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Continental Scale Surface Air Temperature Variations: Experience Derived from the Chinese Region

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Abstract

Although there are still slight differences during some periods, the global surface air temperature (SAT) change series developed by different groups are generally very consistent with each other. However, there are still considerable uncertainties in the analysis of air temperature series at the regional scale. At the slightly larger sub-continental scale, to understand the trend and magnitude of regional climate warming in China, many teams of scientists have tried to establish a series of air temperature changes across the country from the 1880s onwards. However, until recently, the conclusions reached by these different teams remained markedly different, implying clear uncertainties. The reasons for the uncertainties are inhomogeneities in some SAT series, incomplete data and the biased nature of the station distribution. In addition, many studies have attributed the rapid warming rates in China to contributions from urbanization. However, additional research has shown that the characteristics of the periodic variations in temperature change across China in recent decades indicate that China has warmed faster than other areas at the same latitude and the average for the Northern Hemisphere. Although rapid urbanization in some parts of China has led to local-scale warming, due to the relatively small overall sizes of urbanized areas, the latest conclusions confirm that urbanization contributed less than 5% of the regional air temperature changes in China over the past century. Since approximately 1998, the general characteristics of air temperature changes in China have also shown warming, but more in extremes than average values. These phenomena can be explained by the physical mechanisms of atmospheric circulation changes. This paper discusses all these issues including summarizing the process and experience of establishing a series of air temperature changes at the sub-continental scale and estimating the magnitude of climate change by developing a series of regional temperature changes throughout the 20th century.

Keywords: Data homogenization; sampling bias; climate series; climate change observation; uncertainty

1. Introduction

The global climate is experiencing changes characterized by warming. Accurate estimation of the long-term trends in global and regional climate change is crucial for the detection and attribution of impacts and the prediction of climate change. For a long time, many climate research institutions and scientists have created a series of global average temperatures, which have laid the solid foundation for an accurate understanding of the overall changes in global surface air temperature. The Climatic

Research Unit (CRU) of the University of East Anglia in the UK established the global land surface air temperature (SAT) grid data sets – CRUTEM3 and CRUTEM4 (Brohan et al., 2006; Jones et al., 2012). The National Centers for Environment Information of the National Oceanic and Atmospheric Administration (NOAA/NCEI; or the former National Climate Data Center (NCDC)) established the Global Historical Climate Network Monthly Dataset (GHCN, version 3, it should be mentioned that it has been updated to version 4 in June 2019) (Lawrimore et al., 2011; Karl et al., 2015). NASA's Goddard Institute for Space Studies (GISS) set up a global land temperature data set (GISTEMP) based on the GHCN dataset and revised the urban heat island effect assessment and added observations from Antarctica (Hassen et al., 1999; 2010). The long-term trends over the past 140 years of global and hemispheric land surface air temperatures based on these datasets are regarded as some of the key scientific findings of all previous IPCC scientific assessment reports, and these also provide baseline observations (Thorne et al., 2018; Li et al., 2018) for studies on global and regional-scale climate change detection, attribution and impact assessment (Hansen et al., 1999).

The Berkeley Earth Surface Temperature (BEST) project has also developed a set of global land temperature data using different regional interpolation methods and concluded similar results and trends at global and hemispheric scales with other datasets (Rohde et al., 2013). The Japan Meteorological Agency (JMA) also released a global series of land surface temperatures for climate/climate change monitoring, but there was no discussion of quality control or homogenization of the published SAT dataset, and the dataset was almost completely based on the GHCN monthly mean temperature before 2000. Scientists from the Sun Yat-Sen University, China Meteorological Administration (CMA), CRU, Environment and Climate Change, Canada (ECCC), Australia's Bureau of Meteorology (BOM) and the University of New York at Albany jointly published a new "integrated and homogenized" SAT dataset (China-Land Surface Air Temperature (C-LSAT)) in 2018 that both directly integrates numerous national data sources from many National Meteorological & Hydrological Services (NMHS) or from their website resources and systematically homogenized these additional and potentially inhomogeneous data series. Thus, this is another global land SAT dataset that meets the global and regional climate change accuracy requirements (Xu et al., 2018). It can be seen from comparisons of these series that although there are some differences among the datasets in the number of stations and statistical processing methods, there are few differences between their estimations of centennial warming rates (see IPCC, AR4, 2007, Figure 3.1). Recently, the International Surface Temperature Initiative (ISTI) project led by NOAA/NCEI and the Met Office Hadley Centre (MOHC) collected the largest observational database based of many new homogenized dataset products, and more stations are expected to be added in improved versions of the datasets in the near future (Rennie et al., 2013). The study by Karl et al. (2015) used a homogenized dataset derived from the ISTI project.

While the above datasets are already very similar in terms of the global/hemispheric average surface air temperature trends over 100 years (Hansen et al., 2010; Hartman et al., 2013), there are still significant differences in the SAT trends at sub-continental scales (Xu et al., 2018). We know that in the study of global/hemispheric SAT change trends, because of the strong spatial autocorrelation of temperature data, we do not need a very high-density of sites to establish a global series of temperature variations. The resulting global/hemispheric series tend to be highly accurate, and even ignoring/removing datasets of some countries from the global datasets does not matter (Jones et al., 2012 and Jones, 2016). At regional and local scales, missing data often lead to greater uncertainties (Parker, 2010a; Li et al., 2010a; Xu et al., 2018) and inhomogeneities in some station series tend to have greater impacts than when looking at regional average series (Peterson et al., 1998; Li et al., 2004a, b; 2017). As a result, the regional SAT series are more susceptible to smaller-scale impacts (urbanization, land use, etc.). Therefore, in the context of global or hemispheric climate change, further improvement of the accuracy of regional climate change trend detection has become an important direction of future climate change observation research (Stott and Thorne, 2010).

Lower density observational networks have always been evident in many regions such as the Arctic, Antarctic, South America and Africa (Xu et al., 2018). This has led to some difficulties in assessing the uncertainties and in the construction of precise regional surface air temperature series. Using the Arctic as an example, some recent studies have concluded that the absence of data from the sea-ice regions resulted in a sampling "bias" that could also affect the global series of surface air temperature (SAT) series (especially in the period since 1998) (Karl et al., 2015; Cowtan and Way, 2014; Huang et al., 2017a). Cowtan and Way (2014) used satellite data to reconstruct an SAT series including sea-ice regions (for both Polar Regions) and Africa that are not covered by Hadley Centre & Climatic Research Unit Temperature version 4 (HadCRUT4) data (about 16% of global area). This study increased the temperature trend from 0.046degC/decade to 0.119degC/decade in the period 1997-2012. Huang et al (2017a) interpolated data from the International Arctic Buoy Observatory data and found that the trend of warming was 0.112 degC/decade over the period 1998-2012, which is higher than the trend in the NOAAGlobalTemp (formerly MLOST) data over the same period (about 0.050 degC/decade). In other larger (continental scales) areas countries like China and Canada similar problems can occur due to much sparser station density in some mountainous parts in earlier decades of the 20th century. It is possible to establish a more reliable regional temperature series on century times scales when the uncertainties from different biases are carefully assessed.

China is located in a typical Asian monsoon region (Figure 1). Due to the specific land-sea configuration, the annual seasonal winds occur in most areas in a specific season, resulting in unique monsoon climate characteristics in the monsoon region of East China: cold and dry winters and warm and rainy summers. In addition, the southwestern part of China is the "roof of the world", or the Qinghai-Tibet Plateau, which has an important impact on the general circulation of East Asia. These common influences have not only led to complex climate characteristics in China but also played an important role in global-scale climate change. At the same time, in East Asia, the climate is also significantly affected by the El Niño/Southern Oscillation (ENSO) phenomenon and other climate oscillations (Lau, 1992; Yang et al., 2002a; Wu et al., 2003). Due to the characteristics of its larger land area, it is appropriate to take China as a typical example of regional-scale study area and this paper provides such an analysis. Chinese scientists began to reconstruct and analyse regional air temperature series across the country and perform systematic comparisons of variations in surface air temperatures in China and at global scales in the 1970s (Zhang et al., 1974; 1979; Zhang, 1978; Zhang and Li, 1982; Tu, 1984; Wang, 1990; Tang and Lin, 1992; Ding and Dai, 1994; Lin et al., 1995; Wang et al., 1998; Wang and Gong, 2000; Wang et al., 2004; Tang and Ren, 2005; Li et al., 2010a; Cao et al., 2013; Soon et al., 2015;2018). All these studies sought to accurately estimate the change in air temperature since the start of the 20th century (Li et al., 2017).

Five series were discussed in Li et al. (2017) (for the CRU dataset, we retained only CRUTEM4 in this paper). In this paper, we add two new series : 1) Using the global temperature dataset GHCNv3 (Lawrimore et al., 2011), 160 station series (mean, maximum and minimum temperature) were extracted from China to build another Chinese series (referred to here as GHCN): 2) Cao et al. (2013) averaged 13 homogenized and statistically interpolated station series in central and eastern China and used this as a Chinese air temperature series after comparing the average of 13 stations with the whole Chinese series after 1950, and this is indicated as the Cao series (Table 1). Figure 2 shows comparisons of these seven different air temperature change series. Due to the differences in the observation networks, processing technology and scientific issues with the data, different researchers/teams have utilized different series, but the differences are not very large; the long-term trends for multiple series are essentially about 0.09 degC/decade, according to Li et al. (2010a), with the exception of the linear trend of the Cao et al. (2013) series, which reaches 0.15 degC/decade.

Almost all studies suggest that there were two rapid warming periods (from the 1920s to the 1940s and from the 1990s) and one period of cooling (from the 1950s to the 1970s) across China during the 20th century (Figure 2). However, there are differences in the amplitude of the first warming period and also in the long-term trends of the series, which are reflected in the large differences at decadal scales. As seen from Figure 2, the differences are mainly apparent in the first half of the 20th century. Although, the raw observational data adopted by each team are basically the same, there are differences in quality control processing or homogenization (Li et al., 2017, their Table 1).

This paper first reviews and compares the related work and systematically analyses the inhomogeneity, sampling biases, station data gridding methods (section 2), and biases of urbanization from climatic data and climate series (section 3); SAT variations both in China and globally are then compared in section 4, and then a set of common processes for building a series of regional (continental scales) and assessments of the detection of climate change trends are summarized in section 5.

2. Century-scale regional SAT series construction

2.1 Chinese meteorological observations and climate data

2.1.1 Brief review of the China Meteorological Network before the 1950s

Research on the series of air temperature changes in China and the trends are generally based on air temperature observations from surface meteorological stations over the last century. Meteorological observations across China have however undergone a long and variable history, so the quality of the climate data is also complicated.

During the instrumental observation period, the earliest meteorological observations in China date back to the earliest observations collected by thermometers: Antoine Gaubil, a French missionary, that is, Brother Cope, as Mr. Zhu Kezhen noted in “Meteorological Records of Former Qing Dynasty in Beijing”. He began to collect meteorological observations at his apartment in Beijing using an alcohol thermometer in July 1743 and left approximately 250 sets of air temperature observations (Cao Jilu, 1995; Zhang De’er, 2005). For 21st years of the Qing dynasty (from AD 1841) in Daoguang, the Russian Orthodox Church in Beijing conducted continuous meteorological observations with the elements including air temperature, pressure, humidity, wind, rain/snow and sky conditions, and these observations represent the earliest systematic observations in China. In 1849, the first meteorological observatory, the "Beijing Geomagnetic Observatory" (39 ° 57'N, 116 ° 28'E), was established, which was later replaced by other stations in 1914. In 1872, Shanghai Xujiahui established a second observatory (31 ° 12'N, 121 ° 26'E) that has been maintained by the Father of Jesuits of Paris since 1872 and is the longest and most well-preserved meteorological station in China (Figure 3). Since then, according to incomplete statistics, more than 80 meteorological observation stations were established by foreign missionary organizations and schools in China from the late-19th century to the 1940s. The colonial governments also established more than 100 weather stations in China, and there are more than 70 stations with observation lengths exceeding 30 years, including the famous "Hong Kong Royal Observatory" (22 ° 18'N, 114 ° 10'E, established in 1884) and Qingdao Observatory (36 ° 04'N, 120 ° 19'E, established in 1889) (Li et al., 2018). In addition, the General Administration of Customs of the Qing Dynasty government (actually controlled by the colonial governments) also established more than 70 weather stations in coastal areas of China, along the Yangtze River and on Chinese islands (including Taiwan with meteorological observations beginning in 1885) (approximately 46 of which have observation data over 30 years in length). In 1908, the Chinese government formally established its first "weather station". Since then, the Beiyang government, the Central Meteorological Institute/Central Weather Bureau, universities, private organizations, military groups, aviation organizations and other agencies have established thousands of weather stations, but the observation records are not very long, and the preservation of these stations has been poor. It was not until 1949 after the founding of the People's Republic of China that a systematic network of meteorological stations was formally and systematically established and operated, which gradually formed China's current meteorological observatory network (Wu, 2007, and Table 2 in this paper)

2.1.2 China's regional climate data problems

The development of the station networks discussed above has also resulted in a series of problems in China's long-term air temperature observation data.

1) Missing observations

Missing data are quite common for such a complex and variable observation network in China (Table 2). Different networks built by different units/colonial countries have different observational rules, some observations have not been properly stored and preserved, and in particular, China has experienced many years of internal and external warfare that halted the observations at many weather stations in the 1930s and the 1940s.

2) The uneven distribution of meteorological stations

Meteorological stations were first built in the eastern regions of China, and stations in some plateau and desert areas in the western regions of China (west to 105 ° E) were not evident until the 1920s. The earliest western meteorological observations were first conducted by Mr. Chen Yide in 1927 in Kunming (Figure 4) (although he started to collect scattered weather observations in 1911). As a result, the

"China SAT change series" established by many previous teams was actually only "the SAT change series in eastern China" for this period. Although the studies show that the series of temperature changes in the east and west are highly correlated and consistent (Cao et al., 2013; 2017; Li et al., 2017), from the physical point of view, these two series should still exhibit some differences. The eastern part of China is mainly located in the monsoon region; thus, the air temperature change in this region is dominated by the monsoon system. Conversely, the western part is mainly dominated by continental climate and areas such as the plateau and the desert account for large proportions of the western area. Therefore, another problem is raised, namely, the influence of sampling "biases" on the bias of the series in the sparsely populated stations (discussed in more detail later in section 2.2.2).

3) Data quality

We know that climate data are "second-hand meteorological data" that must be systematically quality-controlled and bias-adjusted before they can be applied to climate or climate change research. However, for many years, quality control and assurance have not been sufficiently conducted on historical climate data, which has led to some systematic biases and errors that are difficult to correct. On the other hand, no formal meteorological observation rules have been recorded which can be used as a guideline for the operations before 1950; thus, the meteorological stations lack unified management: the station locations are informally determined (in university campuses, towns, suburbs, mountains, etc.), meteorological instruments have no uniform standards, and the times of observations vary widely. As a result, very few long-term and complete station observational records or series are available for climatic use, and the integrity and homogeneity of climate data are difficult to guarantee. Taking the calculation of the daily mean temperature as an example, before the 1950s, the numbers of daily observations at the stations were very uneven. There could be two, three, four, six, seven, eight, twenty and twenty-four observations each day. Thus, there are differences in how daily average temperatures were calculated from the different observation times. For many stations, daily values calculated as averages of the observations at fixed hours are obviously lower than modern values calculated by averaging the maximum and minimum temperatures), but it is difficult to determine the differences between stations due to the lack of good comparative data (Yan et al., 2001; Li et al., 2010a; Li et al., 2018).

2.1.3 Climate data homogenization and climate datasets

Most decade-to-century-scale time series of atmospheric data have been adversely impacted by inhomogeneities caused, for example, by changes in instrumentation, station moves, changes in the local environment such as urbanization, or the introduction of different observing practices like a new formula for calculating mean daily temperature or different observation times (Peterson et al., 1998; Trewin, 2010). Although some individual researchers question the adjustment of the data inhomogeneity (e.g. Soon et al., 2018), data homogenization is necessary to determine the precise course of temperature change across China.

The People's Republic of China (PR China) built a new weather and climate observation system in 1951. The system includes National Reference Stations (NRS, 24 (every hour) manual observations each day), National Basic Stations (NBS, 4 (02, 08, 14, 20 Beijing Time (BT)) manual observations each day), and National Synoptic Stations (NSS, 3 (08, 14, 20 BT) manual observations each day). The numbers of different stations vary over time, with current numbers being approximately 140 for NRS, 685 for NBS, and 1650 for NSS, respectively. Approximately 78.2% of the NRS and NBS (a total of 825 in 2010) in the country have been relocated at least once over the last 60 years (Figure 5). Additionally, almost all the stations were changed to automated observations during the 2000s (Figure 6). All of the above changes heavily impact the data inhomogeneity over China. Studies have shown that inhomogeneity exists in many climatic elements in China since the beginning of the 20th Century (Liu and Li, 2003; Zhai and Eskridge, 1996; Yan et al., 2001).

Previous studies indicated that inhomogeneity exists in approximately 40% of the air temperature station series (Liu and Li, 2013; Li et al., 2004; Xu et al., 2013). Li et al. (2004a) attempted to make a systematically homogenized adjustment to the monthly air temperature data over China. In 2006, the China Meteorological Administration (CMA) released the first homogenized air temperature data set in China, CHHT1.0 (Li et al., 2009), and the updated version (daily temperature homogenization dataset) of the dataset was published in 2013 (Xu et al., 2013). Xu et al. (2013) also noted that the adjustments of the inhomogeneities were mostly due to station relocations and their automatic adjustments corrected for the positive and negative biases, respectively, over the last 60 years (see their Figure 3). Studies from universities and research institutes in China also began to recognize the importance of the homogeneity of air temperature data, and these experts also conducted research on the inhomogeneities of the climate series (Table 2; Feng et al., 2004; Yan and Jones, 2008; Li and Dong, 2009; Li and Yan, 2009; Li et al., 2010a; You et al., 2011; Li et al., 2015). From these studies, the air temperature data homogeneity since the 1950s has made the data more reliable, with the inhomogeneity problems of the station series mainly caused by the relocation of stations and changes in the daily average calculation methods. In addition, although there are large differences between the raw and adjusted series in some local areas, the air temperature change trends across all of China detected by all the datasets (including raw and homogenized ones) exhibited few differences.

The homogeneity of air temperature data before the 1950s is much more complicated, mainly because it is difficult to find suitable reference series for the detection of the homogeneity of the station series and the lack of detailed metadata. Since changes in observation times before the 1950s are difficult to address, many studies have used monthly mean maximum and minimum temperature observations. Most meteorological stations in China began to observe the elements of maximum and minimum temperature from the early 20th century. Therefore, when building a century-scale temperature series, the arithmetic mean of the daily maximum and minimum temperature is generally used as the daily mean temperature (Tang and Ren, 2005; Li et al., 2010a). This agrees well with the common practice for the existing global baseline climate datasets (Jones et al., 1999; Lawrimore, 2011).

From the previous results (Li et al., 2017), the Chinese regional air temperature series based on homogenized datasets show very good agreement with each other, and this series is significantly different from the series constructed from the inhomogeneous data (Li et al., 2017); that is to say, the inhomogeneity in climate data is a very important factor that leads to substantial differences in different series. Figure 7 further indicates the differences between the average air temperature in China calculated with raw and homogenized data. The differences exist mainly in the first half of the last century, as previously stated, and overall, the homogenization slightly increased the century-time-series trends by 0.014 deg C/decade.

2.2 Methodology of building regional SAT change series

2.2.1 Spatial interpolation or gridding method

When studying global or large regional climate change series, climate data are often first gridded to ensure that each grid series represents the same/similar local areas; thus, the calculated regional average series is more representative. The five global land baseline datasets mentioned in section 1 are no exception, but the mathematical methods used are different (Table 4).

The method adopted by Jones et al. (1986) (as well as Xu et al., 2018) is the climate anomaly method (CAM), whose basic idea is to calculate the average of climate anomalies. Hansen and Lebedeff (1987)'s RSM (reference station method) selects the station with the longest series in a larger grid as a reference station and calculates the distance weighted average of all stations at each time to form the grid series. Peterson and Vose (1997) proposed a first-difference method (FDM) that makes use of all station data (series of any lengths) as much as possible. Regardless of which method is used, the resulting global/hemispherical land temperature changes are similar (IPCC, 2001; 2007; 2013) mainly because all three methods have similar features: they all use a fixed-grid approach that takes the latitude and longitude of the grid, in which the gridded series are represented by weighted averages of station series in the grid. Even if there are some local differences, they will not lead to large-scale differences after the calculation of global/hemispheric averages (Jones et al., 1997; Rennie et al., 2013). Rohde et al. (2013) used a geostatistical method (kriging) to grid the station data and developed a new global series incorporating the reliability of the station data. However, their final result was also consistent with the other four series.

For the average of the regional air temperature series in China, any one of the above methods or other methods may be used. For practical applications, 5 of the 7 Chinese time series data set (Table 1) adopted the CAM method. The advantage of this method is that the calculation is relatively simple, the physical meaning is obvious, and any errors will not be extrapolated beyond each grid box. However, 2 of the time series used a different approach: 1) WangS (Wang et al., 1998) is based on a hybrid "complete" regional air temperature dataset and series. They divided China into 16 climatic regions and, instead of using a uniform gridding method, interpolated missing values for some regional series in western China with proxy data (information from tree rings and also ice cores). Finally, they calculated the area weights for each region to produce the national series; 2) Wang et al. (2014) directly used the "optimal unbiased" sampling method to directly calculate the regional average of the temperature anomalies across the country without gridding. From a practical point of comparison, interpolation or gridding does not seem to be the main reason that leads to substantial differences between the methods.

2.2.2 Correction of sampling biases in early data

As mentioned earlier, the missing climate data in China in the early 20th century (especially in the western areas) may affect the establishment of the Chinese average SAT change series. When developing an average air temperature series over a region, we generally give an "optimal estimate" and an "uncertainty range". From this perspective, it seems that the missing early data coverage only influences the "magnitude of the uncertainty" without affecting its "optimal estimate" (Jones et al, 1997; Brohan et al., 2006; Li et al., 2010a). Additionally, large-scale averaging at the hemispheric level further favours the elimination of this bias (Jones, 2016)

Therefore, the key point at sub-continental scales is that it is necessary to "correct" the biased distribution of samples in the station series. According to Figure 2, one of the most obvious differences among several Chinese air temperature series is the anomalies during the 1940s (warm episode) and 1910s (cold episode). According to Li et al. (2010a, their Figure 1), during the 1910s and 1940s, the density of the observation stations is relatively low, and almost all of the stations are located in eastern China (there were approximately 50 stations in the 1910s and station numbers reached approximately 200 in the 1940s). There were some sites in the west, but during the 1940s, many observations at stations (especially for some eastern stations where the cities were involved in the war) were missing or irregular in China due to World War II. In other words, the observed temperatures during the 1910s and 1940s are based on relatively small numbers of and the observed temperatures during the 1910s and 1940s are based on unevenly distributed station data, so their reliability can naturally be questioned. If we assume that the temperature anomalies in these areas are consistently (overwhelmingly) high/low, then the higher/lower temperature anomalies will certainly be reflected throughout the national series, and an abnormal "high"/"low” temperature period is not surprising.

To solve this problem, the sampling biases of the temperature series must be "corrected". A number of methods have been developed. These are discussed for China by Wang et al. (2014) and Li et al. (2017) and for the global and hemispheric averages by Cowtan and Way (2014), Simmons et al. (2016), Huang et al. (2017a) and Xu et al. (2018).

The issues discussed in this section are illustrated in Figure 8. Further, Li et al. (2017) compared the Chinese regional average series reconstructed (sampling biases corrected) with a homogenized dataset with the historical simulation output of 43

CMIP5 models (Taylor et al., 2012) and found that the output of CMIP5 can basically reproduce the inter-decadal mean air temperature and the long-term trend of the regional average temperature in China from 1900 to 2005. The correlation coefficient between the mean observational air temperature series and the ensemble mean series of the eight "best" models reached 0.81. The consistency of this physical (model) and observation enhances the confidence of both.

3. Impact of urbanization on air temperature observations and temperature change series

3.1 Urbanization in China and its research indicators

3.1.1 The overall situation of urbanization in China

From 1978 to 2014, the urban population of China increased from 170 million to 750 million, the urbanization rate (defined as urban resident population *100%/total national population) exhibited an average increase of approximately 1% per year, and the number of the cities increased from 193 to 653 (based on 4 indicators: population, Regional economy, Urban Resources and Environment Infrastructure and Regional Basic Public Services); moreover, the urban built-up area increased from 7,000 square kilometres in 1981 to 49,000 square kilometres in 2015 (from "China national new urbanization report 2015"). Although the rate of urbanization in China is impressive, as indicated by the total population or urbanization rate index, if we just consider the total area of built-up regions, it accounts for only approximately 0.5% of the total land area (see Wang et al., 2015a), which is still very low (Figure 1). Figure 1 shows the urban areas indicated by Defense Meteorological Satellite Program / Operational Linescan System (DMSP/OLS) nigh time light data in 2013 (On average, most of China's regional night time light index reaches 40 (western China) to 63 in urban areas since 1990s (Wang et al., 2013)).

3.1.2 Urbanization studies undertaken around the world

Many studies of the influence of urbanization on surface air temperatures have been undertaken around the world, but the specifics of how urbanized areas are measured (e.g. areas, population etc.) is very particular to the country being studied. In this paper, we will emphasize the extensive previous studies that are specific to China. Studies undertaken in other countries are less relevant, but bringing results together from other countries indicates that the overall urbanization effect is small (e.g. Hausfather et al., 2013 for the United States, and a number of global-scale studies undertaken by Parker, 2004, 2010a and 2010b).

3.1.3 Meteorological stations or regional urbanization indicators

The effect of urbanization for China has generally been defined as the difference between the trends of air temperature changes in urban areas compared to those in the surrounding countryside. Three approaches have been used to estimate these differences: the first is the direct use of the difference of air temperature series between urban and rural (reference) stations (e.g., Li et al. 2004b; Ren et, al., 2007; Hua et al., 2008; Yang et al., 2011; Li et al., 2013; Wang et al., 2015); the second is the use of the difference between station observations and reanalysis data (e.g., Kalnay and Cai, 2003; Zhou et al., 2004; Zhang et al., 2005; Wang, J., et al., 2013);

the third is the use of the differences derived from air temperature observations compared with reference data (such as radiosonde, SST, and satellite remote sensing observations) (Jones et al., 2008; Huang, et al., 2004).

All three approaches provide a measure of the effect from the series differences. The expectation is that the urban series will have undergone increases compared to rural/reanalysis/other temperatures. These different approaches lead to a range of results depending on the method used and particularly on the period of reanalysis. For example, the second approach (observation minus analysis data, i.e. OMR) requires that 1) the reanalysis data are good enough to represent the regional air temperature changes; 2) the corresponding reanalysis system did not assimilate any surface air temperature data during the development of the reanalysis datasets; and 3) the period of overlap is long enough. The third approach (observation minus other reference data) has similar requirements: 1) the reference data are representative of the regional air temperature changes; 2) the reference data themselves are not affected by the urban heat island effect. In general, the latter two approaches are mainly used to estimate the effect of urbanization where it is believed that nearby rural station locations might also be affected by urbanization via advection of air from the warm cities.

For the first approach, the key aspect is to determine the stations that are to be classified as urban or rural stations. There are three types of data/metadata for the station urbanization indices: 1) the government census data on the city population (resident population of the city where the observation station is located), and metadata including the location of the station in the city or the surrounding environment (Li et al., 2004b; 2010b); 2) DMSP/OLS urban night light data from satellite observations (the specific methods for determining whether a site is affected by urbanization can be found in the literature (Yang et al., 2011); 3) Moderate Resolution Imaging Spectroradiometer (MODIS) satellite observations of the ground classification (urban and buildings grouped into a category). With the 740 national reference/standard stations used by Li et al. (2004b), there is considerable uncertainty regarding the use of different metadata and urbanization/station classification methods (Table 5), although regardless of the method, approximately 35-40% of the stations are classified as urban stations, but only 144 urban stations (<20%) were simultaneously judged this way by all three measures. Obviously, according to the different classification criteria, the contribution rate of urbanization to regional air temperature change is likely to be different. Based on all three classification criteria, Chu et al. (2016) found that the positive contribution of urbanization in the southeast region of China (including the Yangtze River and South China regions) to the warming of the regional air temperature passed the significance test, but there were no clear positive contributions in other regions.

3.2 Influence of urbanization on local air temperature change

With all urbanization studies using instrumental air temperature data, analyses compare local station temperatures and then scale-up to larger regional or national averages. The key factor in this scaling up, is the link between the larger-scale urban influence and the local influence at single or multiple station(s). In an extreme case, for example, how representative is the estimate of urbanization at a single site (e.g. Beijing) of the national average for China?

Li et al. (2004b) conducted a statistical analysis of the temperature series for several climatic regions in China and found that the observed temperatures at urban stations in each region were significantly higher than those from surrounding reference stations. However, the standard deviations of the temperature changes at urban stations were less than those at rural stations and there was uncertainty regarding the trend of air temperature variations (due to the large number of stations throughout the nation, many of which are much less affected than larger cities) (Li et al., 2004b, their Table 2 and Figure 3).

To determine the impact of urbanization on local air temperature trends in China, other scientists conducted additional research and analyses: Ren et al. (2007) showed that Wuhan’s and Beijing's urbanization contributed to more than 60% and 80%, respectively, of the warming from 1961-2000; Lin and Yu (2005) indicated that the warming rate of urban heat island intensity over the last 40 years was 0.31 degC/decade, even exceeding the overall natural warming rate of 0.25 degC/decade. However, Yan et al. (2008) re-evaluated Beijing's urbanization based on homogenized air temperature data and found that its contribution to the local warming was less than 40%. Fan et al. (2005) noted that the average temperature increase in Guangzhou during the period from 1973-2003 due to urban development was approximately 0.4 °C, which is equivalent to approximately 33% of the urban warming; moreover, the authors noted that data inhomogeneity may have had an impact on the estimation results. Li et al. (2005) evaluated the contribution of urbanization in Shenzhen from 1951 to 2001 using homogenized air temperature data, and the result was approximately 60%.

This brief summary highlights differences between studies, some of which are due to different approaches, but also different periods of analysis. It is important therefore, to either combine results from many studies, or analyse results from greater numbers of stations and use common periods. Another conclusion from this summary is that the homogenization of air temperature data is very important for the study of the effect and contribution of urbanization to air temperature change. This result is reflected in many studies (Ren et al., 2007; Yan et al., 2008). Finally, from the above analysis, urbanization has indeed obviously affected the increase in local air temperature change in many cities.

3.3 Impact of urbanization on regional air temperature changes

3.3.1 Observational analysis

There is little doubt regarding the impact of urbanization on global surface air temperature datasets. Changes in air temperature discussed in previous International Panel for Climate Change (IPCC) scientific assessments (IPCC, 2001; 2007) have consistently noted that the warming trend contribution from global urbanization since 1900 does not exceed 0.006 degC/decade in global land surface air temperature change. IPCC (2013) also noted that this effect is even smaller at the global scale when the land data are combined with SST estimates from the much greater area of ocean that covers Earth's surface. These conclusions come from the research results of many scientists from the combination of different approaches (Jones et al., 1990; Easterling et al., 1997; Peterson, 2003, 2005; Parker, 2004, 2010a, 2010b). Also as noted earlier, these results have been confirmed by more recent studies (e.g. Hausfather et al., 2013) for the United States.

However, there may be differences in the research on the contribution of regional climate change in China due to the differences in data and processing methods. Studies across China can be roughly divided into two categories: the first category mainly focuses on how much influence the urban stations have on the average air temperature trend in a certain region, such as the studies by Li et al. (2004b; 2010b) and Hua et al. (2008). Their conclusions indicate that the urbanization effect is small or negligible. For example, Li et al. (2004) used the urban population and the location of the stations to separate the NBS/NCS networks into sets of urban and rural stations, the air temperature data were homogenized, and the air temperature change features for the whole country were divided into five sub-regions. A principal component weighting method was used to establish the temperature series for each sub-region, and then the differences between all stations and references (with urban stations removed) were calculated as the effect of urbanization on the regional air temperature series. The results show that the urbanization effect on the regional average temperature series is significant only in South China and the Yangtze River valley, but the overall contribution is still less than 5% of the warming during 1954-2001.

The second category mainly focuses on the difference in the air temperature series between urban stations and rural/non-urban stations in specific regions (mainly by averaging the earlier local urbanization impacts in section 3.2 in these areas).The latter method tends to yield larger results (Zhao et al., 1991; Ren et al., 2007; 2008; Yang et al., 2011; Li et al., 2013). The difference relates to how representative the more local studies (involving rural/urban pairs) are of the whole area of China. Li et al. (2013) also showed that in East China, the conclusion that urbanization leads to local air temperature warming is location specific and has considerable uncertainty. Wang et al. (2015) further assigned the weighting of urbanization area (bearing mind that China’s built-up area is only 0.5% of the total land area of the country, Figure 1) and recalculated the average air temperature series for China. Their conclusion again shows that the contribution of urbanization to the warming trend in China is negligible. It also shows that regional air temperature series in China calculated by the average of the principal component weights for each climate region (Li et al., 2004b) is closest to the area-weighted average.

3.3.2 Additional discussion of urbanization effects and links to larger scales

In recent years, the physical mechanisms of the impact of urbanization on regional climate change has also made some advances. Based on the recognition that "the urban heat island occurs mainly at night and the phenomenon of urban heat island will decrease when wind speeds increase", Parker (2004) found no significant difference in surface air temperature between windy and windless nights. For the Chinese region, there has been much discussion that most of the national reference/standard meteorological stations are located in urban areas, so current evaluations could indicate that the urbanization impact could be larger (e.g. Wang et al., 2009; Ren et al., 2014). However, Li et al. (2010b) noted that the use of more rural sites (selected from approximately 1700 ordinary climate stations) does not change the temperature trend in China over the past 50 years. Taking northern China (Northeast and North China) as a typical representative region, the authors note that the air temperature changes in the region over the past decades have been characterized by a statistically significant regime shift (the shift times are in the late 1980s and the late 1990s), which explains nearly 50% of the contribution of regional warming; it is theoretically difficult to explain that this kind of sudden change is connected to the influence of gradual urbanization. More recently, using global climate indices, Zhao et al. (2014) analysed the primary causes of warming in eastern China, and they suggest that more than 80% of the warming contribution can be explained by large-scale climatic indices such as the tropical Indian Ocean SST and the Siberian Atmospheric Circulation System. A recommendation of this review, could be that studies of the effects of urbanization on air temperatures, should additionally analyse data where the effects of large-scale climate influences have been removed.

4. SAT variations in China and their comparisons with global SAT change during the recent 100 years

4.1 Mean Anomalies, 1900-2017

The Chinese and global mean land surface air temperature anomalies since 1900 are compared in Figure 9 based on the C-LSAT analysis of meteorological station data (Xu et al., 2018). In both China and globally, land surface air temperatures rose from the 1910s to the 1940s, fell slightly between the 1940s and the middle or the end of the 1960s, and rose again after that. However, the amplitudes of the increases/decreases in China are greater than those of the global land temperatures. There are also differences between the two series during the extremely warm years. In China, 2017 was the warmest year (1.52 °C), followed by 2007 (1.52°C), 2016 (1.49 °C), 2015(1.48 °C), 1998 (1.37 °C), in descending order. Globally, the 5 warmest land temperature anomalies during 1900-2017 occurred during 2016 (1.30 °C), 2017 (1.27 °C), 2015 (1.19 °C), 2007 (0.97 °C), 2010 (0.97 °C) according to C-LSAT. The warmest year in China before 1950 was 1946, but globally it was 1938 for global land SAT, which shows that the early warming in the last century in China lasted longer than it did globally, and the cooling occurred later in China.

4.2 Warming rate (long-term trend)

Table 6 gives the rates of change for all 7 Chinese series discussed in Table 1 and Figure 2, as well as the global series for C-LSAT. Trends are calculated over 6 periods: 1900-2017, 1909-1950, 1951-2006, 1979-2006 and 1998-2017, although not all series can be extended to 2017. Warming rates for the ‘China’ averages from Li et al. (2010a), CRUTEM4 and GHCN3 for 1900 to 2017 were 0.127degC/decade, 0.130 degC/decade and 0.114 degC/decade. From 1951 to 2006, the national average temperature warming rates were 0.224 degC/decade, 0.244 degC/decade and 0.217 degC/decade, showing good consistency. However, it is worth mentioning that there are still uncertainties regarding the recent trends from 1998-2017. The extended series of Li et al. (2010a) and the Chinese components of CRUTEM4 and GHCN3 are 0.181 degC/decade, 0.096 degC/decade and 0.063 degC/decade, respectively. These differences are mainly due to the possible limitations of CRUTEM4 and GHCN3 with data collection in China in recent years (fewer stations, later data updating and homogenization), and it should be noted that only the trend from the extended series of Li et al. (2010a) for this short period passed the 5% significance test. Table 6 also shows that the greater differences in the evaluations of air temperature change trends are mainly concentrated in the 1900s-1950s, which is due to fewer stations and inhomogeneities in the data discussed in Section 2.

For global scales, warming trends are lower than those at the China regional scale in all periods except for 1998-2017, when the global SAT continued to increase at a rate similar to that in 1951-2017, while the increase in the China SAT slowed and exhibited broader 95% uncertainty ranges (Table 6).

Trend studies at the seasonal scale are rare, mainly because some groups did not provide seasonal-scale averages. According to Wang et al. (2009), the average seasonal anomalies since 1880 are given by 71 stations in eastern China. According to their data analysis, air temperature has been increasing in all seasons since 1880, but there are some differences between the seasons. Winter, spring, summer and autumn warming rates were 0.152 degC/decade, 0.088 degC/decade, 0.044 degC/decade and 0.086 degC/decade, respectively. More recently, Li et al. (2010a) compared the four seasons and the annual average temperatures. Generally speaking, the warming trends in winter (0.140 degC/decade) and spring (0.110 degC/decade) since 1900 are larger than the warming trends in summer (0.040 degC/decade) and autumn (0.070 degC/decade) and are similar to those presented in Wang Shaowu et al. (2009). Li et al. (2010a) further showed that the greatest warming since 1954 occurred in winter (0.350 degC/decade), then spring (0.250 degC/decade) and autumn (0.220 degC/decade) and the lowest warming occurred in summer (0.160 degC/decade); warming rates in the four seasons since 1979 were greatest in winter (0.50 degC/decade), spring (0.520 degC/decade) and autumn (0.500 degC/decade), but they were slightly slower in summer (0.370 degC/decade). The least warming in summer may be related to the long-term trends of the East Asian summer monsoon and winter monsoon (Guo et al., 2004; Wang et al., 2010; Ding et al., 2014).

The emphasis here has been entirely on LSAT data for China. In Figure 10, we show global LSAT series from C-LSAT, CRUTEM4 and GHCN3, while in Figure 11, we combine C-LSAT with ERSSTv5 data for the oceans (Huang et al., 2017b). Combining with marine data dampens individual annual extremes, emphasising more the long-term warming trend, and reducing the effect of the cooling between the 1940s and the 1970s (Li et al., 2019; Yun et al., 2019).

4.3 Two relative “warmer” periods in China before and after the 1950s

The characteristics of the Chinese air temperature changes since 1900, as reflected in most of the series (as evident in Figure 2), are as follows: a decreasing period during approximately the first 10 years of the 20th century and then a warming lasting until the mid-to-late 1940s and then a slight cooling until approximately 1970. Thereafter, the temperature increases rapidly until the recent "slowdown of warming” period (1998- now) (the Third National Assessment Report on Climate Change, 2015; Li et al., 2015; Xie et al., 2016). Thus there are two relatively warm periods since 1900: 1940s, and the recent 20 years (1998-now).

Nearly all Chinese series show that 1946 was the warmest year before the 1950s, but the anomaly was highest in Tang and Ren (2005), followed by Wang et al. (1998), and the anomalies in Li et al. (2010a), Wang et al. (2014), CRUTEM3, and GHCN are slightly lower but similar to each other (see 2.2.2). Of the seven series, Wang et al. (1998) showed higher air temperature anomalies in the 1910s than those in the other series, and these results agree with Tang and Ren (2005) until approximately 1930, when these two series were approximately 0.3-0.4 °C higher than the others before reaching agreement after 1951 (Li et al., 2010a). These differences are likely related to their use of the proxies in western China before the 1950s (Soon et al., 2018). Improved analyses show that the 1940s were not as warm as suggested by Wang S.

(1990), and that they were clearly cooler than the warmth in China during the last two decades (1998-2017). Figure 2 does show a slowdown in warming in China during these two decades compared to the rate of warming between the early 1970s and 2000 (see also Table 6). Figure 12 shows that globally there are large variations in spatial patterns of air temperature change during the relatively short period of 1997 to 2012. The shortness of the period means that few of the trends in Figure 12 are statistically significant.

Research on the regional "slowdown of warming" in China has also received wide spread attention (Li et al., 2015; Duan and Xiao, 2015; Liao et al., 2015; An et al., 2016; Zhou and Wang, 2016). According to Li et al. (2015), the average air temperature in China has increased by 0.304 degC/decade over the past 60 years (1961-2017). However, from 1998 to 2017, the average air temperature trend reached 0.181 degC/decade across China, with 95% range uncertainties of ±0.13 degC/decade (Table 6). These features in the China average since 1998 are also reflected in the lower warming in the CRUTEM4 and GHCN3 datasets (Table 6), but as noted earlier none of the three trends are statistically significant. It is clear, though, that this warming rate is slower than global air temperature warming for the same period. However, on a seasonal scale, the “slowdown of warming” in China has obvious unique characteristics (Li et al., 2015) due to the contrast between the lack of warming in summer in contrast to the stronger warming in winter.

5. Discussions and conclusion

With the continuous collection of temperature data and the improvement of data quality control and assurance technology and spatiotemporal analysis methods, the series of global/hemispheric land surface air temperature (global surface temperature) changes given by different researchers and climate change research institutes have become quite consistent. However, there are still some uncertainties in the study of SAT changes at regional scales. In particular, the regional differentiation of SAT change trends in recent decades has attracted increasing attention (Cowtan and Way, 2014; Karl et al., 2015; Xu et al., 2018). The demand for accurately estimating the magnitude of climate change at a regional scale is increasing every day. China is a large country with an area comparable to that of a continent and its histories of changes in its meteorological observations are complicated. Thus, in some ways it is a typical region for conducting this type of analysis. This paper summarizes the processes and experiences of establishing a series of air temperature changes at the continental scale and estimating the magnitude of climate change (Figure 13) and unravelling all the issues of developing a series of regional temperature changes in China since the beginning of the 20th century. It is noteworthy that this process is similar to the establishment of a global series of temperature changes, but there are some specific issues (the bold red text in Figure 13) that are unique or require special emphasis when evaluating series of regional temperature changes.

A complete high-quality observational climate dataset is a key foundation for establishing a regional air temperature series, but this is not available everywhere across China. Due to the relocation of station sites, improvements in instruments, changes in statistical calculation methods and changes in observational operations, inhomogeneities of climatic series and observational errors result in the fact that climate datasets are often "polluted" by a wide range of data, and it is difficult to obtain data with high "integrity". The station series cannot cover a large number of climate-critical areas at the same time point/time period. Much work has had to be undertaken by scientists to ensure that the data they use are suitable for their use during the development of a regional climate change series and for an accurate analysis of the magnitude of climate change. Spatial and temporal analysis of technical methods is another factor that may affect regional climate series. Different methods (e.g. CAM, FDM, RSM, kriging, etc., see section 2.2.1) have their own advantages and disadvantages for the global temperature series. However, for regional air temperature series, it is very important to combine the characteristics and shortcomings of the dataset itself, and it is very important to adopt appropriate methods.

Climate observations and the verification of physical climate processes are increasingly important. Over recent times, scientists have begun to rely heavily on atmospheric reanalysis data mainly because of their lack of missing values, gridded structure, full geographical coverage, and the number of physical variables that are interrelated. However, there are still many gaps in the simulation of surface climate with weather/climate models. Various reanalysis data still have many problems in assimilating all the integrated observational data. As a result, considerable issues could be introduced when these reanalysis or model output data are used in climate change research topics (see e.g. Parker, 2016; Hoffman et al., 2017). Due to these issues, the detection of climate change still relies on high-quality meteorological observations. However, due to these many problems, high-quality "climate data products" can only be realized in some countries and continents. Current "climate data products" can be developed only as a single element dataset (such as air temperature or precipitation) and this can lead to some uncertainties. It is particularly important to consider the physical coherence of different climate elements.

The average air temperature series for China is of great significance for understanding the trend of SAT change and the overall climate trends in this region. Due to the significant data inhomogeneity and sampling biases in the pre-1950s data, there were large differences among the series obtained by various teams since the 1980s. In particular, the warm bias in the 1940s is mainly due to the inhomogeneity of the climatic series, while the better homogenization of climate data greatly reduces this bias. Urbanization issues exhibit certain impacts on the temperature at many local cities or some regional areas; however, the impact on the national average air temperature series in China is relatively small, mainly because the overall proportion of urban areas is very small and its weight is very low when calculating the average of large-scale areas. When considering urbanization, it is important to not just use common periods but to also consider the removal of the impacts of circulation features known to significantly impact Chinese temperatures (see e.g. Zhao et al., 2014).

Based on the new temperature series obtained by means of homogenized data and sampling bias corrections, the latest air temperature change trend in China over the 1900-2017 period (using the C-LSAT dataset) has been estimated to be 0.121 degC/decade. Similar trends have been produced by CRUTEM4 and GHCN3 using markedly fewer station series. Seasonally, warming since 1900 or since 1950 has been greatest in winter, slightly less in spring than autumn, and least in summer.

Conflict of Interest File

The authors have no conflicts of interest.

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Tables Captions:

TABLE 1. Seven centennial-scale temperature change series across China

TABLE 2. Meteorological observation networks developed across China before 1950

TABLE 3. The homogenization across the whole Chinese network after 1950

TABLE 4. The spatial interpolation or gridding methods used by the 5 global land SAT series

TABLE 5. Classification of the 740 national reference/standard stations by 3 classification criteria

TABLE 6. Comparisons between seven series in China and globally of the century-scale SAT change trends (degC/decade)

Table 1. Seven centennial-scale temperature change series across China

Series	Data coverage	Quality control	Mean temperature	Calculation method for regional series	References
WangS	Observations from CMA and proxy data	—	The arithmetic average of fixed observations (the times were different)	Sub-regional series by arithmetic means of single series and national series by area weighting average from 10 regional series	Wang et al. (1998)
Tang	Observations from CMA	—	The arithmetic average of Tx and Tn	Gridding then calculating the regional series by the climate anomaly method (CAM)	Tang and Ren (2006)
Li	Same as above	Homogenized station series	Same as above	CAM	Li et al. (2010a)
WangJ	Same as above	Same as above	Same as above	BSHADE-MSN, which considers prior knowledge of geographical spatial autocorrelation and nonhomogeneity of target domains, remedies the biased sample and maximizes an objective function for the best linear unbiased estimation of the regional mean quantity	Wang et al. (2014)
CRUTEM4	Temperature data CRU collected and processed	Same as above	Same as above	CAM	Jones et al. (2012)
GNCN-M3	Temperature data NOAA/NCEI collected and processed	Same as above	Same as above	CAM	Lawrimore et al. (2011)
Cao	Observations from CMA (16 stations in eastern China)	Same as above	Same as above	Arithmetic mean	Cao et al. (2013)

Table 2. Meteorological observation networks developed across China before 1950

Institution	Foreign institutions			Domestic institutions					
	Missionary	Colonial Countries	Customs	Qing Government	Beiyang Government	The People‘s Republic of China	College/Civilian	Military/ Aviation	JiefangQu Government
Overview of the Network	Beijing (1841-1914), Shanghai (1872-1950) Num.>80 (established during the 1920s-1940s)	Hong Kong (1884-1950), Qingdao (1898-1950) Num.>100 (70+ stations have more than 30 years of observations)	Num.>70 (beginning in 1869, 46 of them have more than 30 years of observations). Including Taiwan (stopped in 1895)	Numbers unknown. Start in 1903. Nonstandard, and the data are not effectively preserved	Began in 1913, 26 stations in total, stopped in the 1920s	Began in 1929. 29 stations in 1941, 52 in 1946, 93 in 1948, and 69 in 1949	College: more than 30 stations; Nantong (~1916), Kunming (~1911)	Began in 1939 with 16 stations, 165 stations in 1943. Core network during Anti-Japanese War, but the data are not effectively preserved	Began in 1945, 232 stations in 1949

Table 3. The homogenization across the whole Chinese network after 1950

Duration	Number of stations	Detection method	Adjustment method	Reference
1951-2004	731, All basic and reference stations	Two-phase Regression (TPR)	Monthly mean differences adjustment	Li et al. (2004); Easterling and Peterson (1995) Li et al. (2009)
1951-2000	731, All basic and reference stations	Standard Normalize Homogenization Test	Monthly mean differences adjustment	Feng et al. (2004)
1960-2008	549, Basic and reference stations	Multiple Analysis of Series for Homogenization (MASH)	MASH	Li and Yan (2009)
1961-2003	303, Basic and reference stations	Revised TPR (RHTest software by Wang (2008))	Monthly mean differences adjustment	You et al. (2011) Wang (2008)
1951-2011	825, All basic and reference stations	Revised TPR (RHTest software by Wang (2008))	Quantile Matching (QM) adjustment on daily series.	Xu et al. (2013) Wang (2008
1961-2011	545, Basic and reference stations	MASH	MASH	Li et al. (2015)
1951-2013	2419, All national stations	Same with Xu et al. (2013)	Same with Xu et al. (2013)	Cao et al. (2016)

Table 4. The spatial interpolation or gridding methods used by the 5 global land SAT series

Dataset	Duration	Gridding method	Reference
CRUTEM4	1851-present	CAM	Jones et al., 2012
C-LSAT	1900-present	CAM	Xu et al., 2018
GHCN-M3	1880-present	FDM & CAM	Lawrimore et al., 2011
GISSTemp	1880-present	RSM	Hassen et al., 2010
BEST	1753-present	Kriging	Rohde et al., 2013

Table 5. Classification of the 740 national reference/standard stations by 3 classification criteria

	Night-time light	Population & metadata	MODIS
Urban station	289	260	266
Rural station	451	480	474

Table 6. Comparisons between seven series in China and globally of the century-scale SAT change trends (degC/decade)

		1900-2017	1909-1950	1951-2006	1909-2006	1979-2006	1998-2017
China	Li	0.127±0.009	0.124±0.027	0.224±0.025	0.113±0.011	0.471±0.063	0.181±0.13
	WangJ	/	0.161±0.033	0.221±0.028	0.098±0.013	0.499±0.065	/
	WangS	/	0.246±0.035	0.209±0.027	0.049±0.015	0.443±0.069	/
	Tang&Ren	/	0.335±0.039	0.216±0.028	0.092±0.015	0.473±0.066	/
	CRUTEM4	0.130±0.009	0.191±0.031	0.244±0.026	0.123±0.012	0.475±0.063	0.096±0.14
	GHCN3	0.114±0.009	0.195±0.032	0.217±0.026	0.107±0.011	0.417±0.066	0.063±0.14
	Cao	/	0.168±0.044	0.283±0.034	0.142±0.015	0.548±0.078	/
Global (C-LSAT)		0.108±0.006	0.104±0.020	0.170±0.017	0.0930±0.008	0.308±0.038	0.252±0.058

Figures Captions:

FIG. 1. Location map of China, with night time lightness to show the urbanization level (with 11 regional center cities in China highlighted).

FIG. 2. Seven temperature change series in China over the last century collected for this study.

FIG. 3. Shanghai Xujiahui Observatory (left) and temperature observation shutter box (right)

FIG. 4. The meteorological observation diary from 1930 at the Chen Yide private weather station.

FIG. 5. The ratios and numbers of NCS and NBS relocations

FIG. 6. The numbers of stations that changed to automated observations in the recent 10 years

FIG. 7. The differences of the SAT series between the average air temperature across China with homogenized and non- homogenized data

FIG. 8. Analysis of the causes of warmer (higher anomalies) in China from the 1910s to 1940s

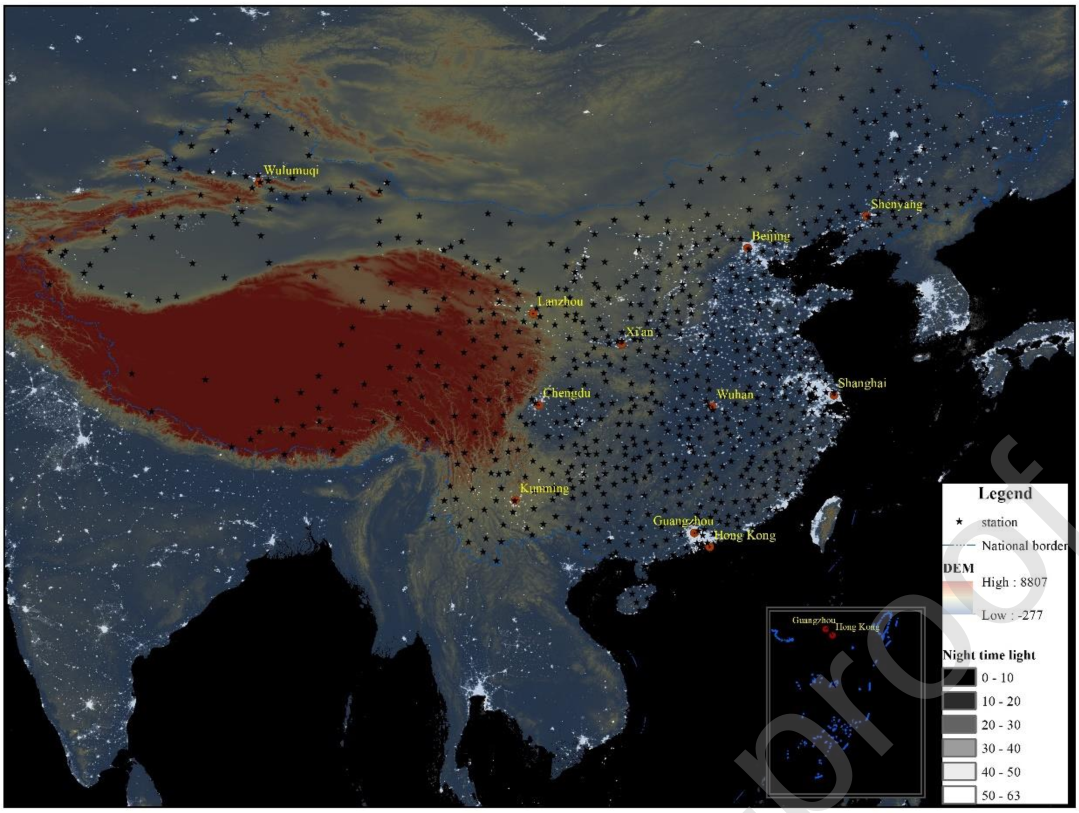
FIG. 9. Annual and 5-year running-mean SAT for China (left panel); global annual and 5-year running-mean SAT based on the meteorological stations (right panel; based on the C-LSAT, Xu et al., 2018) (SAT anomalies calculated relative to the 1961-1990 mean)

FIG. 10. Three global series of surface air temperature changes from 1900 to 2017

FIG. 11. The global series of surface temperature changes from 1900 to 2017 (based on CLSAT and ERSSTv5)

FIG. 12. 1997-2012 trends from Xu et al. (2018)

FIG. 13. Process for estimating continental-scale SAT change series and climate change trends



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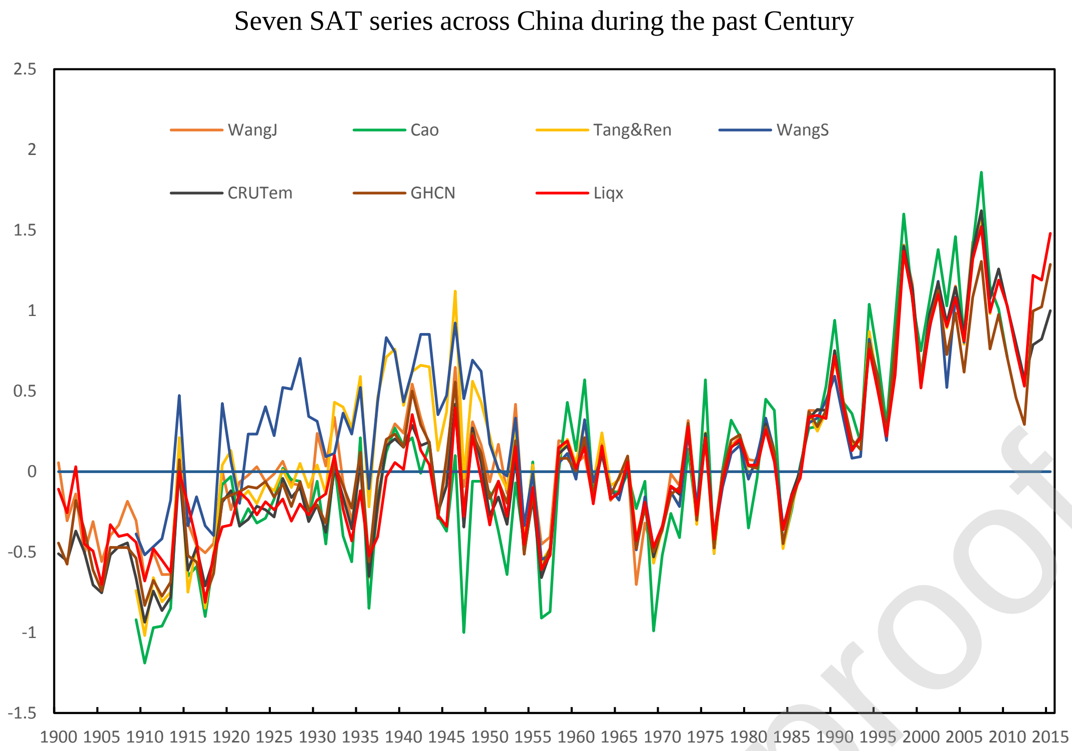

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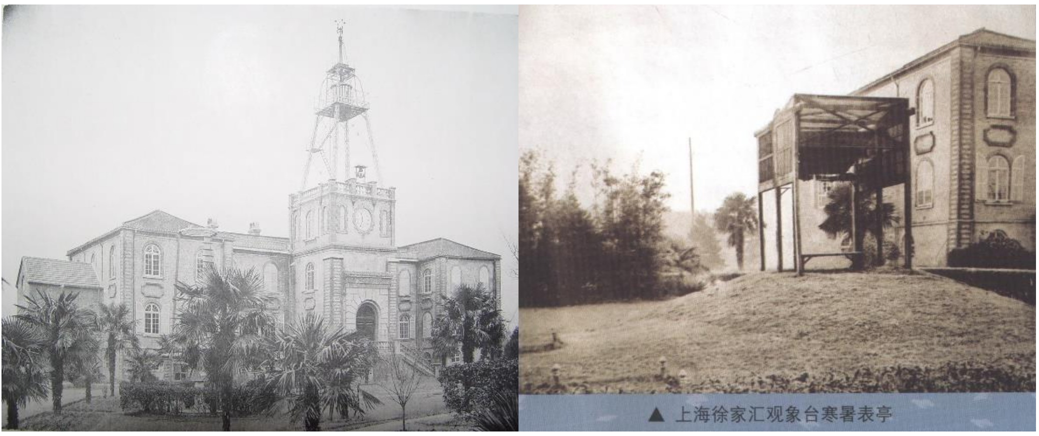

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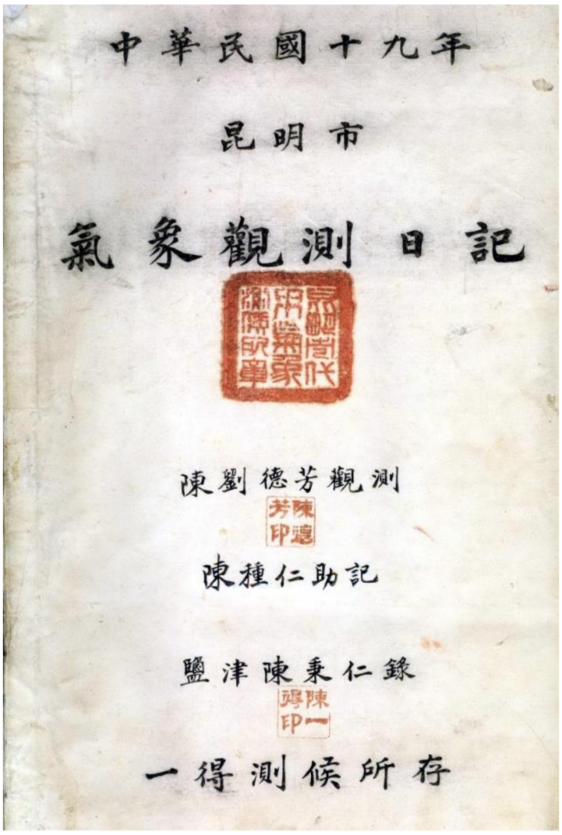


中華民國十九年

昆明市

氣象觀測日記

陳劉德芳觀測

陳德芳印

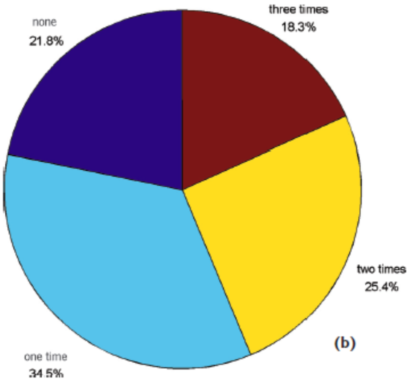
陳種仁助記

鹽津陳秉仁錄

陳一得印

一得測候所存

Figure 4. The meteorological observation diary from 1930 at the Chen Yide private weather station



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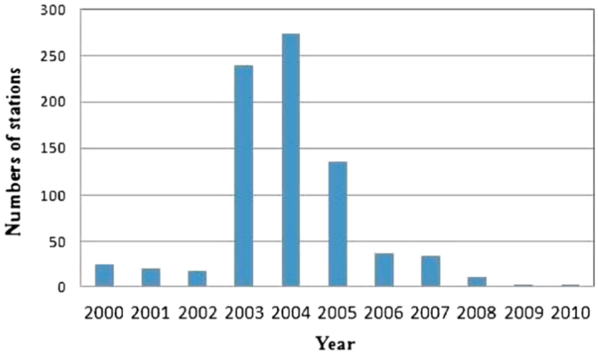

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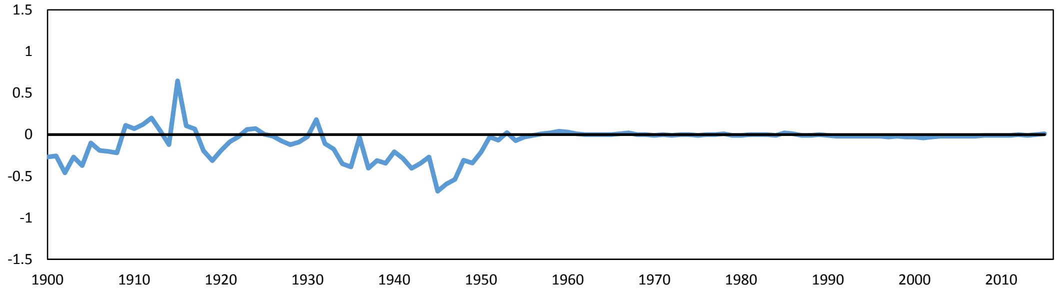

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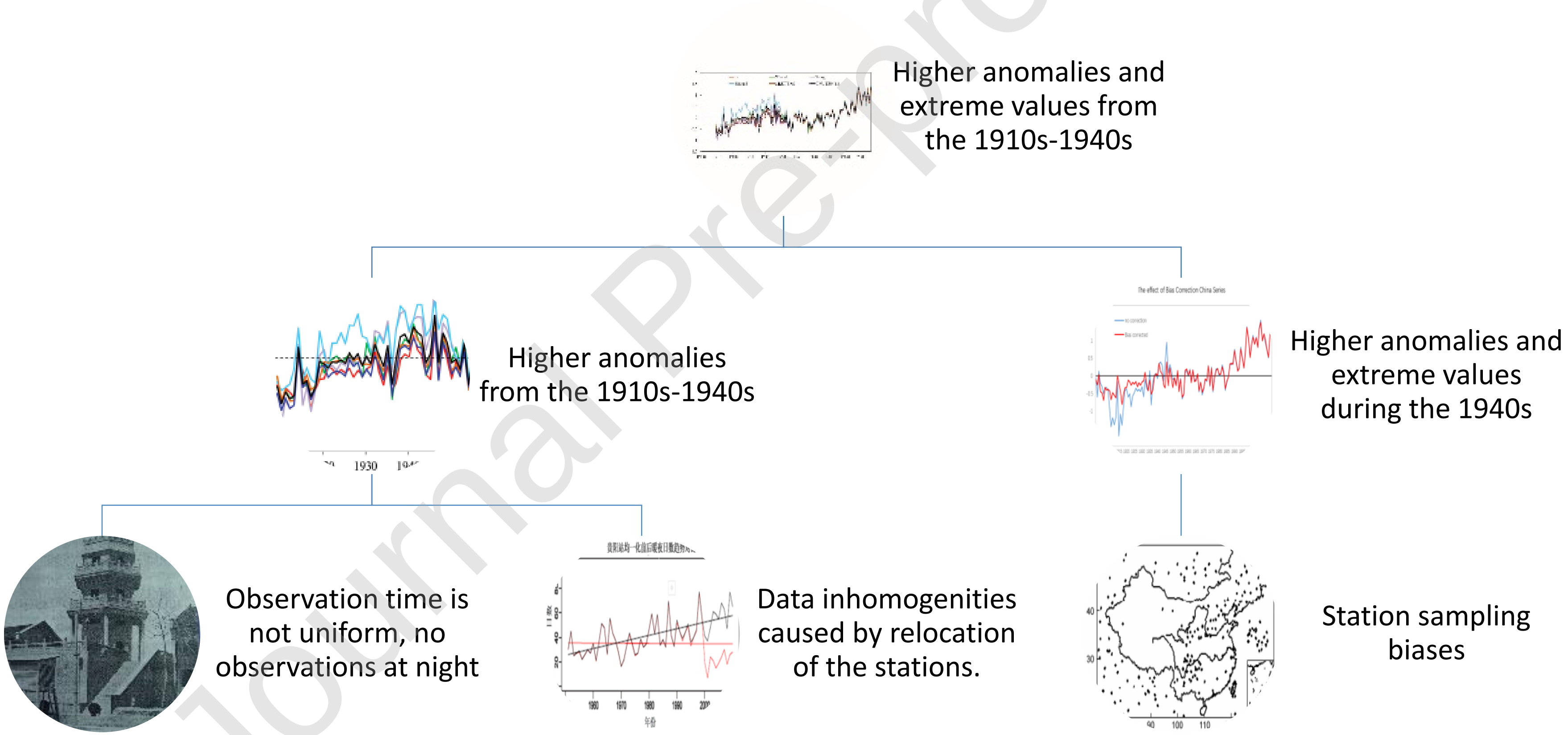

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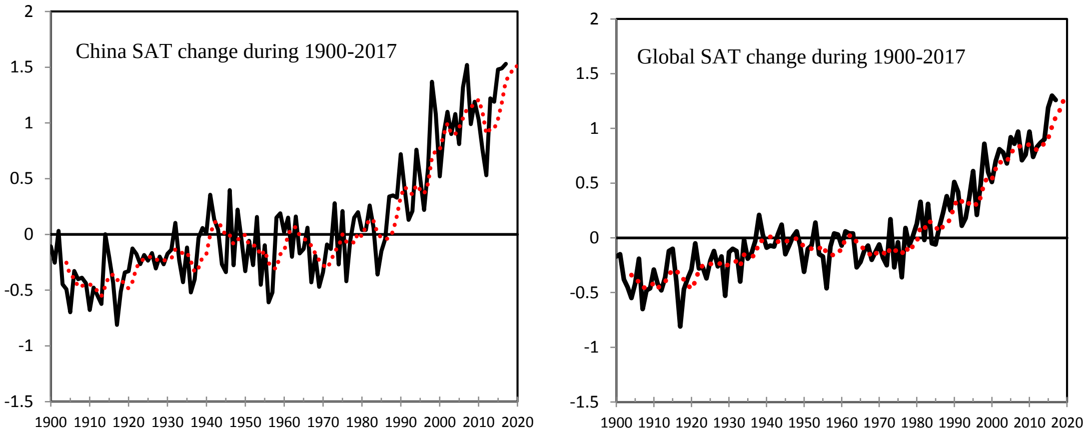

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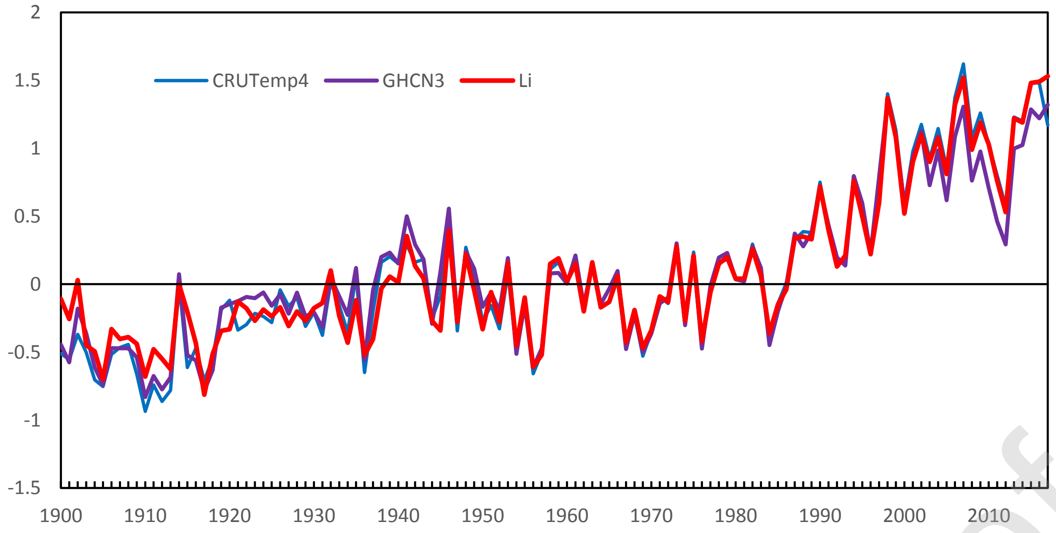

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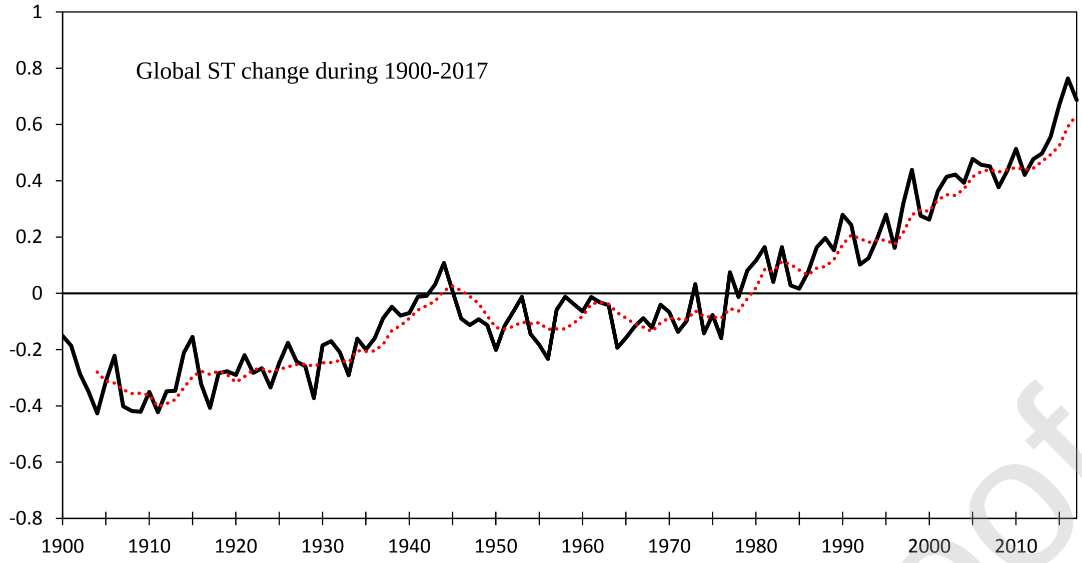
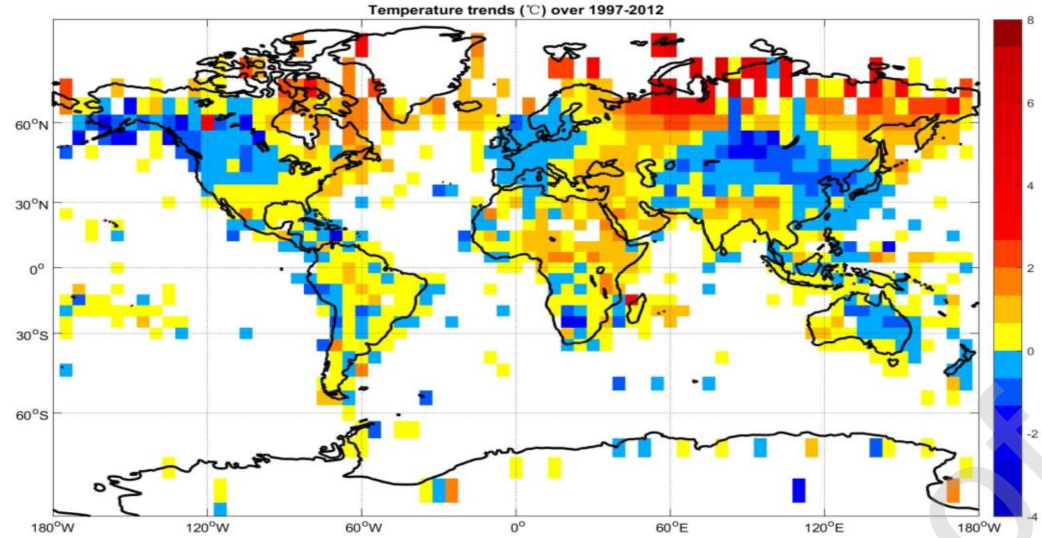


Figure 11. The global series of surface temperature (ST) changes anomalies (relative to 1961-1990 mean) from 1900 to 2017 (based on CMST, Yun et al.(2019))



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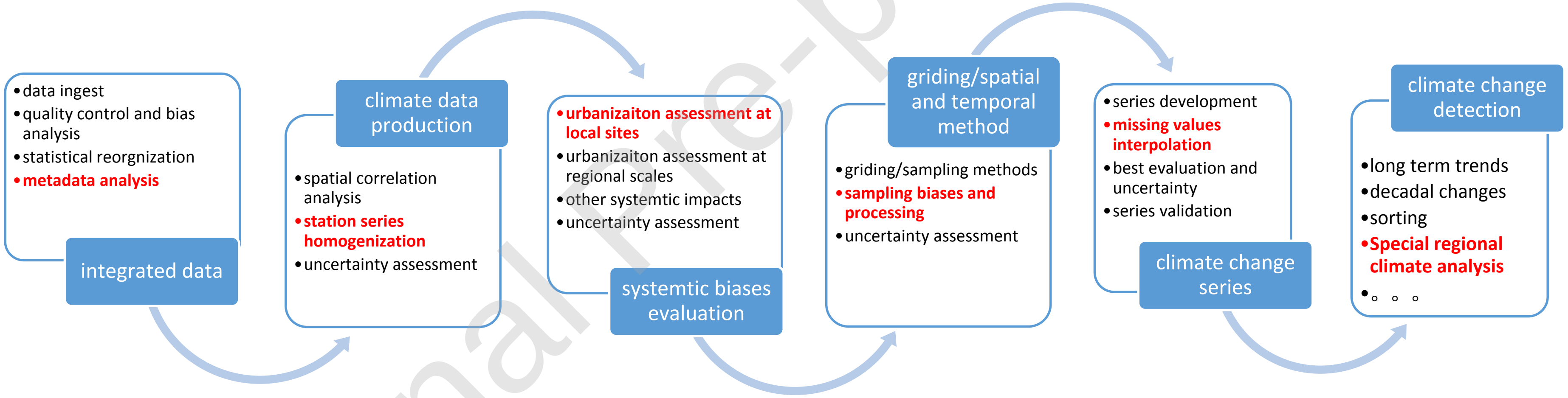

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