Re-Assessing Climatic Warming in China since 1900

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ABSTRACT

The regional mean surface air temperature (SAT) in China has risen with a rate of 1.3–1.7°C (100 yr)−1 since 1900, based on the recently developed homogenized observations. This estimate is larger than those [0.5–0.8°C (100 yr)−1] adopted in the early National Reports of Climate Change in China. The present paper reviews the studies of the long-term SAT series of China, highlighting the homogenization of station observations as the key progress. The SAT series of China in early studies showed a prominent warm peak in the 1940s, mainly due to inhomogeneous records associated with site-moves of a number of stations from urban to outskirts in the early 1950s, thus leading to underestimates of the centennial warming trend. Parts of China were relatively warm around the 1940s but with different-phase interdecadal variations, while some parts were even relatively cool. This fact is supported by proxy data and could partly be explained by interdecadal changes in large-scale circulation. The effect of urbanization should have a minor contribution to the observed warming in China, although the estimates of such contributions for individual urban stations remain controversial. Further studies relevant to the present topic are discussed.

Key words: global warming, regional climate variability, centennial trend, interdecadal variations, effect of urbanization

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1. Global warming versus warming in China

Global climate warming since the Industrial Revolution has been evident, as indicated in the series of assessment reports of the Intergovernmental Panel on Climate Change (Hartmann et al., 2013). According to the latest global surface temperature observation datasets (Xu et al., 2018; Yun et al., 2019), the global mean land surface air temperature has increased by 1.00 ± 0.06°C (100 yr)−1 and the global mean surface temperature has increased by 0.86 ± 0.06°C (100 yr)−1 since 1900. Record-setting global oceanic warmth continued in 2019 (Cheng et al., 2020): the heat content in the upper layer (2000 m) of global ocean has significantly increased since 1958 and accelerated after the 1990s (Cheng et al., 2019). During the same period, climate extremes or extreme weather phenomena such as droughts, floods, and heat waves increased in many regions such as China (Song et al., 2019); while in general, global glaciers, sea ice, and snow cover decreased and the growing season lengthened almost everywhere, reflecting global warming in various aspects (WMO, 2019).

However, the rates of climate warming were not the same in different regions. In general, the rate of warming was larger in the continent than in the ocean, and larger in the mid–high latitudes than in the tropics. For instance, the northern Asian inland from Siberia to Mongolia was one of the fastest warming regions since the last
century, with a rate of over 2°C (100 yr)^{-1} (Zhao et al., 2014; Wang et al., 2018; Yan et al., 2019). As the sensitivity of the human society and ecosystem to climate warming varies for different regions, it is meaningful to quantify the rate or extent of regional climate warming. Quantitative assessments of regional climate changes are also needed for decision- and policy-making upon adaptation to climate changes.

China is located in the eastern part of Eurasia with a typical continental climate. In particular, temperature in this region is of strong interannual variability mainly associated with the various winter monsoons originated from the inland upstream areas of North Asia. Undoubtedly, the strong warming in northern Asia during the past century should have a quite direct impact on climate warming in China. However, the long-term warming trend in China was estimated as only about 0.5–0.8°C (100 yr)^{-1} in the early National Climate Change Assessment Reports (NCCAR Writing Committee, 2007, 2011). This rate is even smaller than that of the global mean warming, which mainly reflects the relatively slow change in global ocean surface temperature. In recent years, especially with emerging homogenized long-term series of station temperature observations, there have been increasing studies showing that the warming trend in China since the last century should be far greater than the previously estimated.

The present paper reviews the studies of long-term instrumental temperature series in China, highlights some key progresses with novel understandings, and discusses the relevant problems that deserve further investigations in order to improve the knowledge of regional climate changes with global warming.

2. Warming in China in early studies: 0.5–0.8°C (100 yr)^{-1}

The study of centennial-scale temperature observation series for China started in the 1980s (Zhang and Li, 1982; Wang, 1994). The difficulty of constructing centennial climate series arose mainly from the lack of observations before the 1950s. Early researchers tried different methods to utilize the limited observations, which were sometimes combined with proxy data, for the early years. In their classical work, Zhang and Li (1982) converted the instrumental temperature records into temperature grades for seven typical climate sub-regions in China separately, then integrated them into the annual temperature anomaly series for China. The regionalized grading processing appeared to have alleviated the problem due to sparse observations in the early time. However, the grade-based series could hardly be used to quantify the warming trend in China, though the mean temperature anomaly corresponding to each grade for each sub-region could be estimated. Moreover, if temperature records were available only at one station and systematically biased in a certain period, the grading would result in relatively enlarged bias for that period in the sub-region series.

An improved approach was developed by Wang et al. (1998), who utilized different types of data for different periods for different sub-regions. They divided China into 10 sub-regions, with consideration of the different types of data available for the different sub-regions. For each sub-region, they applied instrumental temperature records to make the mean temperature anomaly series back to as early as possible, and then proxy data (including the grade data, ice cores, tree rings, and/or historical documentary records, wherever available), to extend the series for the earlier years with estimated temperature anomalies. The temperature anomaly series for China was then obtained by area-weighted averaging of the 10 sub-region series. In such a way, they tended to make full use of the quantitative advantage of modern instrumental records for each sub-region. However, the uncertainty in estimating the centennial warming trend in China arose greatly from the use of proxy data for the early years. This problem could be avoided by using only instrumental temperature records from standard meteorological stations (Lin et al., 1995). Nevertheless, long-term instrumental records could also be biased between different sub-series due to changes in the observation system at local stations.

Since the 2000s, gridded climate data have increasingly been developed with commonly recognized interpolation methods. Tang et al. (2005, 2009) transformed the station temperature records into 5° × 5° grid temperature anomalies, and then constructed the temperature anomaly series for China by grid-area-weighted average. Similar with the use of regionalized data, the use of gridded data also alleviates the problem of sparse observations in early years. Although the number of grids with long-term series of temperature anomalies remained limited, this limitation itself should not much bias the estimate of the large-scale mean long-term warming trend in China as implied in relevant studies (e.g., Jones et al., 2008). In methodology, it is easier to verify and improve the gridded data than the regionalized data, with one of the reasons being that the regional division is quite arbitrary. However, if the station records were systematically biased especially in the case of sparse observations in the
early years, the grid data processing would also result in some enlarged bias in the gridded data series.

Although these early studies have used different approaches, their data sources are not much different from each other, and the resultant temperature series for China exhibit very similar interannual and interdecadal variations, as well as a similar long-term warming trend. A remarkable common feature is a prominent warm peak in the 1940s. The existence of this early warm peak caused a much underestimated long-term warming trend in the series. Although a few recent reviews emphasized uncertainties (Ding and Wang, 2016; Ren et al., 2017; Li and Yang, 2019), the 1st and 2nd National Climate Change Assessment Reports (NCCAR Writing Committee, 2007, 2011) concluded that the centennial-scale warming trend in China was about 0.5–0.8°C (100 yr)$^{-1}$, based on these early studies.

3. Warming in China based on homogenized observations: 1.3–1.7°C (100 yr)$^{-1}$

Long-term meteorological observation series unavoidably underwent some systematic changes such as relocation of observing site, replacement of instruments, and amendment in observing rules, etc., which could result in systematic (inhomogeneous) biases in the observation series for the corresponding parts relative to the other parts of the series. Homogenization of long-term climate series is therefore critical for estimating climate trends in the observation series, especially for China with relatively frequent changes in the station history (Yan et al., 2014; see Appendix for terminology of homogenization). The influence of inhomogeneity in observations on estimation of climate change has received increasing attention since the 1980s, when global warming began to be one of the most popular topics. A milestone progress was made in the European Union funded project called IMPROVeEd Understanding of Past Climatic Variability from Early Daily European Instrumental Sources in the late 1990s, which resulted in a set of homogenized daily temperature series derived from the longest (back to the 18th century) meteorological station observations in Europe, a unique database for modern climate change studies (Camuffo and Jones, 2002; Yan et al., 2002).

Regarding the need of long-term climate observations in China, an international collaboration was established between the Chinese Academy of Sciences and the US Department of Energy during the 1980s, which resulted in a set of long-term climate observation series from 60 stations in China (Tao et al., 1991). This dataset included details of station history (metadata), which were expected to be useful for detecting and adjusting possible inhomogeneous biases in the observation series. Unfortunately, the project did not end up with a set of homogenized climate series. Using this dataset, however, Yan et al. (2001) homogenized the long-term daily temperature series for Beijing and Shanghai. The raw data showed obviously different long-term trends between the two stations not only for the last century but even for the recent decades; while the homogenized series showed very close long-term trends at the two places. Note that the two station series were homogenized separately by using their own neighboring reference station records, which were independent of each other. Clearly, such adjustments eliminated the local biases in the raw data, while the homogenized temperature series better represented the large-scale regional climate change.

In recent years, the early meteorological data in China have increasingly been explored and compiled. Cao et al. (2013, 2017) developed a homogenized dataset of long-term monthly temperature series at 32 stations in China, by using the Relative Homogeneity test (RHtest) method with the most updated metadata archived at the National Meteorological Information Center, China Meteorological Administration. However, some biases remained un-adjusted as the authors routinely accepted a detected change point only if it was supported by the metadata, which were surely incomplete. Based on this dataset, Li et al. (2018) developed a further adjusted dataset by using the Multiple Analysis of Series for Homogenization (MASH) method. Although the long-term temperature series for China based on the different homogenized datasets are not identical (Fig. 1), the estimated long-term warming trends in China based on homogenized observations so far are quite consistent, mainly within a range of 1.3–1.7°C (100 yr)$^{-1}$.

To help understand uncertainty in the temperature series for China, we calculated the 90% confidence interval of the series of T-Cao in Fig. 1 based on the 32-station series of Cao et al. (2017), by using the method of Wang et al. (2018) for estimating the uncertainty of a regional mean value due to sparse observations. As Fig. 1 shows, the range of uncertainty is larger for the earlier years due to sparse stations and becomes quite small for the recent years since the 1950s. The series of the other authors are mostly within this uncertainty range, except for a few early years. According to Cao et al. (2017), the correlation coefficient between the 32-station-mean temperature series and that of 2419 stations in China was 0.99 for the period since 1951, although the former is of slightly larger interannual variability. This suggests that the mean temperature series based on the homogenized
series from 32 stations can well represent that of the whole region of China. A 1000 sample series were randomly generated within the 90% confidence interval of the series of T-Cao. Their long-term trends range from 1.51 to 1.73°C (100 yr)$^{-1}$ [median 1.57°C (100 yr)$^{-1}$], which roughly represent the 90% confidence interval of the estimated long-term warming trend. This range of uncertainty can also be a measure for the other series for China in Fig. 1. Nevertheless, uncertainty of long-term regional temperature series, especially for the early poor data period, remains an interesting issue.

For comparison, as indicated in the recently released IPCC Special Report on Climate Change and Land (SRCL), the global mean land surface air temperature in 2006–2015 was 1.53°C (1.38–1.68°C) warmer than that in 1850–1900. This magnitude of change is close to the estimated centennial warming range in China. As shown in Fig. 1, the temperature anomaly series of China exhibits consistent interannual and interdecadal variability with that in the global and Northern Hemisphere series. In particular, there is an overall warming trend, though the trend in China is slightly larger and there tends to be a slight warm fluctuation around the 1940s.

In contrast, the temperature series of China in those early studies mentioned in the last section commonly had a striking warm peak in the 1940s. It was mainly due to this unusual early “warmth” that the centennial climate warming in China was underestimated in the previous studies.

4. False “warmth” in the 1940s

In recent years, increasing studies have suggested that the previously recognized unusual warmth in the 1940s in China should be false. Main arguments are summarized as follows.

A major problem arises from inhomogeneous temperature records. According to Cao et al. (2017), many meteorological stations were relocated from a relatively urban site to outskirts during the early 1950s, as required in the process of urbanization and development in the early stage of the People’s Republic of China. Due to the effect of urban heat island, the temperature records would be systematically higher before than after such a relocation in general. This effect of relocation could be aggravated or offset by those of other superimposed changes such as replacement of instruments and amendment in observing rules at the new site. Consequently, 13 of the 32 stations’ long-term temperature series have displayed significant inhomogeneous warm biases in the earlier temperature records (Cao et al., 2017). After adjusting these biases by using RHtest with neighboring reference records, the authors concluded that the centennial temperature series for China based on the homogenized data no longer display a prominent warm peak in the 1940s.

Recently, Zhu et al. (2020, personal communication$^a$) applied the raw temperature records to reconstruct the centennial temperature series for China by using the methods in those early studies, and the results showed a

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{The annual mean surface air temperature anomaly series for China during 1901–2018 based on homogenized data, compared with the global (GL) and Northern Hemisphere (NH) land surface air temperature anomaly series. The sources of the China series are: T-Cao (Cao et al., 2017), T-LIZ (Li et al., 2018), T-LIQ (Li et al., 2017), and CRUTEM4-CHN (Jones et al., 2012). The source of CRUTEM4-GL and CRUTEM4-NH is UK Met Office CRUTEM4.6.0.0 anomalies. All series have been updated to 2018. The shadow represents the 90% confidence interval of the T-Cao series.}
\end{figure}

$^a$Zhu, Y. N., P. Zhao, L. J. Cao, et al., 2020: Influence of inhomogeneous data on the 1940s’ “warmth” in China.
prominent warm peak in the 1940s as in the early studies. As long as the homogenized data were applied, the resultant temperature series for China no longer had a warm peak in the 1940s, no matter what methods were used. Therefore, the 1940s’ warmth should simply be a false result from the inhomogeneous raw data at a number of the long-term observation stations.

There might be a warm episode around the 1940s for some seasons and some parts of China. For example, Zeng et al. (2003) analyzed two interdecadal warming processes during the last century and pointed out that the warming before the 1940s in eastern China mainly happened for the summer, as reflected in the early temperature records at Beijing and Shanghai. Tong et al. (2018) calculated the interdecadal temperature variations for the winter and found that there was a warm phase around the 1940s in a zone from southeastern to northeastern China, while a cold phase in parts of North and Northeast China.

Due to scarcity of early meteorological observations, it is helpful to find possible evidence in proxy data. Zheng et al. (2015) divided the Chinese mainland into 9 sub-regions and constructed the temperature anomaly series for the past 150 years by using proxy data such as historical documents, tree rings, and ice cores respectively for different sub-regions. The results showed that some sub-regions were relatively warm around the 1940s, while some (e.g., South China) were relatively cool. Therefore, the large-scale average temperature series for China is unlikely of a prominent warm peak in the 1940s.

Diagnoses of mechanisms for the regional climate changes are enlightening. To explain the regional temperature changes, it is beneficial to analyze changes in atmospheric circulations. Tong et al. (2018) applied global gridded sea level pressure data to calculate the geostrophic wind field for winter in China and surrounding areas. Then, they calculated the winter temperature advection and found that around the 1940s, anomalous warm advection prevailed in a zone from Southeast China to most of Northwest China, while anomalous cold advection occurred in a zone covering part of Mongolia and northeastern China. The latter could explain the cold anomalies in parts of Northeast and North China during the same period.

The recently developed theory of “warm Arctic–cold continents” (Cohen et al., 2014) was aimed at explaining the fact that the Arctic had warmed fast while some continental regions in the midlatitudes entered the so-called “warming hiatus” period since 1998. Warming in the Arctic usually corresponds to a weakening Arctic Oscillation (AO) with enhanced longitudinal variations of the circumpolar westerlies, thus favoring cold surges from the Arctic to some midlatitude continental regions of the Northern Hemisphere. Liang et al. (2014, 2019) found that there were more cold surges into Northeast China in winter when AO was weaker. In fact, a cooling trend happened in winter in Northeast China since 1998 (Li et al., 2015). From the early 20th century to the 1940s, there was a warming trend around the Arctic, which should have caused weakening AO (Zeng et al., 2001; Gong and Wang, 2003). Therefore, an overall warming trend across China was unlikely, neither was there a prominent warm peak, in the 1940s for China.

Nevertheless, there was a relatively warm episode around the 1940s even in the global mean temperature series. Ding and Wang (2016) reviewed that the Atlantic Multi-decadal Oscillation (AMO) and the Pacific Decadal Oscillation (PDO) were in positive phase during the 1940s, implying possible roles that these oceanic oscillations played in the warmth of the 1940s for some parts of the world. Gao et al. (2015) comparatively analyzed the observed interdecadal variations in global land surface air temperature and those simulated by the atmospheric general circulation models (AGCM) forced by the observed sea surface temperature (SST) variations, and concluded that AMO and PDO could well explain the first two principal components of the continental temperature variations, respectively. Interestingly, most of the Eurasian continent including most of China was relatively warm in the positive phase of AMO, but many parts of China were relatively cool in the positive phase of PDO. As both AMO and PDO were in positive phase around the 1940s, their combined impacts could be a background for the lack of an overall warmth across China during that time. The mechanisms linking the oceanic oscillations and regional climate changes remain an interesting topic for further studies.

5. Urbanization-induced local effects

In recent decades, China has experienced rapid urbanization. Especially since the early 21st century, the land use in China has been mainly in the form of construction site, expanded by 24,600 km² (Liu et al., 2018). Compared with the total area of China, the proportion of urbanization is fairly small. Therefore, if the observations at a meteorological station are affected by urbanization, it is necessary to quantify the local signal of urbanization for properly assessing large-scale climate change. For temperature observations at an urban site, urbanization may superimpose a local warming trend due to enhanced urban heat island. However, it remains controversial with
regard to the contribution of urbanization to the observed warming trend. From some reviews and discussions (e.g., Wang and Yan, 2016; Yan et al., 2016), we could understand that many of the different results are not directly comparable due to different types of data, sites, time periods, and methods.

As to the large-scale warming trend in China during the last century, Zhao et al. (2014) made a series of multi-variable regression analyses and concluded that large-scale climate changes including those in atmospheric circulation in the surrounding areas could explain more than 80%, while the contribution of urbanization should be less than 20% to the observed warming in eastern China. By comparing the observation series in the last few decades between urban and rural stations, some studies suggested that the contribution of urbanization to the observed warming trend at the urban stations could be far more than 20% (Ren et al., 2007, 2015; Wang et al., 2015). However, considering the limited geographical extent of urbanization, Wang et al. (2015) suggested that the contribution of urbanization to the national-scale warming trend could be negligible (less than 1%).

A key issue in the debate is how to distinguish the large-scale climate change and the local signal of urbanization. Many studies used the so-called “rural” station records to represent large-scale climate change, thus the estimated warming effect of urbanization at the urban stations was very large, because some of the chosen “rural” stations showed little long-term trend. However, it is questionable whether such “rural” stations represent large-scale climate change. Some of these stations even had a false cooling trend due to inhomogeneous records (Peterson, 2003; Yan et al., 2014).

Kalnay and Cai (2003) proposed the method of “Observation minus Reanalysis (OMR),” which was employed in many studies to identify possible urbanization signal from large-scale climate change background. Wang et al. (2017a) used this method to isolate local signals at stations from large-scale climate change background, and then regressed the residual temperature observations at stations upon the changing urban fraction surrounding the stations based on remote sensing data. Their results suggested that for eastern China (the most developed part of China), on average, urbanization contributed about 9% to the observed warming trend in the daily minimum temperature series during 1980–2009, but had little impact in the daily maximum temperature series. Recently, Li et al. (2019) analyzed the correlation between a set of urbanization indices and the temperature records for a number of sub-regions in China, and they concluded that urbanization should have little contribution to the observed temperature trends in China.

Urbanization in China, especially during the last few decades, was usually superimposed with increasing aerosol pollution around the urban sites, which may cause a climatic cooling effect especially for the daytime. This cooling effect is somehow contradictory to the conventionally recognized warming effect of urbanization, though pollution was found to be favorable for nighttime urban heat island (Cao et al., 2016). This fact induced additional uncertainty for assessing the contribution of urbanization to the observed warming trend in China, as well as further complexity for understanding the underlying physical mechanisms.

Nonetheless, based on a comparative analysis between the land surface air temperature series in China and the SST series in the coastal seas, Jones et al. (2008) concluded that urbanization should have a minor effect on the observed warming trend in China. This tends to be affirmed with emerging recent studies.

The impact of urbanization might be appreciable in the changes of some extreme temperature indices. Many observational analyses showed that urbanization might have enhanced the extremely high temperature and heat waves in the urban agglomeration regions during the last few decades (Li et al., 2014; Ren and Zhou, 2014; Luo and Lau, 2017; Yang et al., 2017). Some simulation studies helped understand the underlying mechanisms. In their attribution study based on comparative analyses between observations and climate model simulations, Sun et al. (2014, 2016) concluded that urbanization should have considerably contributed to the increasing temperature extremes in China. Wang et al. (2017b) used a high-resolution regional model to simulate the super heat wave in eastern China during July–August 2013 and found a positive feedback between the heat wave and urban heat island. Note that aerosols are usually well dissipated under the atmospheric conditions of heat waves, thus facilitating direct interaction between the heat wave weather and the urban heat island.

6. Conclusions and discussion

The studies of the centennial-scale temperature series in China began in the 1980s. A key progress emerged from the development of homogenized long-term temperature observation datasets since the beginning of the 21st century. Based on the homogenized observations, the warming trend in China since the last century is estimated within the range of 1.3–1.7°C (100 yr)$^{-1}$.

The relocation of a number of meteorological stations
(1) Reliable long-term observation series are imperative for assessing climate change. Arguments based on inhomogeneous raw data are not helpful at all, as pointed out by Li and Yang (2019). In recent years, great efforts have been made in constructing homogenized temperature database aiming at reasonably assessing the long-term climate warming in China. As a further step, it is beneficial to build up a homogenized database of long-term daily (or even higher-resolution such as hourly) observations and of more climate variables. This will not only help to improve the knowledge on climate change such as occurrences of extreme weather/climate events in this region, but also consolidate the basis for comparative analyses with other regions over the world.

(2) Regarding the aforementioned “hiatus,” interdecadal or multi-decadal variability (MDV) of the climate system is of concern. Although Karl et al. (2015) pointed out that there was no “hiatus” in the global mean surface temperature series after adjusting the inhomogeneous biases in part of ocean observations, there is clear MDV in regional climates. For example, MDV might have caused the relatively warm episode around the 1940s and the relatively cooling since 1998 in some parts of China as well as those in-phase or out-of-phase variations in the other regions. Further MDV-relevant studies are necessary not only for understanding the mechanisms linking regional climate variations and global change, but also for making reasonable near-term projections of climate change.

(3) Urbanization appears to be a special and unavoidable topic for studying climatic change in China. The effects of urbanization upon either the national- or local-scale climate change remain controversial. Some novel way is needed to reconcile the attribution of large-scale climate change and the signal of urbanization. Many researchers started from one-way thinking and tried to excavate the expected urban “signal” from incomplete data, thus often ended up with some exaggerated results. Breakthrough is expected by involving urbanization as an additional local forcing in the current conventional attribution study of large-scale climate change. Further development of specific data products as well as high-resolution modeling techniques is needed.

Appendix

Terminology: Homogenization

In general, if the climate series at a station (candidate) exhibits very different variations with those at the neighboring stations (references), the candidate series is very likely of inhomogeneous biases due to non-climate changes in the local observation system. Homogenization is to detect and adjust such biases. Many methods of homogenization have been developed by scientists over the world. The Multiple Analysis of Series for Homogenization (MASH) and the Relative Homogeneity test (RHtest) are among the most widely applied so far. RHtest (Wang, 2008) can be applied to daily series and it not only adjusts the mean value but also improves the probability distribution of the daily records (Li et al., 2014). MASH (Szentimrey, 1999) is applied to a number of series and does not assume any of them to be homogeneous. MASH detects and adjusts all biased series after mutual comparative analyses among the series, thus solving the dilemma “different orders of adjustments of the biases lead to different results.” Different methods have their own advantages and disadvantages. However, the differences among the adjusted series using different methods are minor, compared with the differences between the raw and adjusted data. Therefore, homogenized climate series always better represent climate change than the raw data do (Li et al., 2016; Squintu et al., 2019).

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