Changes in the Amplitude of the Temperature Annual Cycle in China and Their Implication for Climate Change Research

CHENG QIAN
Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

CONGBIN FU
Institute for Climate and Global Change Research, School of Atmospheric Sciences, Nanjing University, Nanjing, and Key Laboratory of Regional Climate-Environment for Temperate East Asia, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ZHAOHUA WU
Department of Earth, Ocean and Atmospheric Science, and Center for Ocean-Atmospheric Prediction Studies, The Florida State University, Tallahassee, Florida

(Manuscript received 31 December 2010, in final form 20 April 2011)

ABSTRACT

Climate change is not only reflected in the changes in annual means of climate variables but also in the changes in their annual cycles (seasonality), especially in the regions outside the tropics. In this study, the ensemble empirical mode decomposition (EEMD) method is applied to investigate the nonlinear trend in the amplitude of the annual cycle (which contributes 96% of the total variance) of China’s daily mean surface air temperature for the period 1961–2007. The results show that the variation and change in the amplitude are significant, with a peak-to-peak annual amplitude variation of 13% (1.8°C) of its mean amplitude and a significant linear decrease in amplitude by 4.6% (0.63°C) for this period. Also identified is a multidecadal change in amplitude from significant decreasing (-2.1.7% decade-1 or -0.23°C decade-1) to significant increasing (2.2% decade-1 or 0.29°C decade-1) occurring around 1993 that overlaps the systematic linear trend. This multidecadal change can be mainly attributed to the change in surface solar radiation, from dimming to brightening, rather than to a warming trend or an enhanced greenhouse effect. The study further proposes that the combined effect of the global dimming–brightening transition and a gradual increase in greenhouse warming has led to a perceived warming trend that is much larger in winter than in summer and to a perceived accelerated warming in the annual mean since the early 1990s in China. It also notes that the deseasonalization method (considering either the conventional repetitive climatological annual cycle or the time-varying annual cycle) can also affect trend estimation.

1. Introduction

The annual cycle is the dominant component for many climate variables outside the tropics and the most prominent climate oscillation. However, to date only a limited number of analyses have been reported concerning its variability and changes, especially in the seasonality of surface air temperature (SAT), under a changing climate in contrast to the numerous studies focusing on long-term global or regional warming (e.g., Solomon et al. 2007). This is partly because the annual cycle of a climate variable, which is traditionally assumed repetitive from year to year and estimated by averaging the values of that variable for the same day/month over a period of several years, is frequently removed in studies concerning climate variability or changes. However, interannual variations and changes in the annual cycle can be seen in many climate time series (e.g., Van Loon et al. 1993; Thompson 1995, 1999; Thomson 1995; Gu and Philander 1995; Bograd et al. 2002; Hu et al. 2003; Pezzulli et al. 2005;
Paluš et al. 2005; Barbosa et al. 2008; Stine et al. 2009; Qian et al. 2011), and an increasing number of studies since the 1990s have shown that climate change is not only reflected in the change in the annual mean of a climate variable but also in the long-term change in the amplitude and phase of its annual cycle (the yearly period component) (e.g., Thomson 1995, 2009; Stine et al. 2009). Changes in the amplitude of the annual cycle of SAT could affect its trend estimation (Thomson 1995), and it has been suggested that these changes be taken into account in temperature reconstructions (Jones et al. 2003).

Many observational analyses have reported that the amplitude of the annual cycle of land SAT decreases (weakening seasonality) (e.g., Thomson 1995; Mann and Park 1996; Mokhov and Eliseev 1997; Yan et al. 2001; Wallace and Osborn 2002; Jones et al. 2003; Eliseev and Mokhov 2003; Zveryaev 2007; Stine et al. 2009) and that the phase advances (toward earlier seasons) (e.g., Mann and Park 1996; Wallace and Osborn 2002; Stine et al. 2009; Thomson 2009) in much of the Northern Hemisphere (NH) during global warming. Changes in the amplitude and phase of the SAT annual cycle have also been detected in climate models under greenhouse forcing, with some consistency in amplitude changes but no consensus in phase changes (Mann and Park 1996; Wallace and Osborn 2002). However, the causes and significance of these observed changes remain poorly understood (Stine et al. 2009). Some studies have suggested that changes in recent decades are highly anomalous compared to changes in earlier decades (Thomson 1995) and cannot be explained exclusively by solar insolation (e.g., Thomson 1995; Eliseev et al. 2006), indicating a human fingerprint (Thomson 1995; Stine et al. 2009), such as increasing atmospheric CO₂ concentration (Thomson 1995). However, this CO₂ fingerprint explanation encountered some difficulties in explaining the little changes observed in the amplitude of the SAT annual cycle since few of these models reproduce the observed decrease in amplitude (Stine et al. 2009). Therefore, the analysis of observational data remains a major means of understanding changes in the SAT annual cycle.

China is one of the ideal countries for studying changes in the annual cycle and whether they are related to a warming tendency or to an increasing atmospheric CO₂ concentration. China is located in the mid-to-high-latitude temperate zone, where the annual cycle dominates the variance of temperature record. The increase in the annual mean temperature in China for the period 1951–2002 is about 1.1°C, which is more rapid than the increase in the global mean temperature or NH mean temperature over the same period (Ren et al. 2005). Furthermore, China is a big country that occupies a large portion of land territory of the world; thus, it has plenty of meteorological observational sites to provide reasonable spatial data coverage.

The present study aims at investigating changes in the amplitude of the SAT annual cycle in China. Since linear trends are determined over the whole temporal domain of a preselected period and are therefore sensitive to this analysis period or small changes at the beginning and/or end of the selected data domain, here we examine the nonlinear and adaptive trend of a climate variable, which is defined as an intrinsically fitted monotonic function or a function in which there can be at most one extremum within a given data span (Wu et al. 2007). We use an adaptive and temporally local data analysis tool—the ensemble empirical mode decomposition (EEMD) method (Wu and Huang 2009; Huang and Wu 2008)—to extract the annual cycle, referred to as an amplitude–frequency modulated annual cycle (MAC) (Wu et al. 2008), and the nonlinear and adaptive trend (Wu et al. 2007). Moreover, compared with previous studies (e.g., Stine et al. 2009), we use better spatial coverage and more recent data over China. The results reveal a significant change in the amplitude of the annual cycle for the period 1961–90, which often was used as a base period for calculating climate anomaly. For the first time, a multidecadal change in the amplitude of the annual cycle is identified, which challenges the previously revealed relationship between a warming tendency or enhanced CO₂ concentration and a change in the amplitude of the annual cycle.
Section 2 describes the data and analysis methods used in this study. Results are discussed in section 3, and a summary with further discussion is presented in the final section.

2. Data and methods

An updated homogenized daily mean surface air temperature dataset, which is based on 549 meteorological station observations (Fig. 1) scattered across China for the period 1960–2008 (Li and Yan 2009), is used in this study. In this dataset, most of the unnatural local biases (e.g., biases due to changes in meteorological station location and observational protocols) in any directly observed temperature record have been adjusted/homogenized (Li and Yan 2009). After 1960, the numbers and regional distributions of meteorological observational stations over China have been quite stable, avoiding the potential impact of changing spatial coverage on the investigation of changes in the annual cycle.

To investigate whether global warming or an enhanced greenhouse effect relates to changes in the amplitude of the SAT annual cycle, annual global mean near-surface temperature anomalies from 1961 to 2007 and atmospheric CO2 concentration at Mauna Loa (19°32′N, 155°35′W), Hawaii (Mauna Loa CO2), from 1965 (because of data deficiency in February, March, and April of 1964) to 2007 are also analyzed in this study. The global mean temperature data are from Hadley Centre Climate Research Unit version 3 datasets (HadCRUT3), a collaborative product of the Met Office Hadley Centre and the Climatic Research Unit at the University of East Anglia (Brohan et al. 2006). The Mauna Loa CO2 data are from the Carbon Dioxide Information Analysis Center (Keeling and Whorf 2010). Air sampled at Mauna Loa showed little short-term variation caused by local sources and sinks of CO2 and provided the first data from which the global increase of atmospheric CO2 was documented (Solomon et al. 2007).

In addition to the data mentioned above, annual mean observed surface solar radiation (SSR) (Wild 2009) data, including direct radiation and diffuse radiation collected and homogenized by the China Meteorological Administration for the period 1961–2007, averaged from 37 meteorological stations (only 37 of 122 stations have consecutive series from 1961 to 2007) (Fig. 1) scattered throughout China, are also used. To verify that the mean surface solar radiation from these 37 stations can generally represent the surface solar radiation of the mean for all of China, the homogenized daily maximum and minimum SAT dataset based on 549 meteorological station observations for the period 1960–2008 (Li and Yan 2009) is also used to obtain the diurnal temperature range (DTR) (i.e., the difference between daily maximum and minimum temperatures), which can serve as a proxy for surface solar radiation (Wild 2009). Since the solar flux is present only during daylight and the nighttime minimum temperature is mainly governed by the thermal radiative exchanges, the surface solar radiation influences are left as a major forcing factor in DTR (Wild 2009).

The EEMD method (Wu and Huang 2009) is used to extract the MAC from the daily SAT of the China mean (over 549 stations averaged) or of each station. The daily SAT series $X(t)$ for any station is separated into

$$X(t) = H(t) + A(t) + L(t),$$

where $H(t)$ is the high-frequency component (with a time scale of several days to months), $A(t)$ is the MAC (with a quasi-annual period), and $L(t)$ is the low-frequency component (representing interannual and longer timescale variation, with a time scale longer than one year). The EEMD is a novel adaptive and temporally local data analysis method based on the empirical mode decomposition (EMD) method (Huang et al. 1998; Huang and Wu 2008), which decomposes any complicated data series into finite quasi-periodic components at different frequencies. The EMD/EEMD method has been demonstrated to be a powerful tool to analyze nonlinear and nonstationary data in many geophysical fields (e.g., Huang and Wu 2008; Wu et al. 2008; Wu and Huang 2009; Qian et al. 2009, 2010, 2011; Ruzmaikin and Feynman 2009; Franzke 2010; Breaker and Ruzmaikin 2011; Franzke and Woollings 2011). The detailed procedures for using the EEMD to extract the MAC of a climate variable can be found in Wu et al. (2008) for analyzing monthly data and in Qian et al. (2010) for analyzing daily data. The capability and the advantage of using the EEMD method in extracting the annual
cycle component, which has strong amplitude–frequency modulation, from a climate variable have been validated through analyzing synthetic data, monthly SST data, and daily SAT records (Wu et al. 2008; Qian et al. 2011). Qian et al. (2010) presented a multitime-scale analysis of SAT data from 60 stations in which a strong variation in the MAC was revealed. The present study extends the work of Qian et al. (2010) and focuses on changes in the amplitude of the MAC from 549 stations in an updated dataset, as well as on the causes of the changes. The amplitude of the MAC for the China mean or for each station is the instantaneous amplitude modulation part of the MAC, which is the envelope of the MAC and is obtained by fitting the maximums of the $\sqrt{(\text{MAC})^2}$ series with a cubic spline. An example of the amplitude of the MAC, as well as the MAC itself, of the daily SAT for the China mean is presented in Fig. 2a, along with the high-frequency component, the low-frequency component, and the overall adaptive trend (Wu et al. 2007) (the last component of the EEMD result). To provide a visual impression, an enlargement of these variables over 5 yr arbitrarily chosen (from 1 January 1998 to 31 December 2002) is also displayed in Fig. 2 with the raw daily SAT. To reduce the minor end effect in EEMD decomposition, which is within one year at each end of the series as far as the MAC component is concerned (Qian et al. 2010), only the period 1961–2007 is presented and analyzed in this study. Following these principles, the EEMD method is applied to the daily series of each station to extract its MAC. The proportion of the MAC explaining the total variance of daily series in each station is thus calculated (Fig. 3). The EEMD method is also used to decompose the annual amplitude series of the China mean MAC (Fig. 4b) to extract the adaptive multidecadal trend (Wu et al. 2007), which is the combination of the last two components of the EEMD result.

To obtain spatial and temporal structures of the amplitude of the MAC in China, empirical orthogonal function (EOF) analysis is applied to the raw (not the anomalous) daily amplitude of the MAC of stations over China. The reason for applying EOF analysis directly to the raw amplitude instead of to the anomalous amplitude is to illustrate the spatial pattern of the amplitude of annual cycle and its variation with time. If EOF analyses were applied to the anomalous amplitude, then the information of the mean amplitude of the annual cycle would be lost. As a consequence, the obtained spatial pattern cannot reflect the amplitude of the annual cycle; in contrast, the corresponding variability [represented by principal components (PCs)] better reflects the relative strength of the amplitude change at different spatial locations but not the spatially (weighted) average of annual cycle amplitude change. The consistency between the results obtained using this approach and the results obtained using the approach described earlier demonstrates that the results discussed in this paper are...
not sensitive to analysis methods. The resulting first EOF mode (EOF1) is displayed in Fig. 4a; the corresponding first principal component (PC1), which is yearly averaged and further divided by the mean value of this yearly averaged series, is displayed in Fig. 4b. This calculation is similar to standardization but with a mean value of 100% instead of zero. The time series displayed in Fig. 4b are all divided by their corresponding mean values to facilitate comparisons for different variables and to provide a visual impression of the percentages of changes. Correspondingly, the EOF1 displayed in Fig. 4a has been multiplied by the mean value of the original annual PC1 series. Therefore, Fig. 4a represents the climatological mean amplitude of the MAC for each station. The MATLAB 4 griddata method is applied for interpolation to obtain all the geographical distribution patterns displayed in this study. When the linear trend of a time series is estimated, the statistical significance is assessed using the Mann–Kendall test (Mann 1945; Kendall 1955), which is a rank-based, nonparametric statistical test for identifying trend.

3. Results

a. Characteristics of the amplitude of the annual cycle in China

For China as a whole, the MAC (seasonal variation) explains 96.1% of the total variance of the daily SAT series and is the dominant component (red line in Fig. 2a). Its mean amplitude is 13.6°C, but was as small as 12.8°C in 1987 and as large as 14.7°C in 1967, with a difference of 1.9°C. This result shows that the interannual and longer time-scale variability of the MAC of SAT can reach 3.8°C, suggesting a large variation in the MAC. The high-frequency component explains 2.6% of the total variance, with larger variability in winter than in summer (Fig. 2c). The low-frequency component (Figs. 2a and 2d) shows an overall warming tendency. This low-frequency component has a minimum of -2.19°C (anomaly) in December 1976 and a maximum of 1.76°C in December 1998, with a difference of 3.7°C (Fig. 2a). The EEMD secular trend shows an approximately linear trend with a gradual warming by 1.02°C from 1961 to 2007.
For an individual station, the proportion of the total variance of the daily SAT series explained by the MAC has distinct regional differences (Fig. 3). In general, the geographic distribution of this proportion is zonal, with the MAC explaining a greater proportion of the total variance in the north than in the south. North to 32°N, the MAC generally explains more than 90% of the variance, with area explaining greater than 95% of the variance in the central Xinjiang autonomous region. Xinjiang is an inland arid region in northwestern China, where the continental climate is distinct. The station with the maximum proportion of the MAC in the total variance is Turpan (42.9°N, 89.2°E; 34.5 m) (95.6%), a city being called the “Land of Fire” because of its intense summer temperature and rare precipitation. South to 24°N, the MAC generally explains 70%–80% of the variance. In southwestern China the MAC explains less than 70%, with a minimum (65.1%) in Zhanyi County (25.6°N, 103.8°E; 1898.7 m), Yunnan Province. Note that all the proportions of the individual stations are smaller than the China mean. This is because the local-scale weather fluctuation is largely smoothed in the latter. Nevertheless, the MAC is the dominant component of the daily SAT in China, even in terms of individual stations.

The EOF analysis shows that the geographic distribution of the climatological mean amplitude of the MAC of the SAT over China (EOF1, which explains 99.9% of the total variance) is generally a zonal pattern, with the amplitude increasing with the latitude (Fig. 4a). The amplitude is larger than 16°C north to 40°N and can be even larger than 24°C at some locations in the northern parts of northeast and northwest China. The amplitude is smaller than 10°C south to 25°N. The smallest annual cycle appeared in the southern part of Yunnan, a southwestern province of China. This zonal pattern is similar to the pattern of variability in the MAC revealed in the work of Qian et al. (2010), which was based on 60 stations. The physical cause underlying this pattern is mainly the winter–summer solar radiation difference increasing with the latitude. However, such a pattern is different from that of Europe, which has a meridional distribution reflecting a decrease in the influence of the Atlantic Ocean and an increase in the influence of the continental European climate (Zveryaev 2007; Barbosa 2009). This difference further suggests that solar radiation is the main determinant for the amplitude of the SAT annual cycle in China.

From an annual mean perspective, the variability of the annual amplitude of the MAC of the China mean daily SAT ($A_{mac}$) is as large as the variability in the annual China mean temperature (CMT) and is much larger than the variability in the global mean temperature (Fig. 4b). Note that the mean values (for the period 1961–2007) for $A_{mac}$, the China mean temperature, and the global mean temperature are 13.6°C, 11.3°C, and 14°C, respectively. These close values suggest that the relative magnitudes for these three variables shown in Fig. 4b in terms of percentage are quite similar to when they are shown in terms of temperature anomaly (figure not shown). The ratio of the $A_{mac}$ and the mean $A_{mac}$ (for the period 1961–2007) ranges from 1.08 (1.07°C in terms of temperature anomaly) in 1967 to 0.95 (−0.74°C) in 1987, with a difference of 13% of the mean $A_{mac}$ (or 1.81°C in terms of temperature). This result suggests that the variation in $A_{mac}$ is quite significant. For the same time span, the China mean temperature ranges from 1.10 (1.15°C in terms of temperature anomaly) in 2007 to 0.92 (−0.82°C) in 1969, with a difference of 18% (1.97°C). For the same period, the global mean temperature ranges from 1.03 (0.45°C) in 1998 to 0.97 (−0.40°C) in 1964, with a difference of 6% (0.85°C). Note that PC1 of the previous EOF analysis (shown in Fig. 4b) has values very close to those of $A_{mac}$, validating that the latter is a good indicator of the China mean. Therefore, only $A_{mac}$ is further analyzed in this study.

### b. Trend analysis and attribution

We first follow a traditional trend analysis to study linear trends. The linear trend of $A_{mac}$ for the period 1961–2007 shows a descending trend of $-4.6\%$ (47 yr)$^{-1}$ or $-0.63°C$ (47 yr)$^{-1}$, significant at $P < 0.01$ under the Mann–Kendall test. Meanwhile, the China mean temperature has warmed significantly ($P < 0.01$) by 11.6% (47 yr)$^{-1}$ or 1.3°C (47 yr)$^{-1}$, and the global mean temperature has also warmed significantly ($P < 0.01$) by 4.7% (47 yr)$^{-1}$ or 0.66°C (47 yr)$^{-1}$. From 1965 to 2007, the atmospheric CO$_2$ concentration has increased almost linearly. Thus, from the linear trend perspective, one might surmise, although this is not necessarily the real case, that the amplitude of the annual cycle of the land SAT decreases in the course of a warming or an enhanced greenhouse effect, as discussed in section 1. However, a clear turning point occurring around 1993, from decreasing to increasing in the $A_{mac}$, is identified by the adaptive multidecadal trend (nonlinear trend) extracted using the EEMD method. This turning point is estimated from the time when an internal minimum is reached using the EEMD method. This turning point is estimated from the time when an internal minimum

---

1 The conventional Mann–Kendall test assumes independent (nonautocorrelated) samples in a time series in which a spurious trend of the time series is identified. Here we have made a null hypothesis that the amplitude of MAC for any individual year is random around its mean amplitude if there is no physical process that controls its change. The test made here is to nullify this hypothesis only.
(first-order derivative equaling zero) appears (first-order derivative equaling zero) in this nonlinear trend (figure not shown). Before this transition point (from 1961 to 1993), the relationship seems to exist: the linear trend in $A_{\text{mac}}$ has decreased significantly ($P < 0.01$) by 5.6% (33 yr)$^{-1}$ or $-0.76^\circ C$ (33 yr)$^{-1}$, and the China mean temperature (global mean temperature) has warmed by 3.1% (33 yr)$^{-1}$ or 0.35$^\circ C$ (33 yr)$^{-1}$ [2.4% (33 yr)$^{-1}$ or 0.33$^\circ C$ (33 yr)$^{-1}$], significantly at $P < 0.05$ ($P < 0.01$). Yet, linear trends for 1993–2007 in $A_{\text{mac}}$, the China mean temperature, and the global mean temperature have all increased significantly ($P < 0.05$) by 3.25% (15 yr)$^{-1}$ or 0.44$^\circ C$ (15 yr)$^{-1}$, 7.7% (15 yr)$^{-1}$ or 0.86$^\circ C$ (15 yr)$^{-1}$, and 2.4% (15 yr)$^{-1}$ or 0.33$^\circ C$ (15 yr)$^{-1}$, respectively. Meanwhile, the atmospheric CO$_2$ concentration has increased throughout the period. The same sign of these trends (all increasing) in $A_{\text{mac}}$, the China mean temperature, the global mean temperature, and in atmospheric CO$_2$ concentration after 1993 therefore challenges the previously referenced contention that with warming (change in the annual mean) or increasing atmospheric CO$_2$ concentration, the amplitude of the annual cycle decreases (change in the amplitude of annual cycle). At the very least, warming or increasing atmospheric CO$_2$ concentration is not the dominant factor driving the change in the amplitude of the annual cycle. Otherwise, there would have been no transition from a decreasing trend to an increasing trend but a more quickly decreasing trend in the $A_{\text{mac}}$ in the early 1990s, which was the hottest decade during the twentieth century (Solomon et al. 2007).

Climate scientists are aware that the earth’s climate is strongly dependent on the solar radiation input into the lower atmosphere. Solar radiation reaching the ground is a key determinant of surface temperature (Wild et al. 2007; Wild 2009). It should be noted that the influence of solar radiation on the change in the amplitude of the temperature annual cycle has been dismissed in previous studies (e.g., Thomson 1995). In the studies of Thomson (1995) and Mann and Park (1996), the annual cycle is expressed as $A(t) \cos[2\pi t + \theta(t)]$, which is “motivated by the fact that surface temperature seasonality is determined, within a phase lag, by the yearly cycle of isolation at the top of the atmosphere in most locations” (Mann and Park 1996, p. 1111). There is an almost negligible linear trend, “too small to cause the observed changes in temperature” (Thomson 1995, p. 63), on a decadal time scale in the total solar irradiance (TSI) time series (Fröhlich and Lean 1998), which is a measurement of solar radiation on top of the atmosphere. However, solar radiation reaching the land surface (also called surface solar radiation) is not or no longer the same as at the top of the atmosphere because of the nonlinear response of the climate system. Indeed, a widespread decadal change in surface solar radiation, from decreasing to increasing, approximately occurred in the late 1980s and has been observed worldwide based on data since the 1950s (e.g., Wild et al. 2005; Wild 2009), a phenomenon known as “from dimming to brightening” (Wild et al. 2005, p. 847). The surface solar radiation change associated with such a dimming is at least an order of magnitude larger than the change in the estimated energy input to the climate system from the solar output on top of the atmosphere (Wild 2009).

In this study, the China averaged annual mean surface solar radiation is examined to see if its changes are relevant to those in the $A_{\text{mac}}$. The surface solar radiation shows an overall decreasing linear trend (Fig. 4c), the magnitude of which is $-0.38$ W m$^{-2}$ yr$^{-1}$ ($P < 0.01$) during the period 1961–2007 and $-0.74$ W m$^{-2}$ yr$^{-1}$ ($P < 0.01$) during the period 1961–90, which is consistent with the results of Che et al. (2005), who found a decreasing trend of $-0.45$ W m$^{-2}$ yr$^{-1}$ during the period 1961–2000 and $-0.78$ W m$^{-2}$ yr$^{-1}$ during the period 1961–90. The overall decreasing trend of surface solar radiation is believed to be mainly due to changes in the transparency of the atmosphere (Wild 2009). In particular, the increasing emissions of anthropogenic aerosols resulted in less solar radiation reaching the ground (Che et al. 2005; Qian et al. 2006; Streets et al. 2006; Qian et al. 2007; Shi et al. 2008; Wild 2009) despite concurrent increasing trends in cloud-free skies over China (Qian et al. 2006). It should be noted that surface solar radiation has recovered from previous decreasing since the early 1990s (Fig. 4c), which is similar to the well-known global dimming–brightening transition (Wild et al. 2005). Wild (2009) suggested that the dimming–brightening transition in China may be related to changes in fuel utilization, and thus in aerosol composition and in associated single-scattering albedo (Qian et al. 2007). The reduction and recovery in surface solar radiation can also be identified from the surface solar radiation proxy series, that is, the DTR series (Fig. 4c), which has a correlation coefficient of 0.88 with the surface solar radiation series. Thus, the China mean surface solar radiation series used in this study can generally represent China.

The changes and transitions in the $A_{\text{mac}}$ and in the surface solar radiation before and after the early 1990s are consistent. Moreover, the correlation coefficient between the $A_{\text{mac}}$ and surface solar radiation is 0.45 for the period 1961–2007, with a significant level at $P < 0.01$. All these results imply that the decadal change in solar radiation reaching the land surface, which serves as the dominant source of fluctuation energy for the SAT MAC, may be mainly responsible for the multidecadal change of the $A_{\text{mac}}$ in China in the last 50 yr.
c. Implications of change in the amplitude of the annual cycle

It is well-known that the warming trend is much larger in winter than it is in summer for China as a whole (e.g., Ren et al. 2005). For example, the linear trend for the period 1961–2007 is 0.42°C decade^{-1} [1.97°C (47 yr)^{-1}] for winter and 0.16°C decade^{-1} [0.75°C (47 yr)^{-1}] for summer (Fig. 5a). Previously, this seasonal discrepancy was mainly attributed to an enhanced greenhouse effect. However, for the years 1961–93 the linear trend in summer is −0.03°C decade^{-1} (cooling) and in winter, 0.43°C decade^{-1}. For the period 1993–2007, the linear trend is 0.53°C decade^{-1} for the summer and only
0.04°C decade\(^{-1}\) for the winter (Fig. 5b). In other words, there is a cooling-to-warming transition in the summer temperature occurring around 1993, whereas warming in winter has slowed dramatically since then. Note that the warming trend in summer for the period 1993–2007 is even larger than the trend in winter. These transitions in summer and winter temperatures also result in a corresponding transition in the summer-minus-winter series, from decreasing to increasing around 1993 (Fig. 5c). Such transitions (Figs. 5b and 5c) obviously cannot be explained exclusively by the enhanced greenhouse effect, which did not end after 1993. Here, we propose that these transitions are mainly attributable to the combined effect of a global dimming–brightening transition and a gradual increase in greenhouse warming. To illustrate this point, the mean MACs for three consecutive years around the maximum (1967) of \(A_{\text{mac}}\) (Fig. 4b) and the minimum (1987) are displayed in Fig. 5d to provide a visual impression. Note that if the mean MAC for the first 5 yr and that for the last 5 yr of the period 1961–93 are compared, then the conclusion is the same although their difference is smaller than the one displayed. Since the upper and lower envelopes of the MAC are symmetric with respect to zero, a weak (strong) MAC implies a relatively warmer (cooler) winter and a relatively cooler (warmer) summer, as Fig. 5d illustrates. This effect rides on the systematic secular warming trend (Fig. 2a), which has a fingerprint of an enhanced greenhouse effect. During the period 1961–93, the combined effect of a weakening MAC (caused by the dimming) and the secular warming trend made the warming in winter more prominent (due to these two effects reinforcing each other) and led to a slight cooling in summer (due to the competition of these two effects). In contrast, for the period 1993–2007, the brightening-led strengthening MAC enhanced the secular warming trend in summer and offset it in winter, making the summer warming trend larger than the winter warming trend. Likewise, for the period 1961–2007, the overall dimming-led decreasing trend in the amplitude of the MAC explains why the warming trend displayed in Fig. 5a is much larger in winter than in summer.

Other than explaining the seasonal warming discrepancy, the nonlinear trend in the amplitude of the MAC (decreasing—increasing transition) can also explain the different warming rates in the annual mean. The linear trend for CMT is 0.11°C decade\(^{-1}\) for the period 1961–93 and 0.58°C decade\(^{-1}\) for the period 1993–2007 (Fig. 5e). In other words, the linear warming rate after 1993 is almost 5 times the rate before 1993. However, if the annual mean is calculated after the MAC component is excluded from the raw daily SAT (deseasonalization), then the differences in the linear trends for the period 1961–93 (0.19°C decade\(^{-1}\)) and for the period 1993–2007 (0.21°C decade\(^{-1}\)) are minor (Fig. 5f). These deseasonalized linear trends are mainly due to the secular warming trend (Fig. 2a). Therefore, the dimming-led weakening MAC partly offsets the secular warming trend for the period 1961–93, while the brightening-led strengthening MAC enhances the secular warming for the period 1993–2007, causing an overall accelerated warming after 1993. This impact of the dimming–brightening transition on the warming trend in the annual mean temperature is consistent with the findings of Wild et al. (2007) but viewed from a different angle. The present result is also to some extent consistent with the results of previous studies analyzing climate models, which found that both the greenhouse gas and other forcings, such as anthropogenic aerosols, contributed to the SAT change over China during the second half of the twentieth century (e.g., Zhou and Yu 2006).

In climate research, a trend in a climate variable is often estimated from anomaly series that have been deseasonalized by subtracting the repetitive climatological annual cycle [traditional anomaly (TA)], usually the one averaged over the period 1961–90. When this anomaly series is yearly averaged, it is the same as the departure from annual mean of a variable (e.g., Figs. 5e and 5f). Therefore, changes in the TA of the SAT can also be explained by a nonlinear trend in the amplitude of the MAC (Fig. 5f). Moreover, the difference in trend estimation of different deseasonalized anomalies (deseasonalizing either a stationary annual cycle or a time-varying annual cycle) is not small (e.g., for the period of 1961–90) and therefore is not negligible.

4. Summary and discussions

In this study, we have investigated the nonlinear trend in the amplitude of the SAT annual cycle (MAC), extracted adaptively and temporally locally by the EEMD method, in China for the period 1961–2007 as well as its implications for climate research. The main results are summarized below.

1) The MAC is the dominant component of the daily SAT in China. It explains 96% of the total variance for China as a whole and 65%–95% for an individual station. The geographic distributions of this proportion of the MAC explaining total variance at each station as well as the mean amplitude of the MAC itself are both dominantly zonal.

2) The variation and change in the amplitude of the MAC are notable: the annual amplitude has a peak-to-peak variation by 13% of its mean amplitude or 1.8°C for China as a whole and a significant \((P < 0.01)\) decreasing by \(-4.6\%\) or \(-0.63°C\) for the period
1961–2007. These results show that the change in the annual cycle is not small, and therefore we need to be more cautious when defining climate anomaly in climate research.

3) A multidecadal change from decreasing to increasing around 1993 in the amplitude of the MAC is identified from the nonlinear trend by the EEMD method. The decreasing linear trend for the period 1961–93 is 5.6% (33 yr$^{-1}$) [−0.76°C (33 yr$^{-1}$)], significant at $P < 0.01$, and the increasing linear trend for the period 1993–2007 is 3.25% (15 yr$^{-1}$) [0.44°C (15 yr$^{-1}$)], significant at $P < 0.05$. Change in the amplitude of the MAC is attributed mainly to change in surface solar radiation, which experienced dimming to brightening, rather than to an enhanced greenhouse effect. We argue that the combining effect of the global dimming–brightening transition and a gradual increase in greenhouse warming has led to the warming trend in winter being much larger than in summer, and to the accelerated warming in the annual mean after the early 1990s in China. We also point out that the difference in trend estimations from different deseasonalization methods (i.e., either deseasonalizing a stationary annual cycle, as most of the previous studies applied, or deseasonalizing a time-varying annual cycle) is notable.

Although we strongly suggest that the change in the amplitude of the SAT annual cycle in China can be attributed largely to change in the surface solar radiation (dimming and brightening effect), it should be cautioned that we cannot rule out the role the decadal-scale ocean variability played in the modulated annual cycle. Further studies are needed to determine the role of the ocean in modulating the annual cycle.

The notable difference in trend estimations from different deseasonalization methods and the implications of nonlinear trend in the amplitude of the annual cycle suggested in the present study support the work of Thomson (1995, p. 66), who suggested that “anomaly series used in climate research that have been deseasonalized by subtracting monthly averages need to be recomputed” and that it is “possible that suitable information can be extracted from the modulations on the annual cycle.” However, the nonlinear trend revealed in the present study suggests that changes in the annual cycle are somehow independent of the changes in the annual mean. This is consistent with a study by Qian et al. (2011), who analyzed changes in the spring phase of the SAT annual cycle in northern China and found an advancing trend in the east and a delaying trend in the west, different from the zonal pattern in the long-term warming in the annual mean. In addition, changes related to anthropogenic aerosols in surface solar radiation are proposed to be responsible for the changes in the amplitude of the annual cycle (which is often regarded as climate normal), rather than the increasing CO$_2$ concentration as Thomson (1995) proposed. Nevertheless, this study agrees with Thomson (2009) and Stine et al. (2009) that “the observational evidence for human influence on the climate system is overwhelming” (Thomson 2009, p. 392).

Acknowledgments. This research was jointly sponsored by the National Basic Research Program of China (Grant 2011CB952000), the “Strategic Priority Research Program” of the Chinese Academy of Sciences (Grant XDA05090103), and the National Natural Science Foundation of China (Grants 41005309 and 40810059003); Wu was sponsored by the NSF of the United States (Grant ATM-0917743). We thank Dr. Shiguang Qin for helping process surface solar radiation data and Ms. Kathy Fearon of the Florida State University for helping polish the manuscript. We are grateful to editor Nathan Gillett and three anonymous reviewers for their many constructive suggestions.

REFERENCES