Trends in day-to-day variability of surface air temperature in China during 1961–2012

LI Shang-Fengabc, JIANG Da-Banga, LIAN Yib and YAO Yao-Xiand

abcInstitute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China; dLaboratory of Research for Middle-High Latitude Circulation Systems and East Asian Monsoon, Institute of Meteorological Sciences of Jilin Province, Changchun, China; cCollege of Earth Science, University of Chinese Academy of Sciences, Beijing, China; dDepartment of Science and Technology and Forecast of Jilin Meteorological Bureau, Changchun, China

ABSTRACT
Using daily mean, maximum, and minimum surface air temperature (abbreviated as $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$, respectively) data from CN05.2 and the Met Office Hadley Centre observation data-sets for 1961–2012, the trends in day-to-day variability of $T_{\text{mean}}$, $T_{\text{max}}$, and $T_{\text{min}}$ (abbreviated as DVTT$T_{\text{mean}}$, DVTT$T_{\text{max}}$, and DVTT$T_{\text{min}}$, respectively) are examined. It is revealed that the annual trends of DVTT$T_{\text{mean}}$, DVTT$T_{\text{max}}$, and DVTT$T_{\text{min}}$ are all negative in Northeast China (NEC), and more obvious in North China than in South China. Seasonal trends of DVTT$T_{\text{mean}}$ are also negative in NEC, except in summer. For DVTT$T_{\text{max}}$, trends are generally more obvious than DVTT$T_{\text{min}}$ in all seasons in NEC; moreover, trends in spring are obvious in both the north and the south, but trends in summer and winter are more obvious in the southern region than in the northern part. As far as DVTT$T_{\text{min}}$ is concerned, except in autumn, seasonal trends are more obvious in the north than in other regions of the country.

1. Introduction
A large number of studies have examined surface air temperature (SAT) variability and change at global and regional scales since the mid-nineteenth century (Hansen et al. 2010; Lawrimore et al. 2011). There is agreement in the literature that warming has been an obvious phenomenon over recent decades. Specifically, it has been confirmed that, over 1880–2012, the globally averaged SAT, as calculated by a linear trend, shows a warming of 0.85 °C (0.65–1.06 °C) (IPCC 2014). Meanwhile, surface warming has been spatially and temporally non-uniform, and has accelerated at all latitudes from 1955 onwards (Ji et al. 2014). Besides, in recent decades the greatest warming has been found between the subtropical and the original high-latitude band in the northern hemisphere. Using sub-daily data, Ren et al. (2015) indicated that Northeast China (NEC) witnessed the largest nighttime warming during 1973–1992, but an evening and nighttime cooling during 1992–2011.

The linkage between the warming and extreme events has also been investigated in recent decades. Katz and Brown (1992) found global warming has strong implications for the occurrence of extreme weather and climate-related events—a view confirmed latterly by other researchers (Chou et al. 2012; Dittus et al. 2015; Trenberth 1999, 2011). IPCC (2013) documented that, since approximately 1950, it is very likely that there has been an overall decrease in the number of cold days and nights, and an overall increase in the number of warm days and nights at the global scale; moreover, heat wave frequency has increased in large parts of Europe, Asia, and Australia. Since extreme climate events...
have overwhelming impacts on society and environment, often causing tremendous losses of human life and property (Christoph and Gerd 2004; Levinson and Waple 2004; Tao and Wei 2008), increasing attention has been paid to them in recent decades (Easterling et al. 2000; Vincent et al. 2011; Wu, Zhou, and Xu 2015; Zhou et al. 2014, 2016). Over many land regions, where data are sufficient, increasing heavy precipitation has been observed (Alexander et al. 2006; Groisman et al. 2005; Wang and Zhou 2005). Some researchers have attributed these phenomena to increasing temperature, pointing out that global warming tends to accelerate the hydrological cycle (Allen and Ingram 2002; Ohmura and Wild 2002). Further support in this regard was provided by Allan and Soden (2008), who argued that extreme precipitation events might become more common in a warmer climate. Additionally, Chou et al. (2012) demonstrated that increases in water vapor content lead to increases in both the frequency and intensity of heavy precipitation in the tropics.

Along with the rest of the world, China has also experienced significant temperature changes during recent decades. Ding and Dai (1994) reported that the peak temperature in China occurred in the 1940s rather than after the 1980s, and since the 1950s surface warming (cooling) has taken place in Northeast and North (Southwest) China. Based on station observations, Ding et al. (2007) pointed out that the country-averaged annual SAT had increased by 1.1 °C over the past 50 years and 0.5–0.8 °C over the past 100 years in China—slightly higher than the global SAT increase for the same periods. Based on multi-source instrumental and documentary data, Wang, Zhu, and Cai (2004) reported that the linear trend of SAT during 1880–2002 was 0.58 °C/100 yr in China, which was less than the global mean of 0.6 °C/100 yr; Qian and Qin (2006) found that the trend of SAT was approximately 0.2–0.3 °C/10 yr in northern China and less than 0.1 °C/10 yr in southern China; Huang, Qian, and Zhu (2010) indicated that both the frequency and intensity of seasonal warm extreme events had a significant increasing trend, especially over northeastern China and along the Yangtze River valley in spring and winter; and Zhao et al. (2014) indicated that the regional-mean SAT over Eastern China showed a warming trend of 1.5 °C/100 yr during 1909–2010.

Taken together, most previous studies have focused on climate variability and changes to climatological means or interannual variability over China. No attention, however, has been given to day-to-day temperature variability and its trend. Given this issue is an important indicator of climate change, we address the following question in the present paper: Are there any robust trends of day-to-day variability in daily mean, maximum, and minimum temperatures that can be identified directly from observations on annual and seasonal scales?

2. Data and method

2.1. Data

The present study uses two data-sets: the Met Office Hadley Centre observational data-set (Caesar, Alexander, and Vose 2006) and the gridded data-set of CN05.2 (Wu and Gao 2013; Xu et al. 2009). Daily maximum SAT ($T_{\text{max}}$), mean SAT ($T_{\text{mean}}$), and minimum SAT ($T_{\text{min}}$) are available from the CN05.2 data-set. Owing to no available $T_{\text{mean}}$ in the Hadley data-set, we obtain $T_{\text{mean}}$ by calculating the arithmetic average of $T_{\text{max}}$ and $T_{\text{min}}$ (i.e. $T_{\text{mean}} = (T_{\text{max}} + T_{\text{min}})/2$). The Hadley data span from 1870 to the present day and have a horizontal resolution of 3.75° × 2.5°, whereas the CN05.2 data are available from 1961 to 2012 and have a horizontal resolution of 0.5° × 0.5° over China. In the following sections, the winter (December–February) of one year refers to December of that year to February of the next year; and spring, summer, and autumn refer to March–April–May, June–July–August, and September–October–November, respectively.

2.2. Method

Taking spring $T_{\text{mean}}$ as an example, the trend in day-to-day variability of spring $T_{\text{mean}}$ for the whole period is calculated according to the following sequential steps:

Step (1): Create a new series of $T_{\text{mean}}(i,j)$ ($i = 1, 2, 3, ..., 92$, indicating 92 days in spring for each year, and $j = 1, 2, 3, ..., 52$, meaning 52 years for 1961–2012), and then the 11-day running average is subtracted from the original data of $T_{\text{mean}}(i,j)$ in each year. The new residual data hereafter are referred to as $dT(i,j)$:

$$dT(i,j) = T_{\text{mean}}(i,j) - \frac{1}{11} \sum_{i=1}^{11} T_{\text{mean}}(i,j).$$  \hspace{1cm} (1)

Step (2): Calculate the standard deviation of $s(j)$:

$$s(j) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (dT(i,j) - \bar{d}T(i,j))^2},$$  \hspace{1cm} (2)

where the superscript $n$ in the Equation (2) denotes 92 days in spring for each year.

Step (3): Use a least-squares approach for fitting the linear trend of $s(j)$, and then the trend value is what we want (i.e. the trend in spring day-to-day variability for 1961–2012).

The two-tailed Student’s $t$-test is used to evaluate the statistical significance of time series. In this paper, a trend
is considered to be statistically significant if it is significant at the 95% confidence level.

3. Results

3.1. Characteristics of $DVTT_{\text{mean}}$

$DVTT_{\text{mean}}$ at each grid point over the whole period of 1961–2012 is assessed in Figure 1. The Hadley data are also employed as a comparison with the CN05.2 data. The regions where the results are consistent between the two data-sets are mainly discussed in the following sections, and the areas where the density of observation stations is high, such as the eastern, central, and northeastern provinces of China, will be a particular focus. Additionally, the most significant positive trends occur in western Inner Mongolia; additionally, in Northwest and Southwest China the trends are also positive.

$DVTT_{\text{mean}}$ in spring (Figure 1(c) and (d)), autumn (Figure 1(g) and (h)), and winter (Figure 1(i) and (j)) all display most significant negative trends in NEC. By contrast, positive trends in NEC are generally more significant than in the south. By contrast, the most significant positive trends occur in western Inner Mongolia; additionally, in Northwest and Southwest China the trends are also positive.

$DVTT_{\text{mean}}$ in spring (Figure 1(c) and (d)), autumn (Figure 1(g) and (h)), and winter (Figure 1(i) and (j)) all display most significant negative trends in NEC. By contrast, positive trends are significant in this region in summer (Figure 1(e) and (f)). Generally, $DVTT_{\text{mean}}$ in NEC are more prominent than in other regions in China for all seasons. This feature is supported by both CN05.2 and Hadley data. Moreover, the largest negative trends of $DVTT_{\text{mean}}$ in NEC occur in winter. By contrast, in summer, the trend of $DVTT_{\text{mean}}$ is positive over NEC, which has undergone continuous warming since the 1990s (Ren et al. 2015).

There are also other regions showing significant trends in specific seasons. For instance, it is clear that, in spring, positive trends occur in Gansu, western Inner Mongolia, Sichuan, Yunnan, Guangxi, and Guangzhou provinces, but the opposite holds for summer. Over those regions, negative trends become clear in autumn and strengthen remarkably in winter. The trends are generally not significant in the Yangtze River and Huai River valleys in all seasons.

3.2. Characteristics of $DVTT_{\text{max}}$

For $DVTT_{\text{max}}$ NEC still features the most prominent trends on annual and seasonal scales for both datasets. More specifically, Figure 2 shows negative trends to be mainly located in NEC on the annual scale. In other regions, such as western Inner Mongolia, Xinjiang, Gansu, Sichuan, and Yunnan provinces, positive trends are significant. As such, annual trends (Figure 2(a) and (b)) in the northern and southwestern regions are more obvious than in the south. In other words, the day-to-day variability of $T_{\text{max}}$ is most active in northern and southwestern China on the annual scale in recent decades, but the opposite is true for NEC. Comparatively, the day-to-day variability of $T_{\text{max}}$ is stronger than that of $T_{\text{mean}}$ in these regions.

In NEC, negative trends of $DVTT_{\text{max}}$ appear significantly in all seasons except for summer. Moreover, negative trends in this region are rather prominent for the transition seasons, i.e. spring (Figure 2(c) and (d)) and autumn (Figure 2(g) and (h)). For Sichuan, Guizhou, Hunan, Jiangxi, and Fujian provinces, positive trends are clear in spring and become stronger in summer (Figure 2(e) and (f)) but weaker in autumn, whereas they turn negative in winter (Figure 2(i) and (j)). In Yunnan, Guangxi, and Guangzhou provinces, positive trends are most obvious in spring, and then weaken somewhat in summer; whereas, negative trends occur in autumn and strengthen in winter. In southern China, positive trends are significant in spring and autumn, and enhance in summer; whereas, negative trends dominate in winter.

3.3. Characteristics of $DVTT_{\text{min}}$

The trend of $DVTT_{\text{min}}$ is also obvious in NEC, but less notable relative to $DVTT_{\text{max}}$ on both annual and seasonal scales. Specifically, annual $DVTT_{\text{min}}$ trends (Figure 3(a) and (b)) are negative in most of mainland China, except for central Inner Mongolia and Shanxi. On the seasonal scale for these areas, positive trends are significant in spring (Figure 3(c) and (d)), and occur in winter (Figure 3(i) and (j)); whereas, negative trends are characteristic in summer (Figure 3(e) and (f)), and become stronger in autumn (Figure 3(g) and (h)). In southern China, positive trends are robust in spring and hold for summer, whereas significant negative trends occur in autumn and become weak in winter. Similar to $DVTT_{\text{max}}$, $DVTT_{\text{min}}$ displays obvious trend changes in the transitional seasons, i.e. spring and autumn. Moreover, values for Jianghan Plain and the region south of the Yangtze River valley are generally not significant. Overall, the annual and seasonal trends of $DVTT_{\text{min}}$ in the north of China are more obvious than in the south.
Figure 1. Trends of annual and seasonal $DVTT_{\text{mean}}$ (trend in the day-to-day variability of daily mean temperature) from CN05.2 and Hadley data over 1961–2012 (units: °C/yr).

Note: The dotted areas indicate the 95% confidence level, based on a two-tailed Student’s $t$-test.
Figure 2. Trends of annual and seasonal $DV_{TT,\text{max}}$ (trend in the day-to-day variability of daily maximum temperature) from CN05.2 and Hadley data over 1961–2012 (units: °C/yr).

Note: The dotted areas indicate the 95% confidence level, based on a two-tailed Student’s t-test.
Figure 3. Trends of annual and seasonal $\text{DVT}_\text{min}$ (trend in the day-to-day variability of daily minimum temperature) from CN05.2 and Hadley data over 1961–2012 (units: °C/yr).

Note: The dotted areas indicate the 95% confidence level, based on a two-tailed Student’s $t$-test.
4. Conclusion

The trends of day-to-day variability in daily mean, maximum, and minimum SATs are examined using the daily data of CN05.2 and the Hadley data-set for 1961–2012. Our primary conclusions are as follows:

1. Annual and seasonal DVTT$_{\text{min}}$, DVTT$_{\text{mean}}$, and DVTT$_{\text{max}}$ undergo obvious trend changes in NEC. Significant negative trends occur in spring, autumn, and winter, while the opposite holds for summer.

2. In NEC, negative trends are greater for DVTT$_{\text{max}}$ than DVTT$_{\text{min}}$ in spring and autumn, while positive trends of DVTT$_{\text{max}}$ are greater than DVTT$_{\text{min}}$ in summer.

3. In comparison, annual DVTT$_{\text{max}}$ and DVTT$_{\text{min}}$ experience larger trend changes in the north than in the south of the country. On the seasonal scale, the main features lie in positive trends of DVTT$_{\text{max}}$ both in the south and the north in spring and summer, negative trends of DVTT$_{\text{max}}$ in the south in winter, and greater trends of DVTT$_{\text{min}}$ in the north than in the south in spring, summer, and winter.

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Disclosure statement

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