地学雑誌　Journal of Geography (Chigaku Zasshi)　134 (4) 379–399 2025　doi:10.5026/jgeography.134.379

Progress and Uncertainty in Studies of Contemporary Land Climate Warming Rate: From Globe to Region

Guoyu REN[1) 2)], Xiubao SUN[3)], Panfeng ZHANG[1) 4)], Kangmin WEN[5) 6)], Suonam Kealdrup TYSA[1) 7)], Yulian LIU[8)], Siqi ZHANG[1) 2)], Jiajun HE[1)], Yun QIN[1) 2)], Kum-Chol OM[1) 9)], Xiang ZHENG[1)], Yuyu REN[2)], Siqi HUANG[1) 2)] and Lei ZHANG[10)]

[Received 3 November, 2023; Accepted 27 August, 2024]

Abstract

Contemporary land surface air temperature (SAT) change rate is a key issue in studies of climate change or global change. This article reviews the research progress on global land and regional climate warming rates, with a focus on the main results and findings of our own research group in the last two decades. It also discusses uncertainties and scientific questions currently facing researchers in this field and prospects for future research directions. Global land, Asian, Chinese, and smaller regional scale studies have consistently shown significant warming of surface climate over the past century, especially over the past half century. However, there is significant uncertainty in the existing researches regarding the magnitude and rate of the warming. The biggest uncertainty comes from the urbanization bias in the observation data series, followed by the heterogeneity of data spatial coverage and its change over time, and the maximum and minimum temperature average method in calculating daily, monthly and annual mean SAT. These issues need to be further investigated in future in order to obtain more solid and reliable research conclusions.

Key words: progress, surface air temperature, climate warming rate, global land, Asia, China mainland, modern time, data, uncertainty, urbanization bias

1) Department of Atmospheric Science, School of Environmental Studies, China University of Geosciences (CUG), Wuhan 430074, China
2) Laboratory for Climate Studies, National Climate Center, China Meteorological Administration (CMA), Beijing 100081, China
3) State Key Laboratory of Tropical Oceanography, South China Sea Institute of Oceanology, Chinese Academy of Sciences (CAS), Guangzhou 510301, China
4) College of Tourism and Geographical Sciences, Jilin Normal University, Siping 136000, China
5) Fuzhou Meteorological Bureau, Fuzhou 350028, China
6) Fujian Institute of Meteorological Sciences, Fuzhou 350028, China
7) State Key Laboratory of Plateau Ecology and Agriculture, Qinghai University, Xining 810000, China
8) Heilongjiang Climate Center, Heilongjiang Province Metrological Bureau, Harbin 150000, China
9) Department of Meteorology, Faculty of Global Environmental Science, Kim Il Sung University, Pyongyang 999093, DPR Korea
10) Tianjin Meteorological Information Center, Tianjin Meteorological Bureau, Tianjin 300074, China

I. Introduction

Global and regional climate warming is the core issue of current climate change research. Since the early 1980s, extensive research has been conducted on the observational facts, causes, and impacts of climate change, and consensus has been reached on many scientific issues. The academic consensus is reflected in numerous assessment reports of international and national climate change and its impact (e.g., IPCC, 2021; Qin and Zhai, 2021).

Regarding the rate of air temperature rise or climate warming on the global land surface, studies have generally indicated that, since 1860 or 1880 (1900), the global average warming rate has been approximately 1.1°C (0.07–0.09°C/decade) (IPCC, 2021), and the warming rate in the United States is approximately 1.0 °C (0.07–0.08°C/decade) (USGCRP, 2018). The warming rate in Chinese mainland is about 1.5°C (0.12°C/decade) (Committee on National Climate Change Assessment, 2022; Wen *et al*., 2023); In the past half century, the global and various regions of the world have witnessed an accelerated rate of climate warming. For example, since 1960, the global land warming rate has reached 0.15°C/decade (IPCC, 2021), and the Chinese mainland has reached 0.25°C/decade (Committee on National Climate Change Assessment, 2022). The Arctic region has experienced a faster rate of warming in the past 40 years, resulting in the so-called "Arctic amplification" phenomenon (Sun *et al*., 2017a; IPCC, 2021).

However, there is still significant uncertainty in estimating the average rate of global land and regional climate warming. The main sources of uncertainty include three aspects: firstly, the early observation data had an uneven spatial coverage, with no observation records in most regions of the world's land, and the spatial coverage of observation data changed over time, resulting in bias in estimating the average warming rate (Brohan *et al*., 2006); secondly, most observation stations are located in or near cities, and the Surface Air Temperature (SAT) data series contains significant urbanization biases, resulting in higher estimates of warming rates (Ren *et al*., 2017); thirdly, many observation stations use daily maximum and minimum temperatures to calculate daily, monthly, and annual average temperatures, resulting in a positive bias in estimates of both annual average values and long-term trend (Liu *et al*., 2019). Most research groups are not fully aware of the importance of the systematic biases in the data.

This article reviews the research progress on global land and regional climate warming rates over the past 20 years, with a focus on the main results and findings of the China National Climate Center and the China University of Geosciences (Wuhan) research group on climate warming rates and their uncertainties in global land, Asia, East Asia, and China. There is greater uncertainty in early ocean surface temperature data (Kent *et al*., 2010), which has not been commented on in this article. This article also provides a review of the main issues currently facing research in this field and prospects for future research directions.

The so-called modern period refers to more than a hundred years since the late 19th or early 20th century (1860, 1880, or 1900). During this period, the spatial coverage and quality of ground meteorological observation data were slightly better. Regardless of which year of the above three years is chosen as the starting point, the estimated warming rates of global land or a large region over the hundred years and plus are basically consistent. The rate of climate warming, also known as the trend of climate warming, refers to the amplitude of the average SAT increase per unit of time, generally expressed as the average SAT increase every 10 years (°C/decade).

II. Longer than thundered year temperature series

The Industrial Revolution began in the mid-18th century. However, for over a hundred years from the mid-18th century to the mid-19th century, only a few locations in Europe, North

Table 1 IPCC AR5 and AR6 assessment results of global land surface air temperature trends during time periods since 1880. Unit: °C/decade. All trends are significant at the 99% confidence level (IPCC, 2013, 2021).

	Period	CRUTEM	GHCN	GISTEM	Berkeley	Average
AR5	1880–2012	0.086	0.094	0.095	0.094	0.092
AR6	1880–2020	0.102	0.113	0.106	0.107	0.107

America, and Asia had discontinuous meteorological observation records, resulting in significant uncertainty in estimating the global land and regional warming rates (Hawkins *et al*., 2017). Therefore, researchers generally choose to analyze the rate of large-scale climate warming over a hundred years since the late 19th century or early 20th century (1860, 1880, or 1900).

Since the early 1980s, four research groups have developed and maintained different global monthly average land SAT datasets (e.g., CRUTEM, GHCN, GISTEM, Berkeley Earth) (Hansen *et al*., 2010; Lawrimore *et al*., 2011; Jones *et al*., 2012; Vose *et al*., 2012; Rohde *et al*., 2013; Harris *et al*., 2014; Menne *et al*., 2018). These research groups provide global land and ocean surface temperature data series for various scientific assessments by the Intergovernmental Panel on Climate Change (IPCC). There are certain differences in the number of land observation sites included in each data product, but most long-series station data are shared and therefore they are not independent of each other.

All four sets of data series indicate a significant increase in global land annual mean SAT over the past 120–160 years. Between 1880 and 2012, for example, the global land annual mean SAT increasing trend given by IPCC AR5 ranged from 0.086°C/decade to 0.095°C/decade, with an average of 0.092°C/decade (IPCC, 2013); between 1880 and 2020, the assessment results of the IPCC AR6 ranged between 0.102°C/decade and 0.113°C/decade, with an average of 0.107 °C/decade (Table 1) (IPCC, 2021). All the increasing trends passed the 99% confidence test.

Among these four sets of data series, GHCN and Berkeley Earth generally give a larger warming rate, while CRUT typically obtains the smallest warming rate. This is mainly related to the GHCN's interpolation onto non-data areas and the Berkeley Earth's inclusion of more observation station data. Compared to other data, especially CRUT data, for example, Berkeley Earth includes shorter and more recent observations of the Arctic region. Due to the "Arctic amplification" effect since the 1990s (Sun *et al*., 2017a; Davy *et al*., 2018), the inclusion of these recent observational data in this dataset lead to an increase in the estimated global or northern hemisphere land average warming trend.

Table 1 also indicates that over time, and with updated information, the estimated SAT rising trend based on all datasets has significantly strengthed, with an average increase from 0.092°C/decade in 1880–2012 as reported in AR5 to 0.107°C/decade in 1880–2020 as reported in AR6. This acceleration of warming rate may have been primarily attributed to the culmination of the "global warming slowdown" in 2014–2015 and the afterward new phase of rapid warming.

China Meteorological Administration (CMA) has developed a new global land monthly mean SAT dataset (CMA GLSAT) (Ren *et al*., 2014; Sun *et al*., 2017a; Xu *et al*., 2018). The sources of the CMA GLSAT consist of three original global datasets and 11 regional datasets including those of the China Reference Climate Stations and National Basic Meteorological Stations and the historical datasets from other Asian countries. The dataset contains a total of 10,281 observational stations with length no less than 20 years for monthly mean temperature. The quality of the dataset has been controlled, and the inhomogenities in the data

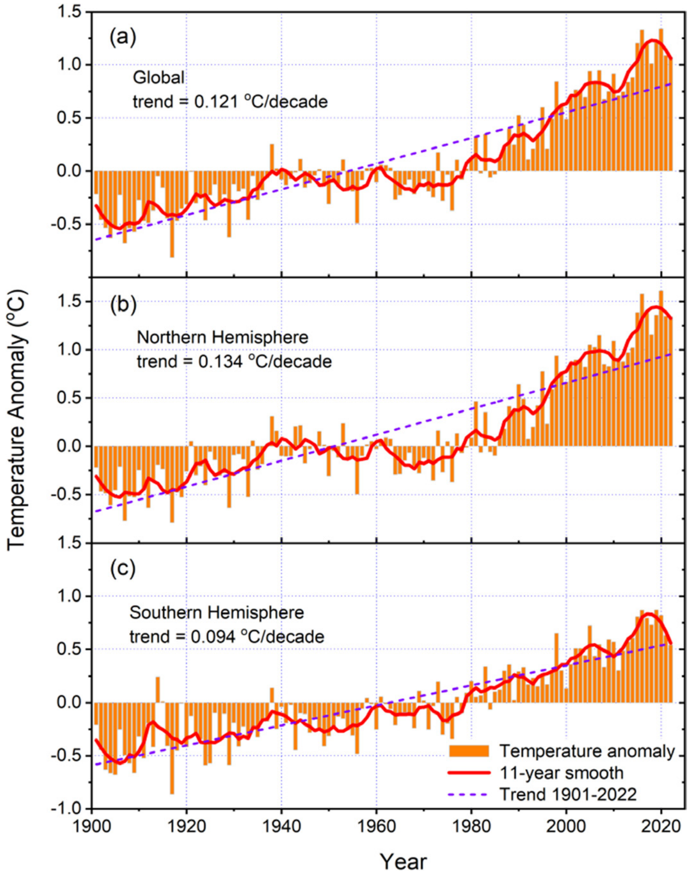

Fig. 1 Annual mean SAT anomaly time series for global land (a) and hemispheres (b NH, c SH) over 1901–2022. Red curve indicates 11-year moving average, and dashed purple line indicates linear trends. Modified and updated from Sun *et al*. (2017a).

series have been adjusted. More importantly, the spatial coverage of data has been improved, especially in regions of Canada, Europe, South America, Africa, and Asia.

Figure 1 shows the annual mean SAT anomaly time series for hemispheres and the global land over 1901–2022. The temperature anomaly curves bear extremely high similarity with those reported in IPCC reports (2013, 2021). The linear trends of annual mean SAT for SH, NH and the globe are 0.094°C/decade, 0.131 °C/decade and 0.119°C/decade respectively, all statistically significant at the 95% confidence level. The land warming beginning from the early 1980s is much more remarkable in the NH than in the SH. It is also clear that the global land mean SAT change to a large extent depends on that of the NH due to the far more grids in the NH than those in the SH.

Table 2 Linear trends of annual mean global land SAT for different temperature datasets (GHCN, CRUTEM, and CMA LSAT) during three different periods. Unit: °C/decade.

Period	GHCN-V4	CRUTEM5.0.1	CMA-LSAT V2
1901–2022	0.135*	0.113*	0.121*
1979–2022	0.331*	0.276*	0.281*
1998–2022	0.346	0.240	0.239

* The trends are significant at the 95% confidence level.

Table 2 compares the CMA GLSAT temperature trends with those of the GHCN and

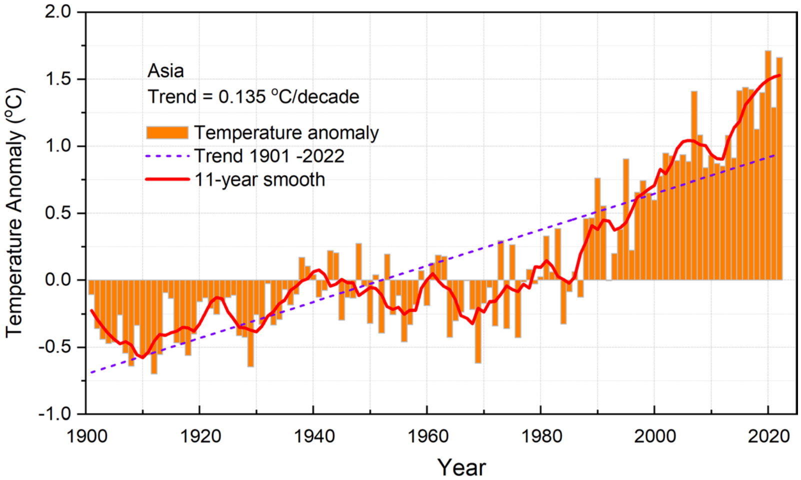

Fig. 2 Annual mean SAT anomaly time series for Asian region over 1901–2022. Dashed purple line indicates linear trends. Modified and updated from Sun *et al*. (2023).

CRUTEM during different periods. In most cases, the CMA GLSAT temperature trends are between those of two other datasets, but the 1998–2022 trend is the lowest among the three datasets. It is also intertesting to note that all of the trends during the warming slowdown are not significant, though the positive trends from all the datasets are prety large. The world may have still been in the global warming hiatus.

Figure 2 shows annual mean SAT anomaly time series in Asian region over 1901–2022. The annual mean land SAT over Asia increases significantly during 1901–2022, and the rising rate reaches 0.135°C/decade. Compared with the global and Northern Hemisphere, Asia experiences a more rapid warming. Similar to the Northern Hemisphere, the warming rate in Asia is stronger at higher latitude, with remarkable "Arctic Amplification" effect since 2000 (Sun *et al*., 2023; Ren *et al*., 2023). Seasonally, the climate warming of Asian continent is significantly stronger in winter than in summer. The long term annual mean SAT change in the Hindu Kush Himalayan (HKH) region is characterized by a significant increasing trend, but the largest increase in annual mean SAT occurred in the Tibetan Plateau and south of Pakistan (Ren and Shrestha, 2017; Ren *et al*., 2017).

The observation data series on the African continent have a shorter length and lower data quality, making it highly uncertain to conduct long-term temperature change research. However, existing analysis shows that the average annual mean SAT of the continent as a whole has also significantly increased over the past 120 years, with a rate of approximately 0.06 °C/decade based on the CMA GLSAT data (figure not shown), which is significantly weaker than the global average and the Asian continent. The climate warming in Africa has only occurred since the early 1980s, and there has been no significant SAT increase before. In the 120 years, the warming rate in northern and southern Africa has been almost consistent, but in the past half century, the warming in northern Africa has been more pronounced than in southern Africa (figure not shown).

The research team of China National Climate Center and China University of Geosciences (Wuhan) has developed a new set of long-term monthly SAT data set in China mainland (Wen *et al*., 2023). Compared with the previous dataset, this new dataset has added some early observation records and significantly improved spatial coverage. Analysis based on this dataset indicates that regional average annual mean SAT in China mainland rose by 0.14°C/decade

Table 3 IPCC AR5 and AR6 assessment results of global land surface air temperature trends during time periods since mid-20th century. Unit: °C/decade. All trends are significant at the 99% confidence level.

IPCC	Period	CRUTEM	GHCN	GISTEM	Berkeley	Average
AR5	1951–2012	0.176	0.197	0.188	0.175	0.184
AR6	1960–2020	0.250	0.257	0.260	0.252	0.255

over the period 1901–2022 ($p < 0.01$), slightly higher than the Asian average increase, and much higher than those in Africa and the Hindu Kush Himalayan region. Compared to the previous works (Tang and Ren, 2005; Ren *et al*., 2012), the homogenized SAT data series do not show a marked warm period in 1930s and 1940s, and the warming rate of the whole time period has become much larger than those reported in the early analyses (Tang and Ren, 2005; Ding *et al*., 2007; Ding and Ren, 2008; Ren *et al*., 2012). A main reason for the larger upward trend in SAT may have been related to the recovery of urbanization effect in the data series after homogenization (Ren *et al*., 2015, 2017). This issue will be further discussed in Section 4.

An analysis of SAT change over North Korea for the period 1918–2015 was conducted, based on an independent national dataset (Om *et al*., 2019). It shows a region-averaged annual warming rate of 0.21°C/yr for the period of 1918–2015 based on the data of four stations with long-term, complete and continuous records, and a trend of 0.19°C/yr for the period 1941–2015 based on the data from nine stations. In any condition, the warming rate in the region seems larger than those in Asia on a whole and in China mainland. The warming in the region mainly occurs after the 1970s, with winter experiencing the most rapid warming. During the period of global warming slowdown since 1998, no significant seasonal warming trend of wintertime was detectable.

III. Temperature series of the last six decades

Due to the scarcity of high-quality observations for over a hundred years, relatively continuous observations mainly occurred in countries and regions such as Europe, North America, Australia, and Japan before the mid-20th century. Therefore, many studies have focused on the decades since the mid-20th century. During this period, most parts of the world's land had relatively complete and continuous observation records. Another reason to pay attention to this period is that recent decades have also been a period of accelerated global warming, especially since the mid to late 1970s when the rate of climate warming has been exceptionally fast.

Using the four global land SAT datasets mentioned above, the IPCC also evaluated the warming trends since the mid-20th century. The evaluation result given by AR5 is that, during the period 1951 to 2012, the global average land surface air warming rate obtained from the four datasets ranged from 0.176°C/decade to 0.197°C/decade, with the smallest rate for Berkeley/CRUTEM and the largest for GHCN, and the average value of the datasets being 0.184°C/decade; The result given by AR6 is that, during the period of 1960 to 2020, the global average land surface air warming rates calculated by the four datasets were between 0.250 °C/decade and 0.260°C/decade, with CRUTEM still showing the smallest, but the maximum estimated value coming from GISTEM, with an average of 0.255°C/decade for the four datasets (Table 3).

Compared with the analysis results for the period longer than a century, the warming rate has significantly increased since the mid-20th century, approximately doubling, indicating that climate warming since the late 19th or early 20th century mainly occurred in the latter half of the thundered years, especially after

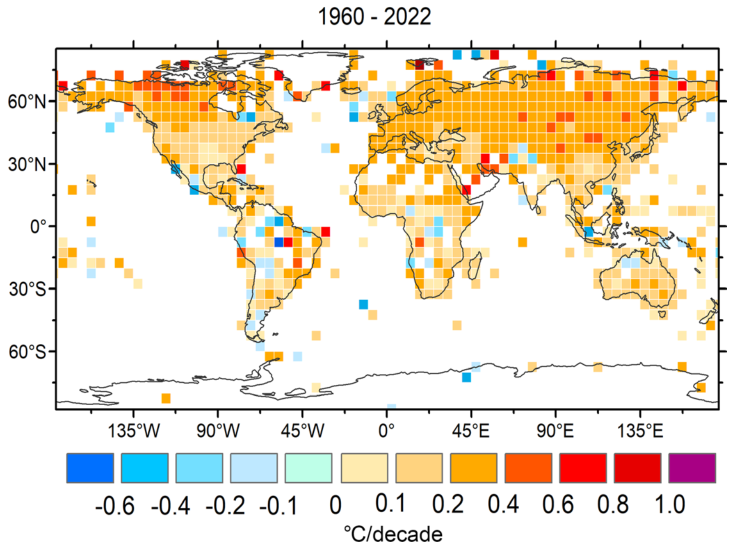

Fig. 3 Spatial distribution of annual mean SAT trends in global land over time period of 1960–2022 that has the relatively good spatial coverage of observational data. Modified and updated from Sun *et al*. (2017a).

the late 1970s. In the past 60 years, with the passage of time and data updates, there have been signs of an increase in the rate of global land climate warming, which is rather different from the analyses as reported before 2015–2020 when a sign of decreased warming rates was frequently shown.

Analysis based on CMA GLSAT data shows that, during the period from 1960 to 2022, the average global land warming rate was 0.240 °C/decade (Fig. 2), which is lower than that based on any of the four international datasets. The warming rate is most pronounced in the mid to high latitude regions of Eurasia and North America, with the Arctic region of the two continents experiencing particularly prominent warming. The warming trend in some areas of the southern hemisphere and islands in the central and western Pacific is relatively weak, and many grid points even show a decreasing trend in SAT (Fig. 3). In the past 60 years, the average warming rate of the southern hemispheric land has been much slower than that of the northern hemisphere.

Since the mid-1950s, the density of the observation network in China mainland has greatly increased, and the quality of observation data has significantly improved, which can be used to explore the detailed spatial and temporal structure of SAT changes. Since the early 1990s, Chinese scholars have conducted extensive research and gained preliminary understanding of the characteristics of climate change in the late 20th century (e.g., Lin and Yu, 1990; Li *et al*., 1990; Chen *et al*., 1991, 1998; Song, 1994; Ren and Zhou, 1994; Zhai and Ren, 1997; Wang *et al*., 2004; Qian and Lin, 2004; Hua *et al*., 2004; Ren *et al*., 2019). However, for a long time, researchers have not paid enough attention to issues such as data quality, inhomogenities, and urbanization bias, resulting in certain uncertainties in the research conclusions.

Several research groups have conducted research on the inhomogenities of air temperature data in China and established monthly and daily SAT datasets with varied numbers of observation stations (Li *et al*., 2004; Ding and Ren, 2008; Yan and Jones, 2008; Li and Yan, 2009; Xu *et al*., 2013; Cao *et al*., 2016; Ren *et al*., 2017, 2019). However, when using homogenized data obtained by different methods for long-term temperature trend analysis, there are still significant differences in the results (Venema *et al*., 2012). In addition, using any method, it is impossible to detect all breakpoints caused by non-climatic factors and make reasonable corrections.

Recently, He *et al*. (2023) applied multiple methods and metadata data to detect breakpoints in the maximum and minimum temperature data series of 662 meteorological stations in North China. It was found that the previously homogenized data series still had a large amount of breakpoints, and existing homogenized temperature products still had problems; they applied the quantitative matching (QM) method to correct the detected breakpoints and obtained new homogenized SAT data for the North China region. Based on the analysis of new data, it has been found that the estimated annual mean SAT increasing rate in the entire region is larger, with the minimum temperature being particularly evident, and the estimated Diurnal Temperature Range (DTR) decline trend is also larger than the previous analysis results.

Ren *et al*. (2005a) analyzed the spatial-temporal characteristics of SAT changes in China mainland over the past 50 years for the first time using the homogenized SAT data of the national reference climate station and basic meteorological station network. It was found that the regional average annual mean SAT rising rate reached 0.25°C/decade, which was generally higher than the previous analysis results, and was also far greater than the global and northern hemisphere land average warming levels at the same time. Later, the analysis based on homogenized data (e.g., Li and Yan, 2009; Ren *et al*., 2012; Cao *et al*., 2016) confirmed this conclusion. This large estimate of warming is not only related to the updated data, which includes the most significant warming in the 1990s, but also to the extent that data homogenization has restored the urbanization bias (Zhang *et al*., 2014; Ren *et al*., 2015).

Due to the fact that homogenization has not only failed to solve the problem of urbanization effect, but also to some extent restored this systematic bias, new requirements have been put forward for the study and correction of urbanization bias. This issue will be discussed in detail in Section 4.

At present, the first set of monthly SAT dataset of national reference climate stations and basic meteorological stations for urbanization-bias correction has been completed (Wen *et al*., 2019a, b). Using this dataset, the analysis of the change trend of SAT in China mainland from 1961 to 2015 shows that the annual mean warming rate of the whole country is 0.23 °C/decade, which is 20% lower than the analysis result based on the SAT data of homogenization only. The spatial distribution pattern of SAT rise has also undergone significant changes, mainly manifested by the emergence of large areas of climate cooling in central China and southern North China, and the significant reduction of the previously reported rapid warming area in North China and Northeast China (Fig. 4).

By using homogenization data or urbanization-bias correction data, the phenomenon of regional warming slowdown in northern and eastern China since 1998 can be detected in the regional average SAT (Li *et al*., 2015; Sun *et al*., 2017b; Wen *et al*., 2019b). For example, in Northeast China, the annual mean SAT consistently exhibits a cooling phenomenon in the period 1998–2014, with the annual mean trends of −0.28°C/10r and a strong contrast to the previous decades. The Northeast China warming slowdown occurred under the circulation background of the negative phase Arctic Oscillation (AO), and of the strengthened Siberia High and East Asian Trough (Sun *et al*., 2017b). Using data corrected for urbanization bias, it was found that the warming slowdown in northern and eastern China became more pronounced after 1998, and the range of regions experiencing cooling during this period expanded (Wen *et al*., 2019b).

IV. Systematic bias of observation data

There are still various errors and biases in the historical data of surface air temperature observation (Karl *et al*., 1994; Pielke *et al*., 2007; IPCC, 2013; Rao *et al*., 2018). The most

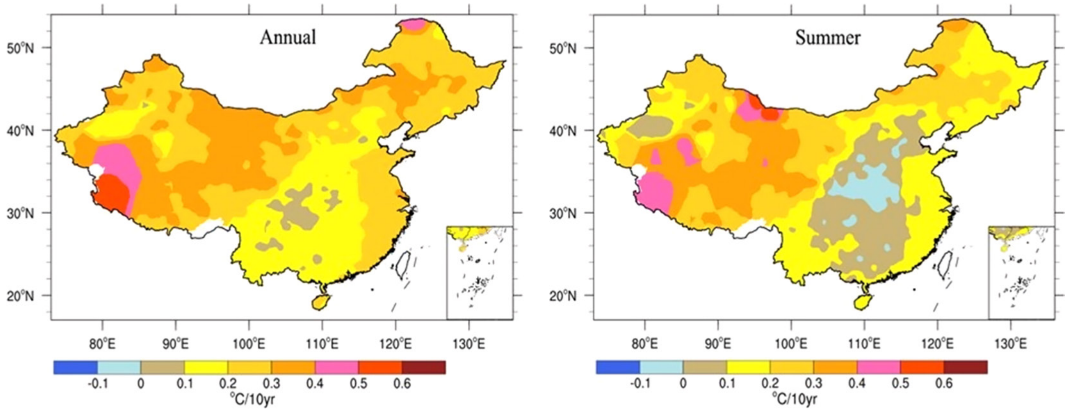

Fig. 4　Spatial distribution of annual and summer mean SAT trends in China mainland over 1961–2022. Modified and updated from Wen *et al*. (2019b).

important biases for climate change monitoring, detection, and attribution include inhomogenity, data spatial coverage bias, urbanization bias, and averaging method of maximum and minimum temperatures bias. Each of these biases can affect the accuracy of global land and regional SAT trend estimation, causing uncertainty in the analysis results.

1) Data inhomogenity

The inhomogenity in SAT data has always been valued in large-scale climate change research (e.g., Vincent *et al*., 2002; Li *et al*., 2004; Menne and Williams, 2009). Generally, inhomogenity is divided into two categories: the first category refers to data series breakpoints or step changes caused by station relocation, instrument replacement, and statistical method changes, and the second category refers to data series trend changes caused by changes in the surrounding environment of the observation station. The first type generally causes systematic bias for single station data series, but for a dense observation network average series, it often acts as a random error; The second type of inhomogenity is actually mainly caused by the impact of urbanization at different spatial scales around observation stations, and accordingly, should not be classified into inhomogenity (Ren *et al*., 2015). It is a systematic bias or urbanization bias for regional and global scale monitoring and research of climate change, and should be treated independently. For local change in climate, including urban climate change, on the other hand, it is an integral part of the entire change (Ren, 2015), and there is no need to remove or make adjustment.

In the first type of inhomogenity, at spatial scales larger than region or under the condition of dense station network, these breakpoints sometimes may act as a systematic error. They can lead to significant deviations in the estimation of regional average SAT trends in this case, and it is still necessary to make a treatment. However, the reasons for causing inhomogenity in various countries and regions are diverse, and the current homogenization methods are still being improved. No method is universally applicable, and no method can correct all breakpoints. Nevertheless, the impact of this type of inhomogenity on the estimation of large-scale (e.g., China mainland, Asia and global land) SAT trend is generally small and insignificant.

In North China, in-depth homogenization seems to increase the estimated value of regional warming trend, which may be due to the fact that the inhomogenities of SAT data in China mainland are mainly caused by station relocation (He *et al*., 2021). Moving stations from cities to suburbs will generally result in a series of cooling breakpoints (Ren *et al*., 2015); homogenization will restore homogeneity of the data series, but it has also restored the warming trend caused by urbanization (Zhang *et al*., 2014). Recently, using homogenized data, it has been found that the rate of annual mean SAT increase in China mainland over a century has been much higher than previously estimated (Cao *et al*., 2013; Wen *et al*., 2023), which should mainly be related to the urbanization bias in the temperature series of urban stations restored after data homogenization.

Regarding the traditional second type of inhomogenity, we suggest not including it in data inhomogenity. It can be collectively referred to as urbanization effect or urbanization bias. This issue will be discussed in the following section.

2) Urbanization effect

Urbanization bias is a progressively upward trend in SAT at observation stations due to changes in land cover and aerosols, as well as the increase in anthropogenic heat release, associated with urban development, near or around urban observation sites. This local warming trend is gradual and may not necessarily lead to breakpoint changes, but it is the main reason for overestimating the trend of regional and even global land SAT rise. Therefore, for large-scale climate change monitoring and research, the impact of urbanization is one of the most important systematic biases in the SAT data series of surface meteorological observation stations, and requires higher attention.

Over the past 20 years, research on urbanization bias in SAT data series has mainly come from developing countries and regions in Asia such as China. In China mainland alone, there are more than hundreds of relevant research papers, which have greatly improved the scientific understanding of the problem (e.g., Ren *et al*., 2005b, 2007, 2008, 2012, 2014, 2015; Chu and Ren, 2005; Hua *et al*., 2008; Zhang *et al*., 2010; Yang *et al*., 2011, 2013; Wang and Ge, 2012; He *et al*., 2013; Zhang *et al*., 2014; Sun *et al*., 2016; Tysa *et al*., 2019). According to the methods used, this research can be divided into five categories: urban-rural, observation-reanalysis, urban-mountainous (upper air), space for time method, and optimal fingerprint attribution. The urban-rural approach has been widely adopted due to the testability of assumptions and its simple, direct, and objective characteristics. According to this method, using rural station data selected based on objective criteria, most studies have shown that urbanization has had a significant impact on the estimation of SAT trends at national observation stations in China since the mid-20th century (e.g., Ren *et al*., 2005b, 2008, 2014; Chu and Ren, 2005; Hua *et al*., 2008; Ding and Ren, 2008; Zhang *et al*., 2010; Yang *et al*., 2011, 2013; Wang and Ge, 2012; He *et al*., 2013; Tysa *et al*., 2019).

Tysa *et al*. (2019) developed a new objective station classification method. Using U1 and U2 stations of the classification as rural stations, they evaluated the urbanization bias in different categries of national stations and different periods of SAT series. The results showed that, during 1960–2015, urbanization contributed more than 18% to the overall estimated SAT increase of all China's national stations (~2400), and the contribution to the overall warming estimates of the national reference climate station and basic meteorological station network (~800) is over 28% (Fig. 5). Due to the compromise made in the selection criteria for rural stations during the process, the rural stations used in this study and other studies based on the urban-rural method are not truly rural stations. Therefore, the urbanization effect (bias) and relative contribution values obtained from the analysis and other similar analyses are all conservative.

The urbanization effect on the estimation of SAT trends in other countries and regions in Asia is also significant. Korean research groups (Cho *et al*., 1988; Choi *et al*., 2003; Chung *et al*., 2004) found that there is a clear relationship between the warming trend of urban stations in South Korea and urbanization, with the increasing trend of minimum temperature being more affected. Studies in Japan found that urbanization has a significant impact on estimating the trend of SAT increase in Japan over the past hundred years (Japan Meteorological

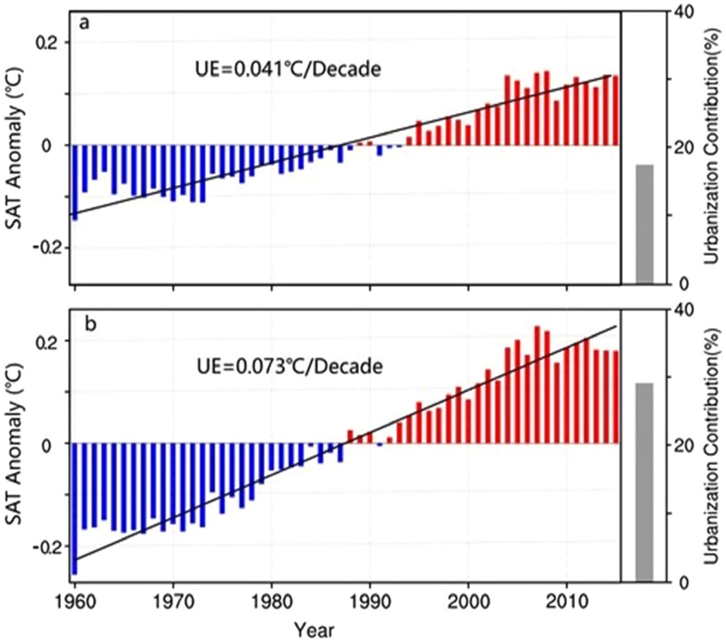

Fig. 5 Difference of annual mean SAT anomalies between national observation networks and rural stations (time series and its trend on left, which is equivalent to Urbanization Effect (UE)), and annual mean urbanization contributions (grey bar on right), in China mainland over period 1960–2015. a, all national stations; b, national reference climate stations and basic meteorological stations. Modified from Tysa *et al*. (2019).

Agency, 2008). Most station observations in Japan are difficult to be used for monitoring regional SAT changes (Das *et al*., 2011; Fujibe, 2009, 2011). In countries and regions such as South Afican, North Korea, Thailand, and the Philippines, it has also been found that there is a significant contribution of urbanization in the annual and seasonal mean SAT trends as estimated based on national observation datasets (Hughes and Balling, 1996; McKitrick and Michaels, 2004; Jongtanom *et al*., 2011; Om *et al*., 2021; Manalo *et al*., 2021).

On global scale, the academic community has long believed that there is no significant urbanization bias in the global land historical SAT data series (Jones *et al*., 1990; IPCC, 2013, 2021). Recently, Zhang *et al*. (2021) used location information of the National Climate Reference Network (CRN) stations in the United States as a reference, and applied machine learning methods to classify observation stations including rural stations, to evaluate the urbanization bias in the annual mean and extreme SAT index series based on the global land daily SAT dataset jointly developed by China University of Geosciences (Wuhan) and CMA. The results indicate that there are significant urbanization bias in the averaged annual mean SAT series of global land and East Asia over 1951–2018 (Fig. 6), while a weak urbanization effect has been detected in the North American continent during the same period. The urbanization contribution to the long-term trend of global average land annual mean SAT is 12.7%. This finding indicates that urbanization bias is not negligible in the current estimates of the global average land SAT trends.

As mentioned earlier, the homogenization of temperature data may not address the issue of urbanization bias. The existing homogenization methods have actually somewhat complicated or have restored this systematic bias. The case study in China shows that, in the case of inhomogeneities caused mainly by station

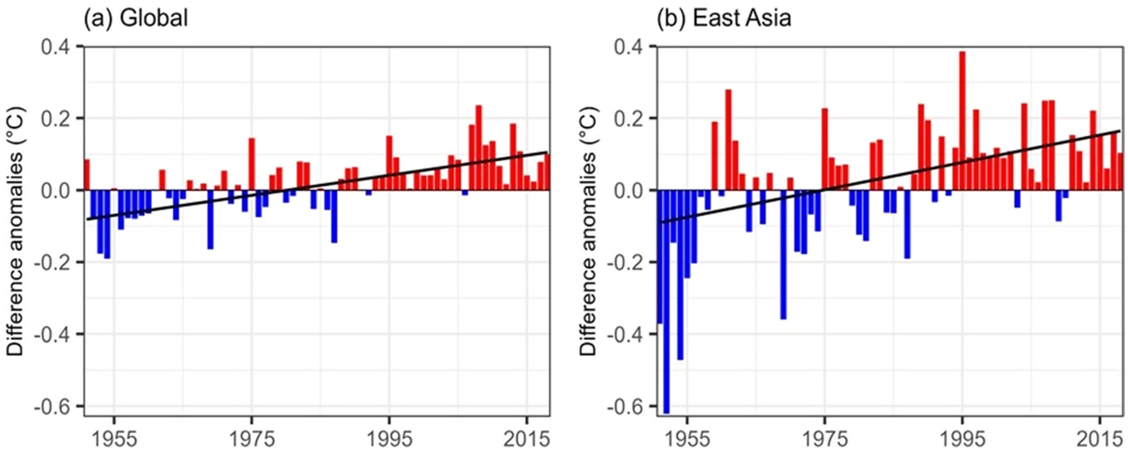

Fig. 6　Difference of global (a) and East Asia (b) land annual mean SAT anomalies between all stations and rural stations over 1951–2018. Modified from Zhang *et al*. (2021).

relocation, data homogenization significantly restores the positive trend of SAT series caused by urbanization, leading to an increase of the urbanization bias in the data series (Zhang *et al*., 2014; Ren *et al*., 2015; Li *et al*., 2014; He *et al*., 2021). In Europe, America, and other regions, the Menne and Williams (2009) method, or similar methods, is used to homogenize historical SAT data series. If the reference series does not use the average homogenized SAT data from rural stations, it may significantly mix the signal of urbanization effects of the regional observation stations with different urbanization levels (Blending effect or aliasing of trend bias) (Hausfather *et al*., 2012). This may have slowed down the urbanization warming of urban stations, while at the same time strengthened the urbanization warming of rural and small-city stations (Soon *et al*., 2018; Katata *et al*., 2023). Obviously, this issue needs to be addressed. In our opinion, the progressively increased urbanization bias caused by local human activities around the observation stations should not be corrected in the stage of SAT data homogenization if the representative rural sations have not been objectively determined for establishing reference data series.

For a long time, the publication review of urbanization bias in land SAT series by IPCC reports seems to be selective, and therefore has not shown sufficient objectivity and impartiality. AR5 acknowledged that, in areas with rapid urbanization, the urbanization effect in recent decades had been significant; AR6, on the other hand, completely ignored the significant urbanization bias found and confirmed by a large number of studies in rapidly developing regions such as China mainland. The conclusion reached in AR5 is: "it is likely that residual biases account for no larger than 10% of the warming trend globally and 25% regionally in rapidly developing regions"; while AR6 emphasized: "it is unlikely that any uncorrected effects from urbanization, or from changes in land use or land cover, have raised global surface air temperature trends on land by more than 10%, although larger signals have been identified in some specific regions, specifically rapidly urbanizing areas as such as Eastern China". These conclusions cannot be regarded accurate. From a global land perspective, since the mid-20th century, the urbanization bias is greater than 12% (Zhang *et al*., 2021); in the China mainland, in the past 50–60 years, the urbanization bias in the annual mean SAT series of the commonly used national reference climate stations and basic meteorological station networks is more than 28% (Ren *et al*., 2005b, 2014; Zhang *et al*., 2010; Tysa *et al*., 2019).

3) Spatial coverage of observation data

The spatial distribution of observational data and its changes over time will have an impact on the estimation of regional and global average land SAT trends (Cowtan and Way, 2014). The existing high-quality SAT observation data are mostly distributed in parts of Europe, North America, Australia, and East Asia (Sun *et al*., 2017a, c). The extent to which observation data in these regions can represent the global land is still an open question. Taking CRUTEM as an example, from the late 19th century to the early 20th century, the number of grid points with observational data accounted for less than 20% of the total number of grid points on global land, indicating that most grid points did not have data. Due to the spatial heterogeneity and significant spatial pattern of natural climate variability at multiple decadal scale and warming trends caused by human activities, the uneven spatial coverage of data undoubtedly leads to a bias in the estimation of global land warming trends (Karl *et al*., 1994; IPCC, 2013). If solid evidence cannot be provided to indicate that less than 20% of the land area can effectively represent global land SAT change and variability, the uncertainty in estimating global land air temperature trends caused by incomplete data spatial coverage cannot be ignored.

What makes this problem even more complex is that the spatial distribution patterns of observation and data coverage are not fixed and may change over time. Although this change also follows a certain pattern, such as expanding from developed regions including Europe and America to developing regions, or from low latitudes to poles in the ocean, if combined with large-scale low-frequency natural climate variability modes, it will certainly cause bias in the estimation of global land SAT change trends.

One example is that, in existing global land SAT datasets, some do not have strict regulations on the time length and age distribution of observation series, adding into the datasets a lot of high latitude land, island, and ocean surface water temperature observation data from the past decade to four decades, or adding satellite remote sensing surface temperature data in the Arctic region where observation stations are scarce. In this case, due to the Arctic region experiencing faster warming than other regions in the past 30 years (Davy *et al*., 2018), the added observational data to the regions including the Arctic region will lead to an increase in the average global or northern hemisphere land warming rate. This introduces a systematic bias caused by the temporal variation of the spatial coverage range of observation data over time.

Another example involves understanding the global warming slowdown phenomenon that began in 1998 or 2000. Global warming hiatus or slowdown attracted much attention for a few years from 2009 to 2015, and various causes had been assumed and investigated for the unexpected phenomenon (e.g., IPCC, 2013; Kosaka and Xie, 2013). However, Karl *et al*. (2015) presented their analysis, suggesting that the rate of warming during 2000–2014 is as great as the last half of the 20th century, indicating that no slowdown of global warming ever occurred. The conclusion is drawn mainly relying on an updated SSTs dataset (ERSST v.4) which had been corrected for a systematic bias of the buoy records (Schmidt, 2009; Huang *et al*., 2019). The correction was made to account for an average difference of −0.12°C between collocated buoy and ship SSTs for every grid cell in ERSST v.4.

The bias correction is necessary for avoiding the incompatibility of different SSTs observations (Huang *et al*., 2019). A major problem with their analysis, however, is another bias likely introduced to the calculation of the global ocean average SSTs anomalies and trends, which is related to the varied spatial distributions of the oceanic buoys, and in less extent the land surface stations, through time, and the spatially heterogeneous warming occurring during the last decades. The bias can be regarded as the time-varying observational configuration bias in constructing any global or regional average temperature series (Brohan *et al*., 2006).

On one hand, buoys and stations have increased in number and in spatial coverage since 1980. A large proportion of the increase occurs in northern Pacific, northern North Atlantic and Arctic Ocean. The number of buoy observations in the high-latitude northern oceans significantly increased from 1998 to 2014, for example, indicating a more expansive coverage of the observations. On the other hand, the surface warming is generally more obvious in mid- to high latitude zones of northern Hemisphere during the last decades. Northern North Atlantic, Arctic Ocean and northwestern Pacific are all among the areas experiencing the largest increase in surface temperature over the world.

In case of buoy and station absence before 1998 or 2000, the relatively larger positive or negative temperature anomalies in these northern high-latitude zones were not accounted in the global average temperature anomaly series; with the expansion of observations toward northern areas, the currently occurred high latitude rapid warming was being incorporated into the global average temperature anomaly series. Furthermore, the positive bias (+0.12 °C) correction of the buoy records had further heightened the effect of incorporating more buoy observations in high latitudes, resulting in an artificial increase of the global mean temperature after 1998 or 2000, and a absence of the warming slowdown since then.

Overall, the systematic bias caused by the spatial coverage of observation data and its changes over time has received little attention from researchers for a long time, but it is a very important technical issue in climate change monitoring and research that needs to be properly addressed in the future.

4) Averaging method of maximum and minimum temperature

Prior to automatic observation, SATs were manually recorded. At national meteorological observation stations of some countries, manual observation not only records the maximum and minimum temperatures (T_{max} and T_{min}) in a day, but also records fixed-time temperature values at equal intervals throughout the day (such as 4 times every 6 hours, 8 times every 3 hours, or 24 times every hour), which were used to calculate the daily mean temperature. However, in many volunteer observations in countries, or in international data exchange, there are often only T_{max} and T_{min} records available, without equidistant fixed-time observations. In this case, it is necessary to use the daily T_{max} and T_{min} to calculate daily, monthly, and annual mean temperatures (Collison and Tabony, 1984). In the current international global land SAT datasets, the monthly and annual mean values of about half or even most stations are obtained based on the average daily T_{max} and T_{min} (i.e., the T_{max} and T_{min} average method) (Jones *et al*., 2007).

According to the CMA *Specifications for Surface Meteorological Observation* (2003), it is stipulated that the daily mean SAT of the national meteorological stations be calculated based on the average of four temperatures recorded at 02:00, 08:00, 14:00 and 20:00 Beijing Time. This 4-time-observation averages are the most frequently used daily, monthly and annual mean SAT in the national meteorological service and the scientific researches conducted in China (e.g., Ren *et al*., 2008, 2012; Cao *et al*., 2016). However, the currently used global land SAT datasets, including the CMA GLSAT dataset, incorporated the monthly and annual mean SATs as calculated based on the T_{max} and T_{min} average method. The analysis of climatological mean and climate change applying these datasets may have been affected by a systematic bias.

The bias of the calculated mean SAT using daily T_{max} and T_{min} records relative to the standard mean SAT of four-time equidistant observations, and its effect on the estimated SAT trend, were analyzed by using a homogenized SAT dataset of China national reference climate stations and national basic meteorological stations (Liu *et al*., 2019). The analysis showed a large positive bias of annual mean SAT, which reaches 0.58°C on national average, with the regional average bias the lowest

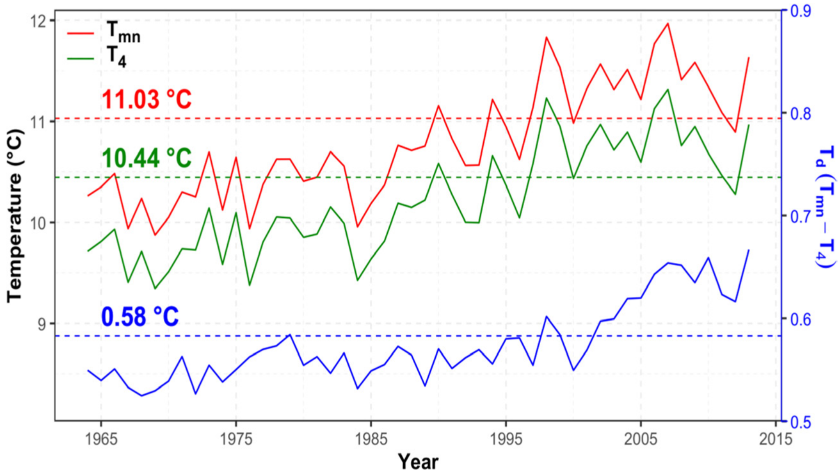

Fig. 7 Difference of annual mean SAT as calculated based on daily mean using T_{max} and T_{min} average method (T_{mn}, red) and daily mean using four-time equidistant observations (T_4, green) in China mainland. T_d denotes difference of annual mean SAT between T_{mn} and T_4 (blue). Dotted line indicates means of T_{mn}, T_4 and T_d over period 1981–2010. Modified from Liu *et al*. (2019).

in the northwest arid region and the highest in the Qinghai-Tibetan Plateau. Furthermore, the analysis showed that the bias has a significant positive trend in the 50 years of 1964–2013, with a rising rate of 0.021°C/decade, which accounts for 12% of the overall warming as estimated from the SAT data of the national observational network (Fig. 7). The largest positive trend bias was found in the northwest arid region, and the most remarkable increase of the bias occurred after early 1990s.

These findings indicate that the method to calculate daily and monthly mean SAT using T_{max} and T_{min} average method significantly overestimates both the climatological mean and the long-term trend of annual mean SAT. Although the bias has not affected the monitoring and studies in China mainland, because the daily, monthly and annual mean SAT data were obtained by calculating four-time equidistant observational records, it may have significantly overestimated the warming trends of other regions and the global land area as a whole, because the data of monthly mean temperatures as calculated using T_{max} and T_{min} average method have been widely used in the popular international SAT datasets. The nature and magnitude of the bias at global land level should be carefully addressed in future studies.

V. Summary and prospects

Global land, Asian, Chinese, and other regional scale studies have consistently shown significant warming of global and regional surface climate over the past century, especially over the past half century. Few people seem to question the observational facts of climate change; however, there is significant uncertainty in the existing research results regarding the magnitude and rate of the warming. Assessing and quantifying these uncertainties has important theoretical and practical significance for climate change science and response.

According to the research of China mainland and other regions, as well as of global land areas, the biggest uncertainty in the estimation of warming rate comes from the urbanization effect near the observation stations, followed by the uneven spatial coverage of observations and its change over time, and the T_{max} and T_{min} average method. Narrowly defined inhomogeneity of SAT data, which refers to breakpoints or step changes in the data series, has a significant impact on single station or small-sample observation network data; for large areas or large-sample observation network data, it mainly manifests as a random error, and has little impact on the estimation of warming rate.

In China mainland, since the mid-20th century, urbanization has contributed at least 28% to the rising trend of annual average ground temperature at national reference climate stations and basic meteorological stations; on global land, since the early 1950s, the urbanization effect has contributed at least 12.7% to the annual average SAT rising trend as estimated based on the global land daily SAT dataset developed by the CMA. Since the late 19th or early 20th century, the estimate of global land surface warming rate has certainly been affected by urbanization, but there is currently no quantitative assessment of the absolute magnitude and relative contribution of this impact. The estimation of global land SAT trends may have also been influenced by biases caused by the average method of T_{max} and T_{min}; if the test results in China mainland can be extended to the whole world, the bias should also be large. The nature and magnitude of the influence resulting from uneven spatial coverage of global observation data and its changes over time are still unclear. We estimate that, since the mid-20th century, the combined effects of urbanization and the overestimation caused by the T_{max} and T_{min} average method may have reached at least 20% of the global land averaged annual mean SAT rising rate estimated by applying existing datasets.

Obviously, there are still many issues that need to be further studied in the future. The most important issues include: inhomogeneity testing, verification, and correction of global land historical SAT data series, evaluation and adjustment of urbanization bias in historical SAT data series of the past hundred years as processed by different methods, detection and treatment of systematic bias caused by spatial heterogeneity of observation data coverage and its changes over time, as well as the correction of systematic biases caused by the T_{max} and T_{min} average method and other statistical methods.

Arknowledgements

This study is financially supported by the National Natural Science Foundation of China (42430610) and the National Key R&D Program of China (2018YFA 0605603). Prof. Jun Guo, Mr. Mingzhi Xu, Ms. Ziying Chu, Ms. Aiying Zhang, Prof. Yaqing Zhou, Prof. Tao Bian, Prof. Zhenghong Chen, Prof. Xuefeng Liu, Prof. Huzhi Bai, Prof. Guoli Tang, and Ms. Yuan Zhang also contributed to the earlier studies which provide basic materials for this article.

References

Brohan, P., Kennedy, J. J., Harris, I., Tett, S.F. and Jones, P.D. (2006): Uncertainty estimates in regional and global observed temperature changes: A new data set from 1850. *Journal of Geophysical Research*, **111**, D12106, doi:10.1029/2005JD006548.

Cao, L.J., Zhu, Y.N., Tang, G.L., Yuan, F. and Yan, Z.W. (2016): Climatic warming in China according to a homogenized data set from 2419 stations. *International Journal of Climatology*, **36**, 4384–4392, doi:10.1002/joc.4639.

Cao, L.K., Zhao, P., Yan, Z.W., Jones, P.D., Zhu, Y.N., Yu, Y. and Tang, G.L. (2013): Instrumental temperature series in eastern and central China back to the nineteen century. *Journal of Geophysical Research*, **118**, 8197–8209.

Chen, L.X., Shao, Y.N. and Zhang, Q.F. (1991): Preliminary analysis of climatic change during the last 39 years in China. *Journal of Applied Meteorological Science*, **2**, 164–174. (in Chinese)

Chen, L.X., Zhu, W.Q. and Wang, W. (1998): Studies on climate change in China in recent 45 years. *Acta Meteorologica Sinica*, **56**, 257–271. (in Chinese)

Cho, H.M., Cho, C.H. and Chung, K.W. (1988): Air temperature changes due to urbanization in Seoul area. *Journal of the Korean Meteorological Society*, **24**(1), 27–37.

Choi, J., Chung, U. and Yun, J.I. (2003): Urban-effect correction to improve accuracy of spatially interpolated temperature estimates in Korea. *Journal of Applied Meteorology*, **42**, 1711–1719.

Chu, Z.Y. and Ren, G.Y. (2005): Change in urban heat island magnitude and its effect on mean air temperature record in Beijing region. *Acta Meteorologica Sinica*, **63**, 534–540. (in Chinese)

Chung, U., Choi, J. and Yun, J.I. (2004): Urbanization effect on observed change in mean monthly temperature between 1951–1980 and 1971–2000 in Korea. *Climate Change*, **66**(1–2), 127–136.

Collison, P. and Tabony, R. C. (1984): The estimation of mean temperature from daily maxima and minima. *Meteorological Magazine*, **113**, 329–337.

Committee on National Climate Change Assessment (2022): *Fourth China National Climate Change*

Assessment Report. Science Press, 1177p.
Cowtan, K. and Way, R.G. (2014): Coverage bias in the HadCRUT4 temperature series and its impact on recent temperature trends. *Quarterly Journal of the Royal Meteorological Society*, **140**, 1935–1944, doi:10.1002/qj.2297.
Das, L., Annan, J.D., Hargreaves, J.C. and Emori, S. (2011): Centennial scale warming over Japan: Are the rural stations really rural? *Atmospheric Science Letters*, **12**, 362–367.
Davy, R., Chen, L. and Hanna, E. (2018): Arctic amplification metrics. *International Journal of Climatology*, **38**, 4384–4394.
Ding, Y.H. and Ren, G.Y. eds. (2008): *Introduction to Climate Change Science of China*. China Meteorological Press, 281p. (in Chinese)
Ding, Y., Ren, G., Zhao, Z., Xu, Y., Luo, Y., Li, Q. and Zhang, J. (2007): Detection, causes and projection of climate change over China: An overview of recent progress. 2007. *Advance in Atmospheric Sciences*, **24**, 954–971, doi:10.1002/joc.5675.
Fujibe, F. (2009): Detection of urban warming in recent temperature trends in Japan. *International Journal of Climatology*, **29**, 1811–1822, doi:10.1002/joc.1822.
Fujibe, F. (2011): Urban warming in Japanese cities and its relation to climate change monitoring. *International Journal of Climatology*, **31**, 162–173, doi: 10.1002/joc.2142.
Hansen, J., Ruedy, R., Sato, M. and Lo, K. (2010): Global surface temperature change. *Reviews of Geophysics*, **48**, RG4004, doi:10.1029/2010RG000345. Gridded data from: data.giss.nasa.gov/pub/gistemp/download_v3/.
Harris, I., Jones, P.D., Osborn, T.J. and Lister, D.H. (2014): Updated high-resolution grids of monthly climatic observations—The CRU TS3.10 Dataset. *International Journal of Climatology*, **34**, 623–642, doi:10.1002/joc.3711.
Hausfather, Z., Menne, M.J., Williams, C.N., Masters, T., Broberg, R. and Jones, D. (2012): The effect of urbanization on U.S. Historical Climatology Network temperature records. *Journal of Geophysical Research*, **118**, 481–494, doi:10.1029/2012JD018509.
Hawkins, E., Ortega, P., Suckling, E., Schurer, A., Hegerl, G., Jones, P., Joshi, M., Osborn, T.J., Masson-Delmotte, V., Mignot, J., Thorne, P. and van Oldenborgh, G.J. (2017): Estimating changes in global temperature since the preindustrial period. *Bulletin of the American Meteorological Society*, **98**, 1841–1856, doi:10.1175/BAMS-D-16-0007.1.
He, J.J., Ren, G.Y. and Zhang, P.F. (2021): Effects of data homogenization on the estimates of temperature trend and urbanization bias: Taking Beijing area as an example. *Advances in Climate Change Research*, **17**, 503–513, doi:10.12006/j.issn.1673-1719.2020.246. (in Chinese)
He, J.J., Ren, G.Y., Zhang, P.F., Zheng, X. and Zhang, S.Q. (2023): Updated analysis of surface warming trends in North China based on in-depth homogenized data (1951–2020). *Climate Research*, **41**, 41–66.
He, Y.T., Jia, G.S., Hu, Y.Y. and Zhou, Z.J. (2013): Detecting urban warming signals in climate records. *Advances in Atmospheric Sciences*, **30**, 1143–1153.
Hua, L.J., Ma, Z.G. and Luo, D.H. (2004): Analysis of temperature range from 1961 through 2000 across China. *Acta Geographica Sinica*, **59**, 680–688.
Hua, L.J., Ma, Z.G. and Guo, W.D. (2008): The impact of urbanization on air temperature across China. *Theoretical and Applied Climatology*, **93**, 179–194, doi:10.1007/s00704-007-0339-8.
Huang, B.Y., Liu, C.Y., Ren, G.Y., Zhang, H.M. and Zhang, L. (2019): The role of Buoy and Argo observations in two SST analyses in the global and tropical Pacific Oceans. *Journal of Climate*, **32**, 2517–2535, doi:10.1175/JCLI-D-18-0368.1.
Hughes, W.S. and Balling, R.C. (1996): Urban influences on South African temperature trends. *International Journal of Climatology*, **16**, 935–940.
IPCC (2013): *Climate Change 2013: The Physical Science Basis*. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Stocker, T.F., Qin, D., Plattner, G.K. *et al*. eds., Cambridge University Press, 1535p.
IPCC (2021): *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte, V., Zhai, P., Pirani, A. *et al*. eds., Cambridge University Press, doi:10.1017/9781009157896.
Japan Meteorological Agency (2008): *Climate Change Monitoring Report 2007*. 29–32.
Jones, P.D., Groisman, P.Y., Coughlan, M., Plummer, N., Wang, W.C. and Karl, T.R. (1990): Assessment of urbanization effects in time series of surface air temperature over land. *Nature*, **347**, 169–172.
Jones, P. D., Trenberth, K. E., Ambenje, P., Bojariu, R., Easterling, D., Klein, T., Parker, D., Renwick, J., Rusticucci, M. and Soden, B. (2007): *Observations: surface and atmospheric climate change*. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK and New York, NY, 235–336.
Jones, P.D., Lister, D.H., Osborn, T.J., Harpham, C., Salmon, M. and Morice, C.P. (2012): Hemispheric and large-scale land-surface air temperature variations: An extensive revision and an update to 2010. *Journal of Geophysical Research*, **117**, D05127, doi: 10.1029/2011JD017139.
Jongtanom, Y., Kositanont, C. and Baulert, S. (2011):

Temporal variations of urban Heat Island intensity in three major cities, Thailand. *Modern Applied Science*, **5**, 105–110, doi:10.5539/mas.v5n510p5.

Karl, T.R., Knight, R.W. and Christy, J.R. (1994): Global and hemispheric temperature trends: Uncertainties related to inadequate spatial sampling. *Journal of Climate*, **7**, 1144–1163.

Karl, T.R., Arguez, A., Huang, B.Y., Lawrimore, J.H., Mcmahon, J.R., Menne, M.J., Peterson, T.C., Vose, R.S. and Zhang, H.M. (2015): Possible artifacts of data biases in the recent global surface warming hiatus. *Science*, **348**, 1469–1472.

Katata, G., Connolly, R. and O'Neill, P. (2023): Evidence of urban blending in homogenized temperature records in Japanand in the United States: Implications for the reliability of global landsurface air temperature data. *Applied Meteorology and Climatology*, **62**, 1095–1114, doi:10.1175/JAMC-D-22-0122.1.

Kent, E.C., Kennedy, J.J., Berry, D.I. and Smith, R.O. (2010): Effects of instrumentation changes on sea surface temperature measured in situ. *Wiley Interdisciplinary Reviews: Climate Change*, **1**, 718–728.

Kosaka, Y. and Xie, S.P. (2013): Recent global-warming hiatus tied to equatorial Pacific surface cooling. *Nature*, **501**, 403–407.

Lawrimore, J.H., Menne, M.J., Gleason, B.E., Williams, C.N., Wuertz, D.B., Vose, R.S. and Rennie, J. (2011): An overview of the Global Historical Climatology Network monthly mean temperature data set, version 3. *Journal of Geophysical Research*, **116**, D19121, doi:10.1029/2011jd016187.

Li, J., Ren, G.Y., Ren, Y.Y. and Zhang, L. (2014): Effect of data homogenization on estimate of temperature trend and urban bias at Shenyang Station. *Transactions of Atmospheric Sciences*, **37**, 297–303. (in Chinese)

Li, K.R., Lin, X.C. and Wang, W.Q. (1990): The long-range variational trend of temperature in China from 1951 to 1988. *Geographical Research*, **9**, 26–37. (in Chinese)

Li, Q.X., Liu, X.N., Zhang, H.Z. and Thomas, C.P. (2004): Detecting and adjusting temporal inhomogeneity in Chinese mean surface air temperature data. *Advances in Atmospheric Sciences*, **21**, 260–268.

Li, Q.X., Yang, S., Xu, W.H., Wang, X.L., Jones, P., Parker, D., Zhou, L., Feng, Y. and Gao, Y. (2015): China experiencing the recent warming hiatus. *Geophysical Research Letters*, **42**, 889–898.

Li, Z. and Yan, Z.W. (2009): Homogenized daily mean/maximum/minimum temperature series for China from 1960 to 2008. *Atmospheric and Oceanic Science Letters*, **2**, 237–243.

Lin, X.C. and Yu, S.Q. (1990): Climatic trend in China for the last 40 years. *Meteorological Monthly*, **16**, 16–21. (in Chinese)

Liu, Y.L., Ren, G.Y., Kang, H.Y. and Sun, X.B. (2019): A significant bias of T_{max} and T_{min} average temperature and its trend. *Journal of Applied Meteorology and Climatology*, **58**, 2235–2246, doi:10.1175/JAMC-D-19-0001.1.

Manalo, J.A., Matsumoto, J., Takahashi, H.G., Villafuerte, M.Q.II, Olaguera, L.M.P., Ren, G.Y. and Cinco, T.A. (2021): The effect of urbanization on temperature indices in the Philippines. *International Journal of Climatology*, **42**, 850–867, doi:10.1002/joc.7276.

McKitrick, R. and Michaels, P.J. (2004): Are temperature trends affected by economic activity? Reply to Benestad (2004). *Climate Research*, **27**, 175–176.

Menne, M.J. and Williams, C.N. (2009): Homogenization of temperature series via pairwise comparisons. *Journal of Climate*, **22**, 1700–1717.

Menne, M.J., Williams, C.N., Gleason, B.E., Rennie, J.J. and Lawrimore, J.H. (2018): The global historical climatology network monthly temperature dataset, version 4. *Journal of Climate*, **31**, 9835–9854, doi:10.1175/JCLI-D-18-0094.1.

Om, K.C., Ren, G.Y., Jong, S.I., Li, S.L., Kang-Chol, O., Ryang, C.H. and Zhang, P.F. (2019): Long-term change in surface air temperature over DPR Korea, 1918–2015. *Theoretical and Applied Climatology*, **138**, 363–372, doi:10.1007/s00704-019-02820-0.

Om, K.C., Ren, G.Y., Kima, H.U., Jonga, S., Nam-Chola, O. and Kima, H.C. (2021): A detectable urbanization effect in observed surface air temperature data series in Pyongyang region, Democratic People's Republic of Korea. *Urban Climate*, **38**, 100907, doi:10.1016/j.uclim.2021.100907.

Pielke, R.A., Davey, C.A., Niyogi, D., Fall, S., Steinweg-Woods, J., Hubbard, K., Lin, X., Cai, M., Lim, Y.-K., Li, H., Nielsen-Gammon, J., Gallo, K., Hale, R., Mahmood, R., Foster, S., McNider, R.T. and Blanken, P. (2007): Unresolved issues with the assessment of multidecadal global land surface temperature trends. *Journal of Geophysical Research: Atmospheres*, **112**(D24), doi:10.1029/2006JD0082.

Qian, W.H. and Lin, X. (2004): Regional trends in recent temperature indices in China. *Climate Research*, **27**, 119–134.

Qin, D.H. and Zhai, P.M. eds. (2021): *Change in Climate and Eco-environment in China: 2021*. Vol. 1 Scientific Basis. Science Press, 609p.

Rao, Y., Liang, S. and Yu, Y. (2018): Land surface air temperature data are considerably different among BEST-LAND, CRU-TEM4v, NASA-GISS, and NOAA-NCEI. *Journal of Geophysical Research: Atmospheres*, **123**, 5881–5900, doi:10.1029/2018JD028355.

Ren, G.Y. (2015): Urbanization as a major driver of urban climate change. *Advances in Climate Change Research*, **6**, 1–6, doi:10.1016/j.accre.2015.08.003.

Ren, G.Y. and Shrestha, A.B. (2017): Climate change in the HKH region. *Advance in Climate Change Research*, **8**, 137–140, doi:10.1016/j.accre.2017.09.001.

Ren, G.Y. and Zhou, W. (1994): A preliminary study on surface air temperature change over the Liaodong Pennisula. *Acta Meteorologica Sinica*, **52**, 493–498. (in Chinese)

Ren, G.Y., Xu, M.Z., Chu, Z.Y., Guo, J., Li, Q.X., Liu, X.N. and Wang, Y. (2005a): Changes of surface air temperature in China during 1951–2004. *Climatic and Environmental Research*, **10**, 717–727. (in Chinese)

Ren, G.Y., Chu, Z.Y., Zhou, Y.Q., Xu, M.Z., Wang, Y., Tang, G.L., Zhai, P.M., Shao, X.M., Zhang, A.Y., Chen, Z.H., Guo, J., Liu, H.-B., Zhou, J.-X., Zhao, Z.-C., Zhang, L., Bai, H.-Z., Liu, X.-F. and Tang, H.-Y. (2005b): Recent progresses in studies of regional temperature changes in China. *Climatic and Environmental Research*, **10**, 701–716. (in Chinese)

Ren, G.Y., Chu, Z.Y., Chen, Z.H. and Ren, Y.Y. (2007): Implications of temporal change in urban heat island intensity observed at Beijing and Wuhan stations. *Geophysical Research Letters*, **34**, L05711.

Ren, G.Y., Zhou, Y., Chu, Z., Zhou, J., Zhang, A., Guo, J. and Liu, X. (2008): Urbanization effect on observed surface air temperature trend in North China. *Journal of Climate*, **21**, 1333–1348.

Ren, G.Y., Ding, Y., Zhao, Z., Zheng, J., Wu, T., Tang, G. and Xu, Y. (2012): Recent progress in studies of climate change in China. *Advance in Atmospheric Sciences*, **29**, 958–977.

Ren, G.Y., Ren, Y.Y., Li, Q.X. and Xu, W.H. (2014): An overview on global land surface air temperature change. *Advances in Earth Science*, **29**, 934–946, doi:10.11867/j.issn.1001-8166.

Ren, G.Y., Li, J., Ren, Y.Y., Chu, Z.Y., Zhang, A.Y., Zhou, Y.Q., Zhang, L., Zhang, Y. and Bian, T. (2015): An integrated procedure to determine a reference station network for evaluating and adjusting urban bias in surface air temperature data. *Journal of Applied Meteorology and Climate*, **54**, 1248–1266.

Ren, G.Y., Ding, Y.H. and Tang, G.L. (2017): An overview of mainland China temperature change research. *Journal of Meteorological Research*, **31**, 3–16, doi:10.1007/s13351-017-6195-2.

Ren, G.Y., Tang, G.L. and Wen, K.M. (2019): Long-term surface air temperature trends over mainland China. *Oxford Research Encyclopedia of Climate Science*, doi:10.1093/acrefore/9780190228620.013.7333.

Ren, G.Y., Zhan, Y.J., Ren, Y.Y., Wen, K.M., Zhang, Y.X., Sun, X.B., Zhang, P.F., Zheng, X., Qin, Y., Zhang, S.Q. and He, J. (2023): Observed changes in temperature and precipitation over Asia: 1901–2020. *Climate Research*, **90**, 31–43, doi:10.3354/cr01713.

Ren, Y.Y., Ren, G.Y., Sun, X.B., Shrestha, A.B., You, Q.L., Krishnan, R., Zhan, Y.J., Rajbhandari, R., Zhang, P.F. and Wen, K.M. (2017): Observed change in surface air temperature and precipitation in the Hindu Kush Himalayan (HKH) region over the last 100-plus 100 years. *Advance in Climate Change Research*, **8**, 148–156.

Rohde, R., Muller, R., Jacobsen, R., Perlmutter, S., Rosenfeld, A., Wurtele, J., Curry, J., Wickham, C. and Mosher, S. (2013): Berkeley earth temperature averaging process. *Geoinformatics & Geostatistics: An Overview*, **1**, 1–13, doi:10.4172/gigs.1000103.

Schmidt, G.A. (2009): Spurious correlations between recent warming and indices of local economic activity. *International Journal of Climatology*, **29**, 2041–2048.

Song, L.C. (1994): Characteristics of temperature in spatial and temporal variation in China during recent 40 years. *Journal of Applied Meteorological Science*, **5**, 119–124.

Soon, W.H., Connolly, R., Connolly, M., O'Neill, P., Zheng, J., Ge, Q., Hao, Z. and Yan, H. (2018): Comparing the current and early 20th century warm periods in China. *Earth-Science Reviews*, **185**, 80–101.

Sun, X, Ren, G., Ren, Y., Lin, W. and Zhang, P. (2023): Asian climate warming since 1901: Observation and simulation. *Climate Research*, **91**, 67–82.

Sun, X.B., Ren, G.Y., Xu, W.H., Li, Q.X. and Ren, Y.Y. (2017a): Global land-surface air temperature change based on the new CMA GLSAT dataset. *Science Bulletin*, **62**, 136–238, doi:0.1016/j.scib.2017.01.017.

Sun, X.B., Ren, G.Y., Ren, Y.Y., Liu, Y.L. and Xue, X.Y. (2017b): A remarkable climate warming hiatus over Northeast China since 1998. *Theoretical and Applied Climatology*, **133**, 579–594, doi:10.1007/s00704-017-2205-7.

Sun, X.B., Ren, G.Y., Ren, Y.Y., Shrestha, A.B., You, Q.L., Krishnan, R., Zhan, Y.J., Xu, Y., Rajbhandari, R. and Sanjay, J. (2017c): Change in extreme temperature events over the Hindu Kush-Karakoram-Himalaya (HKH) during 1961–2015. *Advance in Climate Change Research*, **8**, 157–165.

Sun, Y., Zhang, X.B., Ren, G.Y., Zwiers, F.W. and Hu, T. (2016): Contribution of urbanization to warming in China. *Nature Climate Change*, **6**, 706–709, doi:10.1038/nclimate2956.

Tang, G.L. and Ren, G.Y. (2005): Reanalysis of surface air temperature change of the last 100 years over China. *Climatic and Environmental Research*, **10**, 791–798. (in Chinese)

Tysa, S.K., Ren, G.Y., Qin, Y., Wen, K.M., Ren, Y.Y., Jia, W.Q. and Zhang, P.F. (2019): Urbanization effect in regional temperature series based on a remote-sensing classification scheme of stations. *Journal of Geophysical Research-Atmosphere*, **124**,

10646–10661, doi:10.1029/2019JD030948.
USGCRP (2018): *Impacts, Risks, and Adaptation in the United States: Fourth National Climate Assessment, Volume II: Report-in-brief*, Reidmiller, D.R., Avery, C.W., Easterling, D.R., Kunkel, K.E., Lewis, K.L.M., Maycock, T.K. and Stewart, B.C. eds., U.S. Global Change Research Program, 186p, doi: 10.7930/NCA4.2018.RiB.
Venema, V.K.C., Mestre, O., Aguilar, E., Auer, I., Guijarro, J.A., Domonkos, P., Vertacnik, G., Szentimrey, T., Stepanek, P., Zahradnicek, P., Viarre, J., Müller-Westermeier, G., Lakatos, M., Williams, C.N., Menne, M.J., Lindau, R., Rasol, D., Rustemeier, E., Kolokythas, K., Marinova, T., Andresen, L., Acquaotta, F., Fratianni, S., Cheval, S., Klancar, M., Brunetti, M., Gruber, C., Prohom Duran, M., Likso, T., Esteban, P. and Brandsma, T. (2012): Benchmarking homogenization algorithms for monthly data. *Climate of the Past*, **8**, 89–115.
Vincent, L.A., Zhang, X., Bonsal, B. and Hogg, W. (2002): Homogenization of daily temperatures over Canada. *Journal of Climate*, **15**, 1322–1334.
Vose, R.S., Arndt, D., Banzon, V.F., Easterling, D.R., Gleason, B., B. Huang, Kearns, E., Lawrimore, J.H., Menne, M.J., Peterson, T.C., Reynolds, R.W., Smith, T.M., Williams, C.N. and Wuertz, D.B. (2012): NOAA's merged land–ocean surface temperature analysis. *Bulletin of the American Meteorological Society*, **93**, 1677–1685, doi:10.1175/BAMS-D-11-00241.1.
Wang, F. and Ge, Q.S. (2012): Estimating urban heat island effect in China from 1980 to 2009 based on satellite land use changes. *Chinese Science Bulletin*, **57**, 951–958.
Wang, Z.Y., Ding, Y.H., He, J.H. and Yu, J. (2004): An updated analysis of the climate change in China in recent 50 years. *Acta Meteorologica Sinica*, **62**, 228–236. (in Chinese)
Wen, K.M., Ren, G.Y., Li, J., Ren, Y.Y., Sun, X.B., Zhou, Y.Q. and Zhang, A.Y. (2019a): Adjustment of urbanization bias in surface air temperature over the mainland of China. *Progress in Geography*, **38**, 600–611, doi:10.18306/dlkxjz.2019.04.012.
Wen, K.M., Ren, G.Y., Li, J., Zhang, A.Y., Ren, Y.Y., Sun, X.B. and Zhou, Y.Q. (2019b): Recent surface air temperature change over mainland China based on an urbanization-bias adjusted dataset. *Journal of Climate*, **32**, 2691–2705, doi:10.1175/JCLI-D-18-0395.
Wen, K., Ren, G., Ren, Y., Cao, L., Qin, Y., Zhang, P., He, J., Xue, X. and Sun, X. (2023): Long-term changes in surface air temperature over the Chinese mainland during 1901–2020. *Climate Research*, **90**, 95–115.
Xu, W., Li, Q., Wang, X.L., Yang, S., Cao, L. and Feng, Y. (2013): Homogenization of Chinese daily surface air temperatures and analysis of trends in the extreme temperature indices. *Journal of Geophysical Research: Atmospheres*, **118**, 9708–9720.
Xu, W., Li, Q., Jones, P., Wang, X.L., Trewin, B., Yang, S., Zhu, C., Zhai, P.M., Wang, J.F., Vincent, L., Dai, A., Gao, Y. and Ding, Y. (2018): A new integrated and homogenized global monthly land surface air temperature dataset for the period since 1900. *Climate Dynamics*, **50**, 2513–2536, doi: 10.1007/s00382-017-3755-1.
Yan, Z.W. and Jones, P.D. (2008): Detecting inhomogeneity in daily climate series using wavelet analysis. *Advances in Atmospheric Sciences*, **25**, 157–163.
Yang, X., Hou, Y. and Chen, B. (2011): Observed surface warming induced by urbanization in east China. *Journal of Geophysical Research*, **116**, D14113, doi:10.1029/2010JD015452.
Yang, Y.J., Wu, B.W., Shi, C.E., Zhou, J.H., Li, Y.B., Tang, W.A., Wen, H.Y., Zhang, H.Q. and Shi, T. (2013): Impacts of urbanization and station-relocation on surface air temperature series in Anhui Province, China. *Pure & Applied Geophysics*, **170**, 1969–1983.
Zhai, P.M. and Ren, F.M. (1997): On changes of China's maximum and minimum temperatures in the recent 40 years. *Acta Meteorologica Sinica*, **55**, 418–429. (in Chinese)
Zhang, A., Ren, G., Zhou, Z., Chu, Z., Ren, Y. and Tang, G. (2010): Urbanization effect on surface air temperature trends over China. *Acta Meteorologica Sinica*, **68**, 957–966. (in Chinese)
Zhang, L., Ren, G.Y., Ren, Y.Y., Zhang, A.Y., Chu, Z.Y. and Zhou, Y.Q. (2014): Effect of data homogenization on estimate of temperature trend: A case of Huairou station in Beijing Municipality. *Theoretical and Applied Climatology*, **115**, 365–373.
Zhang, P., Ren, G., Qin, Y., Zhai, Y., Zhai, T., Tysa, S.K. and Sun, X. (2021): Urbanization effect on estimate of global trends in mean and extreme air temperature. *Journal of Climate*, **34**, 1923–1945, doi:10.1175/JCLI-D-20-0389.1.

近年の陸地における気候の温暖化率に関する研究の進展と不確実性

—グローバルからリージョンまで—

任　國　玉[1,2]　孫　秀　寶[3]　張　盼　峯[1,4]
溫　康　民[5,6]　索　南看卓[1,7]　劉　玉　蓮[8]
張　思　齊[1,2]　何　佳　駿[1]　秦　雲[1,2]
嚴　金　哲[1,9]　鄭　翔[1]　任　玉　玉[2]
黄　思　齊[1,2]　張　雷[10]

近年の地表面付近の気温の変化率は，気候変動や地球環境の変動に関する研究において重要な問題である。この論文では，過去20年間における我々の研究グループの主な成果と知見を中心に，気候のグローバルおよびローカルスケールでの温暖化率に関する研究の進展についてレビューする。また，この分野の研究者が現在直面している不確実性や科学的疑問点，今後の研究の方向性に関する展望についても述べる。地球，アジア，中国，そしてより小規模な地域スケールの研究は，過去一世紀，特に過去半世紀における地表付近の気候の著しい温暖化を一貫して示してきた。しかし，温暖化の規模と速度に関して，既存の研究には大きな不確実性がある。最大の不確実性は，観測データにおける都市化の影響に起因し，次いでデータの空間的不均一性とその経年変化，そして地表面付近における日平均，月平均，年平均気温を計算する際の最高値と最低値の平均算出方法に起因する。より確実で信頼性の高い結論を得るためには，今後これらの問題をさらに調査する必要がある。

キーワード：進展，地表気温，気候温暖化率，陸地，アジア，中国大陸，現代，データ，不確実性，都市化バイアス

1) 中国地質大学環境学部
2) 中国気象局国家気候センター
3) 中国科学院南シナ海海洋研究所
4) 吉林師範大学観光地理科学学院
5) 中国福州気象局
6) 福建省気象科学研究所
7) 青海大学
8) 黒龍江省気象局黒龍江気候センター
9) 金日成総合大学地球環境科学部
10) 天津市気象局天津気象情報センター