Disentangling the urbanization effect, multi-decadal variability, and secular trend in temperature in eastern China during 1909–2010

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1. Introduction
Regional climate change information are vital for human adaptation approaches (Jonko, 2015). China covers 6.4% of the global land territory, and its influence on the global average temperature is therefore non-negligible. Investigating the instrumental climate change over a long period can provide background information for understanding short-term changes such as those that have occurred since the 1950s.

Several long-term instrumental datasets of the surface air temperature (SAT) in China during the past 100 years have been produced (see Cao et al., 2013 for a review). Recently, Cao et al. (2013) in collaboration with the Climatic Research Unit (CRU) produced a new continuous and homogenized dataset of 18 stations in eastern and central China. These datasets were made in an open and objective manner using quality control techniques, interpolation of missing records, and homogeneity assessment of long-term series; therefore, they should reduce the uncertainty in assessing long-term climate changes in eastern China (Cao et al., 2013; Zhao et al., 2014). The regional annual mean SAT at 16 locations in eastern China agrees well with the variability of the area-averaged SAT over the same region estimated from a much denser station network and is highly consistent with that of the entire country of China during 1951–2010 (Cao et al., 2013). The estimated linear trend for the regional averaged time series based on these 16 homogenized series during 1909–2010 is 1.52°C(100 years)−1 (Cao et al., 2013). Because this value is significantly larger than the global averaged warming trend, it will be beneficial to explain this discrepancy.

The rather complicated causes of instrumental temperature change in China have been acknowledged in previous studies (e.g. Zhou and Yu, 2006; Soon et al., 2011; Zhao et al., 2014). In addition to greenhouse gases and anthropogenic aerosol forcings, the local urbanization effect has played a certain role during recent decades (e.g. Jones et al., 2008; Ren et al., 2008; Yan et al., 2010; Yang et al., 2011; Ren and Zhou, 2014; Zhao et al., 2014; Qian et al., 2015). For example, Ren and Zhou (2014) attributed approximately 15% of the annual mean warming trend in the mainland China area-averaged time series during 1961–2008 to urbanization. Zhao et al. (2014) reported that urbanization effects estimated by differences in population account for 9–24% of the warming trend for various analysis periods since 1951 in eastern China, among which 24% is for the period 1951–2010. In addition, multi-decadal variability (MDV) is evident in China (e.g. Qian and Zhu, 2001; Soon et al., 2011; Wang et al., 2013; Qian and Zhou, 2014). For example, from instrumental data Qian and Zhou (2014) identified an MDV with a discernible peak (valley) near the late 1930s (mid-1970s), which modulated the temperature evolution in North China region for the period 1900–2010. Investigating the role of MDV in instrumental temperature change will benefit the decadal prediction of future temperature changes at a 10- to 30-year timescale (Meehl et al., 2009; Fu et al., 2011).

The present study attempts to disentangle the urbanization effect, MDV, and secular trend related to large-scale warming of SAT in eastern China on the basis of recently homogenized data recorded during the last 100 years. Moreover, the secular trend after deurbanization is discussed, as is the role of MDV,

Abstract
Understanding surface air temperature (SAT) changes in China during the past 100 years is important; however, this is difficult because the impacts of multi-decadal variability (MDV), the urbanization effect, and other anthropogenic forcings are combined in instrumental records. The present study attempts to disentangle these factors recorded in observations in eastern China based on recently homogenized SAT data during 1909–2010. The estimated linear trend (secular nonlinear trend) in the data after deurbanization is 1.08 (1.74°C(100 years)−1). The MDV has enhanced warming in the early 20th century and during the past 30 years, contributing approximately 30% to the latter period.

Keywords: temperature trend; multi-decadal variability; urbanization; EEMD
particularly in recent rapid-warming decades. The results of this study will help to further understand temperature changes in eastern China that occurred during the last 100 years.

2. Data and methods

SAT data in China were obtained from the homogenized monthly SAT series of 18 stations in eastern and central China dating to the 19th century (Cao et al., 2013). To compare the linear trend in regional temperature with that of the global land mean temperature (GLMT) or global mean temperature (GMT), two datasets were used: the most recent version of the CRUTEM4 dataset (CRUTEM.4.3.0.0; Jones et al., 2012), including land data only, and that of the HadCRUT4 dataset (HadCRUT.4.3.0.0; Morice et al., 2012), combining SAT and sea surface temperature (SST) data. These two datasets incorporate the 18 station series produced by Cao et al. (2013) and include a much larger subset of newly homogenized data after 1951 in the China domain than that in previous versions. The annual mean GLMT and GMT series were directly downloaded from http://www.metoffice.gov.uk/hadobs/index.html. The best estimate GLMT anomaly and the most commonly used best estimate GMT series, namely the median of the 100 ensemble members, were analyzed. The 100 ensemble members have been constructed to allow exploration of the sensitivity of scientific analyses to the estimated observational bias uncertainties (Morice et al., 2012). In addition, the monthly National Oceanic and Atmospheric Administration extended reconstructed SST dataset version 3 (ERSSTv3; Smith et al., 2008) for the period 1909–2010 was used.

The same 16 large city stations across eastern China as those reported by Zhao et al. (2014) were used; only three are located above 200 m (Figure 1). Details about these stations can be found in Zhao et al. (2014). The annual mean anomaly relative to the base period 1961–1990 at each station was first calculated. The eastern China averaged annual mean anomaly series of these 16 stations was calculated by first averaging the values of Beijing and Tianjin and those of Hong Kong, Macao and Guangzhou, respectively, because they are located in close geographical proximity. Then, the resultant 13 series were averaged by using the same simple arithmetic mean as that used by Cao et al. (2013) and Zhao et al. (2014); the resultant average series is referred to as T13. The base period 1961–1990, rather than that of 1971–2000 used by Cao et al. (2013) and Zhao et al. (2014), was used for comparison of the results with those at other global sites because the CRUTEM4 and HadCRUT4 anomaly data are relative to the base period 1961–1990. Moreover, different base periods will result in different mean annual cycles and thus different anomalies (Qian et al., 2011b). The impact of the different base periods on trend estimation will be subsequently illustrated in Section 3. The linear trend in this study was estimated by using ordinary least squares (OLS), and the 95% confidence interval was estimated by allowing positive first-order auto-regressive dependence in the data (Hartmann et al., 2013).

The possible impacts of urbanization in eastern China have been estimated by Zhao et al. (2014), who used five population categories at 245 stations across eastern China. In their study, homogenized temperature data for the period 1951–2010 indicated that stations with different population potentially show an additional trend that accounts for 23.6% of the warming trend in the group of large city stations, whose population is greater than 900 000. Therefore, in the present study, 24% of the linear trend in T13 during 1951–2010 was subtracted through data adjustment beginning with 1951 to mimic deurbanization (Figure 2). The resultant time series is referred to as adjusted T13.

The ensemble empirical mode decomposition (EEMD) method (Huang and Wu, 2008; Wu and Huang, 2009), an adaptive and temporally local (e.g. Wu and Huang, 2009; Qian et al., 2011b; Wu et al., 2011) data analysis tool for the analysis of non-linear and nonstationary data, was used to reveal multi-timescale variability and secular change in T13 (Figure 3). This method decomposes any complicated data series into finite oscillation components possessing various timescales and a nonlinear trend (Wu et al., 2007), expressed as

$X(t) = \sum_{i=1}^{n} C_i(t) + R(t)$,

where $X(t)$, $C_i(t)$, and $R(t)$ are the target data, its $i$th oscillation component, and its nonlinear trend at time
Figure 2. Linear trends (dashed lines) in the annual mean temperature anomaly (solid line) of eastern China averaged series for the period 1909–2010. The blue lines indicate the original T13 series based on the data in Cao et al. (2013). The red lines indicate the adjusted T13 series after deurbanization.

Figure 3. Multi-timescale analyses of the annual mean temperature anomaly series shown in Figure 2 by using the EEMD filter. Blue lines indicate the original T13 (OBS) along with the corresponding oscillation components (from C1 to C5) and nonlinear trend (Trend), whereas the red lines indicate those of the adjusted T13 after deurbanization. The smooth curves fitting the OBS represent a combination of the C5 and trend of the adjusted T13 after deurbanization. The red lines are almost covered by the blue lines.

t, respectively. Details of this method are described in Wu and Huang (2009). In the EEMD calculation, the added noise had a standard deviation of 0.3 times that of the target data, and the ensemble size was 1000. The ensemble means are the final $C_i(t)$ and $R(t)$. The last component of EEMD output is regarded as $R(t)$. It should be noted that the EEMD method uses noise to mimic multiple observations. Following the large ensemble mean, the added noise theoretically cancels each other out. Therefore, the differences of the results using various noise amplitudes are rather minor (figure not shown), as long as the ensemble size increases when using larger noise amplitude. Of course, the noise amplitude cannot be too large; otherwise it is no longer noise. For facilitating comparison of the EEMD trend rate with the linear trend rate, the averaged incremental value of the EEMD trend during 1909–2010 was calculated as

$$\text{Trend}_{\text{EEMD}} = \frac{[R(2010) - R(1909)]}{(2010 - 1909)},$$

(2)

3. Results

3.1. Comparison of regional and global temperature trends

For the comparison of regional and global linear trends, these values were calculated during the same period of 1909–2010 because the linear trend is sensitive to the beginning and ending years. Table 1 shows that the original T13 warmed at a rate of 1.53 °C (100 years)$^{-1}$ (Figure 2), which is nearly twice that in GMT (0.75 °C (100 years)$^{-1}$) and 50% higher than that in GLMT (0.98 °C (100 years)$^{-1}$). However, the linear trend in the adjusted T13 (1.08 °C (100 years)$^{-1}$) is much closer to that in GLMT, although it is still 44% higher than that in GMT. This higher warming rate is attributed to the thermal property difference between the land and sea. It should also be noted that the uncertainty range of the adjusted T13 is also larger than that of GMT. The lower bound of the trend uncertainty range is still comparable to the trend best estimate of GMT. Therefore, due to the existence of urbanization effect, land–sea thermal property differences and sampling uncertainties, the substantially higher warming rate in T13 than that in GMT is not unreasonable.

The linear trend reported herein is slightly higher than that reported in Cao et al. (2013), which is 1.52 °C (100 years)$^{-1}$ because they used the base period 1971–2010. The base period 1961–1990 used herein is the same as that used in GMT and GLMT; therefore, it is necessary and improves the accuracy of the comparison.

3.2. EEMD-based multi-timescale analysis

Figure 3 shows five oscillation components (C1–C5) in addition to the nonlinear trend of EEMD analysis

| Series       | Linear trends in °C (100 years)$^{-1}$ |
|--------------|----------------------------------------|
|              |            | Deurbanization | Global | Global land |
| 1909–2010    | 1.53 ±0.47 | 1.08 ±0.44    | 0.75 ±0.19 | 0.98 ±0.30 |

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for the original T13 and those for the adjusted T13. For the original T13, the mean periods of its five oscillation components were approximately 3, 6–7, 17, 26, and 60–100 years, respectively. The $\text{Trend}_{\text{EEMD}}$ for the original T13 was $2.12 ^{\circ} \text{C} (100 \text{years})^{-1}$ during 1909–2010. However, this rate was unstable over time and tended to accelerate after the 1950s, which is consistent with the global average temperature (Wu et al., 2011). The differences in the EEMD results for the original and adjusted T13 were negligible, except for the nonlinear trend. The $\text{Trend}_{\text{EEMD}}$ for the adjusted T13 was $1.74 ^{\circ} \text{C} (100 \text{years})^{-1}$ during 1909–2010; this rate was more stable than that for the original T13. These results suggest that the urbanization warming trend during recent decades should not have significantly affected the oscillation variability, although it accelerated the nonlinear warming trend considerably during the same time period.

The combination series of $C_5$, which represents the MDV, and the nonlinear trend revealed a smooth, long-term evolution of T13, which includes warming in the early 20th century, cooling (or warming hiatus) during the 1940s–1960s, and more rapid warming after the 1970s than that of the previous warming period. Because the MDV reached its minimum in approximately 1980, warming during the past 30 years (1981–2010) has resulted from superimposition of the upward tendency of the MDV and the nonlinear warming trend. The MDV accounted for approximately 30% of the linear trend during this period. This contribution is estimated by $[C_5(2010) - C_5(1981)]/\text{OLS(30)}$, where $\text{OLS(30)}$ is the linear warming increment in T13 during 1981–2010.

Figures 2 and 3 show that the linear trend considerably changed for the same period 1909–1940s, when only the data after 1950 were adjusted; however, the EEMD nonlinear trend for this period remained nearly identical. These results suggest that the EEMD nonlinear trend for a given time interval is less sensitive to the subsequent evolution and is more easily to be physically interpreted than the linear trend.

4. Discussion

Thus far, the factor responsible for the MDV in T13 remains in question. Correlation coefficients were calculated between this MDV and the global SST anomaly field (Figure 4) to explore a possible related oceanic pacemaker. The result shows a pattern of warm North Atlantic and cold South Atlantic and circum-Antarctic SST anomalies associated with warm MDV in eastern China. This pattern resembles the associated pattern (e.g., Figure 2f in Dai et al., 2015) of Atlantic multi-decadal oscillation (AMO; Kerr, 2000), which has been suggested to be linked with multi-decadal fluctuations of the Atlantic thermohaline circulation (Delworth and Mann, 2000; Knight et al., 2005). Observational composite analyses have revealed that the warm-phase AMO is linked to warmer winters in eastern China on a multi-decadal timescale; this relationship is supported by experiments using three atmospheric general circulation models (Li and Bates, 2007). By using the differences between positive and negative AMO phase experiments of the HadCM3 coupled model, warmer Eurasian summers have been shown (Lu et al., 2006). Using proxy data, Wang et al. (2013) found a close similarity between the AMO and MDV in temperature in China throughout the last millennium.

Figure 4. Correlation coefficients between the multidecadal variability ($C_5$ in Figure 3) of the original T13 and global SST anomalies. Correlation coefficients among ±0.3 are omitted.
Apart from the influence of oceanic teleconnection, solar radiation reaching the ground could directly modulate SAT changes on decadal (Qian et al., 2011a) and multi-decadal to centennial timescales (Soon et al., 2011). The nonlinear warming trend could be primarily related to human influence such as increases in greenhouse gas concentration. The detailed mechanisms for the MDV and secular nonlinear trends of T13 are worthy of further investigation and are beyond the scope of this paper. However, the MDV modulation of future temperature change projection in the forthcoming 10–30 years should be considered (Fu et al., 2011).

5. Summary

In this study, an attempt is made to disentangle the urbanization effect, MDV, and secular nonlinear trend in SAT in eastern China during 1909–2010. The main findings are summarized in the following points:

1. For the original data (the adjusted data after deurbanization), the linear trend is 1.53 \(^{\circ}\)C/(100 years) \(^{-1}\); its nonlinear trend is 2.12 \((1.74)^{\circ}\)C/(100 years) \(^{-1}\) and accelerates with time.

2. MDV, which could be linked to an AMO-like SST anomaly pattern, enhanced early 20th century warming and that of recent decades. Moreover, it contributed approximately 30% of the annual warming trend during the past 30 years (1981–2010).

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