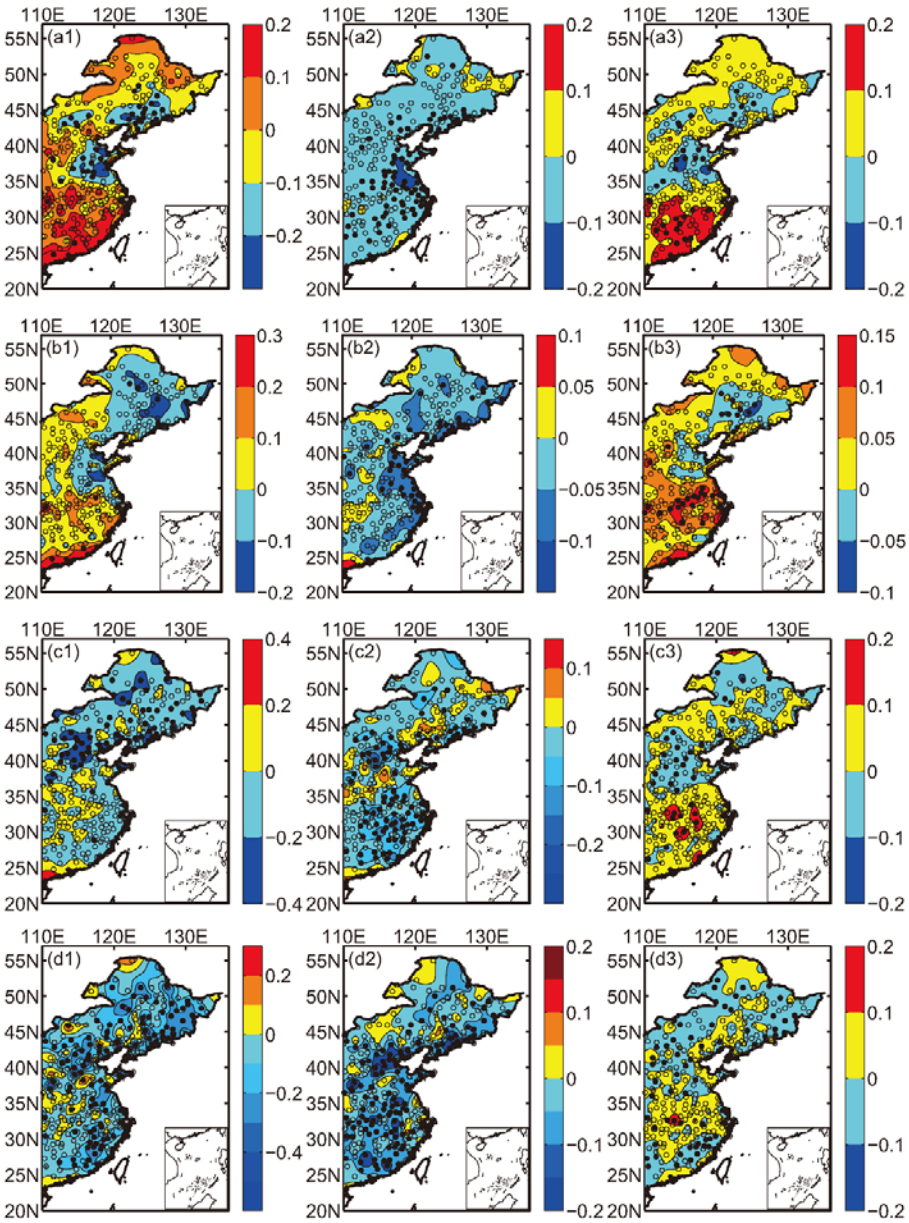

Fig. 6. Same as Fig. 5, but for linear trends in temperature extremes associated exclusively with WIF.

southern Northeast China (Fig. 5b2).

The annual, winter and summer occurrence of warm nights w.r.t. MAC (Figs. 5c1, 5c2 and 5c3) are in general increasing consistently all over eastern China, except for insignificant trends at some stations in the south for winter (Fig. 5c2). It is clear in Figs. 5d1–5d3 that trends in the occurrence of cold nights w.r.t. MAC are more spatially and temporally consistent than those in the occurrence of warm nights w.r.t. MAC. Significant decreasing trends prevail in most of the region studied. In general, the geographic distributions of annual occurrence of warm nights and cold nights w.r.t. MAC are similar to previous studies w.r.t CAC (e.g. Qian and Lin, 2004), thus providing a basis for subsequent analyses to identify the effects of changes in WIF and LV on temperature extremes.

3.3 *Geographic distribution of trends in temperature extremes associated with WIF*

Figures 6a1 and 6a3 show that the distributions of linear trends in the annual and summer occurrence of warm days associated exclusively with WIF are quite similar, decreasing in parts of northern China (mainly Liaoning, mid-Inner Mongolia, Shandong, and Henan Provinces) and increasing in the south. The decreasing trends in the abovementioned areas of northern China are significant, especially for the annual occurrence of warm days associated with WIF. The increasing trends in the south are clearer for the summer occurrence of warm days associated with WIF than the annual case. The winter occurrence of warm days associated with WIF (Fig. 6a2) decreases consistently over most of the region, with significant trends around Bohai Bay and in many places in the south.

In Figs. 6b1–6b3, the distributions of trends in the occurrence of cold days associated with WIF are generally similar to those of the occurrence of warm days. A notable difference arises in that there are few sites with a significant trend in the annual occurrence of cold days (Fig. 6b1); however there are more stations with a significant increasing trend between 30°–35°N for the summer occurrence of cold days (Fig. 6b3) than for warm days.

The distributions of trends in the annual and winter occurrence of warm nights associated with WIF are both coherent over the whole country (Figs. 6c1 and 6c2), decreasing almost everywhere. A notable difference is that significant decreasing trends occur mainly in the north for the annual occurrence of warm nights, but mainly in the south for the winter occurrence of warm nights. In contrast, the summer occurrence of warm nights associated with WIF (Fig. 6c3) exhibits a dipole pattern, with increasing trends in the south and decreasing trends in most of the north. Stations with a significant decreasing trend are located mainly in North China.

Figures 6d1–6d3 show that the distributions of trends in the annual, winter and summer occurrence of cold nights associated with WIF are similar to those of warm nights. It is notable that there are many more stations with a significant decreasing trend in the south for the annual occurrence of cold nights than for warm nights.

In short, the winter occurrence of warm days, cold days, warm nights and cold nights associated with WIF is in general decreasing coherently all over eastern China, whereas those indices in summer generally exhibit a dipole pattern, increasing in the south but decreasing in the north. It is notable that in North China and southern Northeast China, the occurrence of warm days w.r.t. MAC tends to increase, even where the occurrence of warm days associated with WIF is significantly decreasing, e.g. Liaoning Province. This suggests that the increasing frequency of unusually warm days in this region arises mainly from a rise in the mean temperature level, which surpasses the effect of weakening weather fluctuations. An analysis for Liaoning as an example shows that the amplitude of the weather-intraseasonal fluctuations in the daily maximum temperature series has significantly weakened by -0.043°C $(10\ \mathrm{yr})^{-1}$ (corresponding to a 0.2°C weakening in amplitude throughout 1961–2007), compared with a prominent warming rate of 0.3°C $(10\ \mathrm{yr})^{-1}$ (corresponding to a 1.4°C warming throughout 1961–2007) estimated from daily maximum temperature series. In the next subsection, we will show that the Liaoning case represents the situation for a large part of northern China.

3.4 *Geographic distribution of trends in the amplitude of WIF*

It is shown from Fig. 7a1 that in general, the annual mean amplitude of WIF of maximum temperature is decreasing in northern China, at a significant level mainly in the southern part of northeastern China and eastern part of central China by 5%–10%, while it is increasing in southern China, especially in the coastal areas of southeastern China, by 5%–10%. The winter mean amplitude is decreasing, at a significant level mainly in eastern coastal areas of China by 10%–20% (Fig. 7a2). The summer mean amplitude tends to increase by less than 10% in the southern part of northeastern China and eastern part of central China, but significantly by 10%–20%, and even 20%–30%, at some stations in southern China (Fig. 7a3). The annual and winter mean amplitudes of WIF of the minimum temperature are both decreasing throughout the whole region, and more prominently than those of the maximum temperature. The winter amplitude at many stations in southern China decreases by 10%–20% or more. The summer mean amplitude of WIF of the minimum temperature decreases in northern China, while it increases in southern China in general, with a notable increase of 10%–20% around the Yangtze River.

However, except for southern China for the maximum temperature (Figs. 7c1–7c3), the annual, winter and summer mean upper envelopes of the combination of WIF and LV for both maximum and minimum temperatures are all increasing (Figs. 7c1–7c3 and 7d1–7d3), at a significant level mainly in North China (40°–45°N, 110°–120°E), and more prominently for the minimum temperature (Figs. 7d1–7d3) than for the maximum (Figs. 7c1–7c3). Note that the increasing trends in northern China are more prominent than in southern China (Figs. 7d1–7d3), even though trends for WIF in summer are decreasing in northern China and increasing in southern China (Fig. 7b3). This is because warming in China is more prominent in the north compared to the south (e.g. Qian et al.,

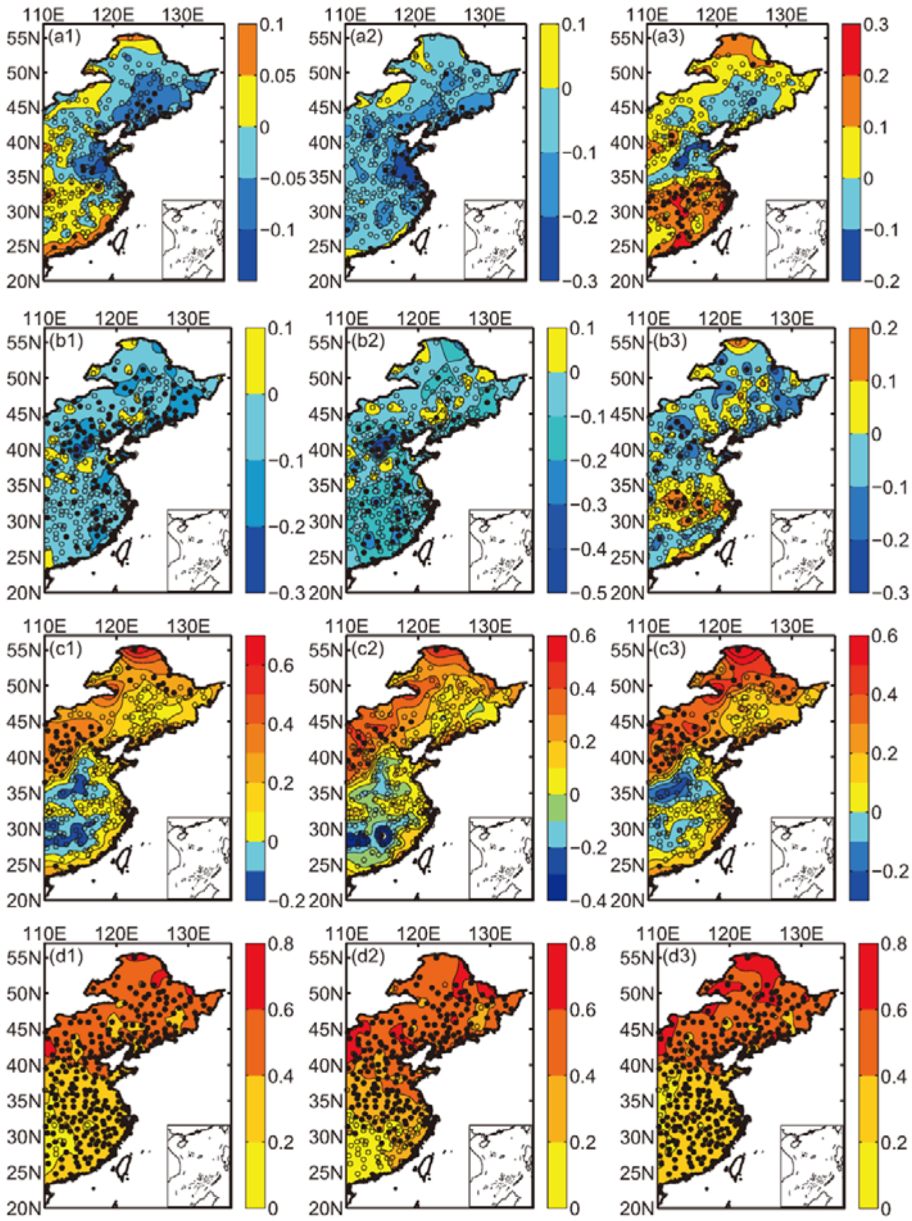

Fig. 7. Geographic distribution of the index "R" of change in the amplitude of WIF [(a) and (b)], and the geographic distribution of linear trends in the upper envelope of the combination of WIF and LV [(c) and (d)]. The first and third rows represent maximum temperatures, and the second and fourth rows minimum temperatures. The left, middle and right columns represent the annual, winter and summer cases, respectively. Solid dots indicate a significant trend (α <0.05) and circles indicate an insignificant trend. Units for panels (c) and (d) are $^{\circ}$C (10 yr)$^{-1}$.

2010). It is also notable that for the maximum temperature in southern China in summer, where the amplitude of WIF is increasing, the upper envelope of the combination of WIF and LV tends to be decreasing (Figs. 7a3 and 7c3). This is because many stations in this part of southern China show a cooling trend, especially for August (Li and Yan, 2009), thus offsetting the enhancement of the amplitude of WIF. In general, the geographic patterns of trends in the amplitude of WIF and in the upper envelope of the combination of WIF and LV are consistent with the observed trends in the warm extremes associated with WIF and w.r.t. MAC. This further suggests that the effect of changes in the mean temperature on trends in warm extremes in eastern China during recent decades surpasses that of the effect of changes in the amplitude of WIF.

4. Summary and discussion

In this study, we have investigated linear trends in four indices of relative temperature extremes (the occurrence of warm days, cold days, warm nights and cold nights) associated exclusively with WIF and with the combination of WIF and longer-term variations w.r.t. MAC, in order to identify the roles of changes of the different timescale climate variations in trends of temperature extremes and to provide some insight into how previously reported changes in temperature extremes are related to a warming trend or to changes in weather variability. The study was based on homogenized daily maximum and minimum temperature observations for the period 1961–2007 in eastern China. The recently developed adaptive data analysis tool, the Ensemble Empirical Mode Decomposition (EEMD) method, was used to isolate the three major timescale components, i.e. the WIF, MAC and longer-term variations. The main results can be summarized as follows:

(1) In the case study of Beijing, located in North China, the annual occurrence of warm nights and cold nights, and winter occurrence of cold days, warm nights, and cold nights associated with WIF, decreased significantly (α <0.05). In contrast, the annual occurrence of warm days and warm nights increased significantly, while the annual occurrence of cold days and cold nights decreased significantly during the period studied. The winter occurrence of warm nights increased significantly, while the cold days and cold nights decreased significantly. The Beijing case was representative of the situation for a large part of northern China. Furthermore, it has shown the advantage of using EEMD in analyzing climate extremes associated with different components in the daily series.

(2) The winter occurrence of warm days, cold days, warm nights and cold nights associated with WIF in general decreased coherently over all of eastern China, whereas the summer extremes associated with WIF exhibited in general a dipole pattern of changes, increasing to the south of 35°N and decreasing in the north. In contrast, linear trends in the annual, winter, and summer occurrence of warm nights and cold nights were in general coherent over all of eastern China, with warm nights having increased significantly throughout most of the region, except for an area to the south of 35°N for winter, and cold nights having decreased significantly throughout most of the region studied. To the north of 40°N, the annual, winter, and summer occurrence of warm days were in general found to have increased, while cold days decreased in general. In North China, these trends were all significant, except for the winter warm days.

(3) Geographic patterns of trends in warm extremes indices and those associated exclusively with WIF were consistent with those in the upper envelope of the combination of WIF and longer-term variations and those in the amplitude of WIF throughout the whole region, respectively. In particular, for maximum temperature, winter WIF tended to weaken almost throughout eastern China, in particular by 10%–20% in coastal areas; summer WIF tended to intensify in southern China by 10%–20%.

(4) In North China and southern Northeast China, although the occurrence of warm days associated with WIF decreased significantly at many stations, the occurrence of warm days tended to increase. This impressive discrepancy suggests the increasing frequency of warm days in this region has arisen mainly from a sufficient rise in the mean temperature level, rather than from changes in weather-intraseasonal fluctuations. The result from the Liaoning case, which represents the situation for a large part of northern China, indicates the amplitude of WIF of maximum temperature significantly weakened by 0.2°C throughout 1961–2007, compared with a prominent warming by 1.4°C.

In short, the winter occurrence of warm days, cold days, warm nights and cold nights associated with WIF in general decreased throughout eastern China. However, the significant decreasing trends mainly occurred in the south part of the country. A possible reason is associated with the weakening Asian winter monsoons during recent decades, which bring cold air masses from the north (Siberia) to the south (China), with a less-southward-propagation of the cold air mass than in earlier decades. Several studies (e.g. Shi et al., 2007; Wang et al., 2009; Qian et al., 2011) have reported a weakening Asian winter monsoon in recent decades. Yan et al. (2002) reported that changes of circulation expressed by daily grid sea level pressure data could explain some regional trends in the indices of temperature extremes w.r.t. CAC in association with weakening winter winds. The present results based on the EEMD decomposition imply that the weakening winter monsoons might mainly influence trends in the temperature extremes associated with WIF. In contrast, recent long-term warming, more prominent in northern China than in the south, is unlikely to have been responsible for the pattern of trends in the winter temperature extremes associated with WIF. Note that in the present analysis, WIF was separated from the long-term component.

The dipole pattern of trends in the summer extreme indices associated with WIF identified in the present study, i.e. in general increasing in the south and decreasing in the north, is consistent with the conclusions from a wavelet analysis of several long-term daily temperature series conducted by Yan et al. (2001) that for summer, weather variability at Shanghai exhibits a slight increasing trend. A possible reason for this dipole pattern is associated with the weakening East Asian summer monsoons, which have tended to extend less northward (i.e. remaining mainly along the mid-lower reaches of the Yangtze River) in recent decades. Many studies have reported that the East Asian summer monsoon, bearing considerable intraseasonal oscillations (e.g. Ju et al., 2005), has weakened over recent decades (e.g. Wang, 2001).

Nevertheless, the present analysis has clearly demonstrated that all the temperature extremes associated with WIF have generally decreased over northern China in recent decades, and the modulation in the annual cycle has slightly affected the trend estimation. This suggests that the increasing frequencies of warm extremes in this region, as reported in many recent studies, should essentially have arisen from an increase of the mean temperature level.

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