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RESEARCH

Assessment of agricultural heat resources based on urbanization-bias-corrected data: case of a county in Heilongjiang, China

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Abstract

The assessment of agro-climatic resources requires that observation data series be free of urbanization bias. However, currently, there is no research on agricultural heat resources based on air temperature data adjusted for urbanization bias. Taking Jixian County, a typical agricultural area in Heilongjiang Province, China, as an example, we assess the agricultural heat resources using temperature data with urbanization-bias corrected. Daily mean air temperature data from the national station, regional stations and farm stations were used. Two farm stations were used as references to correct the urbanization bias of daily mean temperature and ≥10 °C accumulated temperature at Jixian Station, and the accumulated temperature zones in the county were re-evaluated. From 1961 to 2022, both the annual mean temperature and ≥10 °C accumulated temperature of Jixian Station exhibited a significant upward trend. The change rates were 0.42 °C/decade for the annual mean temperature and 81.9 °C/decade for the ≥10 °C accumulated temperature. The contributions of urbanization to the warming trends both reached 18%. After eliminating the urbanization bias, average value of the ≥10 °C accumulated temperature in the county from 1991 to 2022 was 2792.7 °C, which was 77.8 °C lower than that calculated solely from quality-controlled and homogenized data. The distribution of ≥10 °C accumulated temperature zones from the new assessment changed notably. Most areas fell into the second accumulated temperature zone (secondary warm), and the first accumulated temperature zone (warmest) originally obtained based on the data without urbanization-bias correction disappeared. We show that using uncorrected data for calculating≥10 °C accumulated temperature and dividing accumulated temperature zone will significantly overestimate the agricultural heat resources of a region and pose a high risk of out-of-zone planting to agricultural production.

1 Introduction

Heilongjiang Province, situated in the northernmost and highest-latitude region of China, is the country's most crucial commodity grain base. With 15.5 million hectares of cultivated land, it has consistently ranked first in China in terms of grain commodity volume, transfer volume, and reserve volume for many years, thus serving as the bedrock of national food security. In 2023, the total grain output of Heilongjiang Province reached 77.9 billion kilograms, marking the "20th consecutive bumper harvest" of grain production. This output accounted for 11.2% of the national total (https://www.hlj.gov.cn/hlj/c107856/202312/c00_31692751.shtml).

Against the background of global warming, the average temperature in Heilongjiang Province from 1961 to 2023 also exhibited a significant upward trend (0.34℃/decade, according to Monitoring Report on Heilongjiang Climate

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Change, Heilongjiang Climate Center, 2024). Nevertheless, due to its high-latitude location, heat resources have consistently been a crucial factor constraining agricultural production in this major grain-producing province. Such an indicator as accumulated temperature ≥ 10 °C is widely used to assess thermal resources in crop production in various regions of China. In Heilongjiang Province, it is also used as an indicator for estimating the thermal resources available for crop growth, as well as for adjusting the structure of agriculture and selecting varieties.

Nevertheless, there are substantial inter-annual to interdecadal variations in the ≥ 10 °C accumulated temperature. To properly arrange agricultural production and fully utilize heat resources, Heilongjiang Province typically employs the ≥ 10 °C accumulated temperature value with an 80% guarantee rate to delineate the accumulated temperature zones (Sun et al. 1986; Yu et al. 1997; Shi et al. 2005; Song et al. 2014; Zhao et al. 2015). The entire province thus is divided into six accumulated temperature zones (Yan 1996; Ji et al. 2009; Yan et al. 2009):

The first accumulated temperature zone: The accumulated temperature exceeds 2700 °C.

The second accumulated temperature zone: The accumulated temperature is between 2500 and 2700 °C.

The third accumulated temperature zone: The accumulated temperature is between 2300 and 2500 °C.

The fourth accumulated temperature zone: The accumulated temperature is between 2100 and 2300 °C.

The fifth accumulated temperature zone: The accumulated temperature is between 1900 and 2100 °C.

The sixth accumulated temperature zone: The accumulated temperature is less than 1900 °C.

Existing research shows the ≥ 10 °C accumulated temperature in Heilongjiang Province has risen significantly in recent decades. Compared with the 1990 s division, the zones generally shifted northward and expanded eastward (Cao et al. 2014). Ji et al. (2009) noted a rising trend from 1961 to 2005, with a marked increase in the 1990 s; the zones also shifted notably northward and expanded eastward between 1976 and 2005 versus 1961–1990; the first accumulated temperature zone moved northward by an average of 0.5 latitude degrees, and the third accumulated temperature zone expanded eastward by 2 longitude degrees. Yuan et al. (2019) proposed that the accumulated temperature stably passing through 10 °C in Heilongjiang Province from 1961 to 2017 increased significantly at a rate of 27–101 °C/decade. Zhu (2015) showed that the accumulated temperature of ≥ 10 °C in Heilongjiang Province from 1961 to 2014 had an upward trend of 67.7 °C/decade; the proportion of the first accumulated temperature zone in the province increased from 1% (1961–1990) to 8% (1981–2004), while the sixth accumulated temperature zone shrank in scope by 8%.

The above mentioned research has, to a certain extent, revealed the characteristics of the accumulated temperature change at National Stations in Heilongjiang Province. However, these studies generally used homogenized surface air temperature data from National Stations and did not assess and correct the urbanization bias in the data series. Similar to other regions on mainland China, most of the National Stations in Heilongjiang Province are located in or near cities or towns. The observation data contain obvious urbanization bias (Ren et al. 2005; Zhou et al. 2005; Ren et al. 2010; Zhang et al. 2010). Since most of the vast farmlands are far from cities and will not be significantly affected by urbanization in recent decades, using observation data with urbanization bias will inevitably lead to a significant overestimation of the upward trends of surface air temperature and accumulated temperature in the past few decades. Accurately assessing and correcting the urbanization bias in the existing homogenized surface air temperature data series is a basic prerequisite for objectively understanding the changes in ≥ 10 °C accumulated temperature and heat resource conditions in important agricultural areas such as Heilongjiang Province.

In the past 20 years, numerous studies have been carried out on the urbanization effect (bias) on surface air temperature observation data series in regions such as mainland China. Studies that use objective meteorological-station classification methods have all indicated that urbanization has had a significant impact on the estimation of large-scale air temperature change trends since the mid-20th century (e.g. Chung et al. 2004; Ren et al. 2005, 2008; Fujibe 2009; Yang et al. 2011; Tysa et al. 2019; Manalo et al. 2021; Zhang et al. 2021). These studies initially aimed to provide unbiased surface air temperature observation data for regional and global climate change monitoring, detection, attribution, and simulation. In fact, they also provided more reliable basic historical data for research on the impacts and risk assessments of climate change in fields such as agriculture and water resources.

Using the monthly mean surface air temperature data after urbanization bias correction in mainland China (Wen et al. 2019a), Li et al. (2022) analyzed the change trends of accumulated temperature and the distribution characteristics of accumulated temperature zones in Heilongjiang Province before and after the correction of urbanization bias from 1961 to 2020. They found that the ≥ 10 °C accumulated temperature in the whole province showed a significant increasing trend since 1961 ($p < 0.01$), but the contribution rate of urbanization to the increasing trend of accumulated temperature reached 24.6%. After removing the urbanization effect, the extent of northward movement and eastward expansion of all accumulated temperature zones was mitigated compared with the results of the analysis based on original data. It is worth mentioning that compared with the distribution of accumulated temperature zones from 1961 to 1990, the second accumulated temperature zone in the hinterland of the Sanjiang Plain was adjusted to the first accumulated temperature zone based on the original data. After removing the urbanization bias, the scope of this area belonging to the first accumulated temperature zone was significantly reduced.

Jixian County is located in the hinterland of the Sanjiang Plain (Fig. 1). Previous studies have found that the long-term accumulated temperature changes significantly, and it is just in the area where the second accumulated temperature zone is transformed into the first accumulated temperature zone based on the original data (Li et al. 2022). The average annual commodity grain output in this county exceeds 0.75 billion kilograms. It is not only an important commodity grain production base in Heilongjiang Province but also a national advanced county in grain production, and it is known as the 'Hometown of Chinese Soybean Oil Extraction'.

Taking Jixian County - an agricultural area of the hinterland of the Sanjiang Plain - as an example, we depict the actual distribution pattern of accumulated temperature zones after eliminating urbanization bias based on the daily air temperature data from more observation sites and a more rigorous data processing procedure. This research is of great practical significance for guiding local agricultural production and the adjustment of agricultural variety layout, and reducing the risk of out-of-zone planting. It also has certain enlightenment for the assessment of changes in agricultural heat resource conditions in China on a whole and other agricultural regions of the world.

2 Data and methods

2.1 Research area overview

Jixian County is located in the hinterland of the Sanjiang Plain in Heilongjiang Province, between 46.49° and 47.07°N, and between 130.66° and 132.25°E (Fig. 1). The terrain is predominantly characterized by low mountains and hills. The western part is the remaining vein of the Wanda Mountains, and the altitude decreases gradually from the southwest to the northeast. The county is mainly composed of plain areas below 200 m above sea level, accounting for more than 75% of the area. The Sanjiang Plain and Jixian County have a temperate continental monsoon climate, with mild and humid summers and cold and dry winters. Nearly 60% of the annual total precipitation is concentrated in

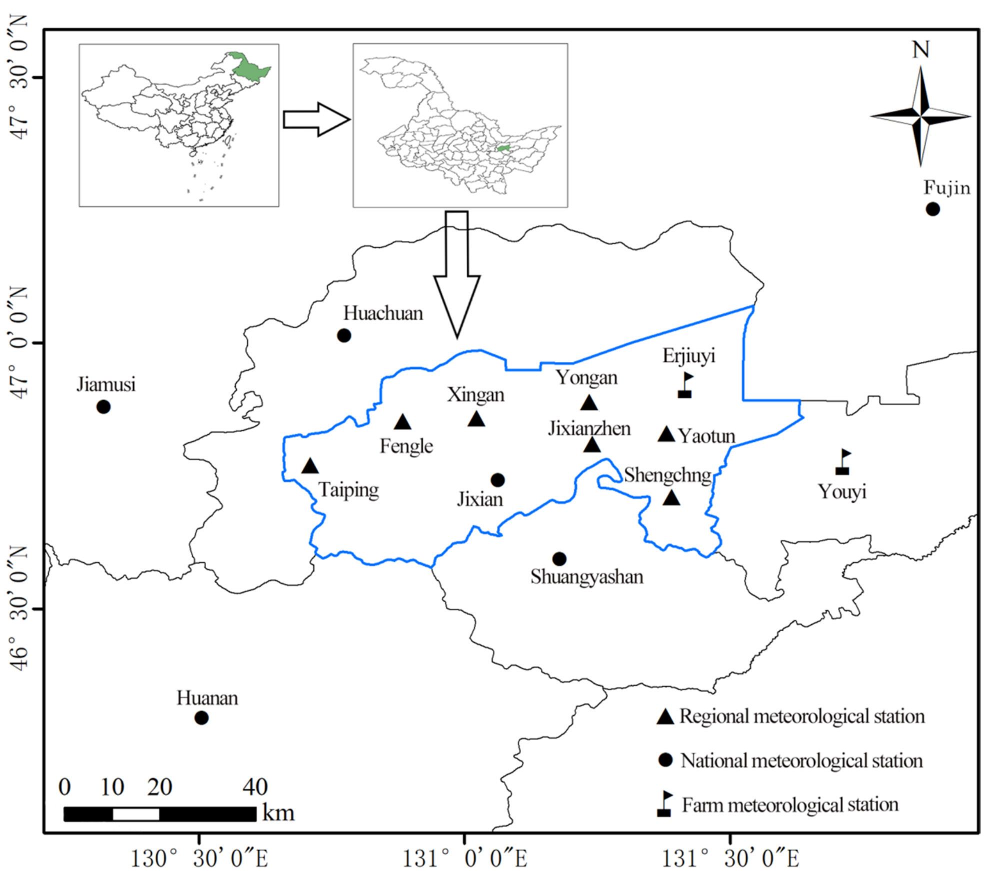

Fig. 1 Location of Jixian County, Heilongjiang Province, China, and the distribution of meteorological stations used in this paper

June-August. Different from other major agricultural areas in China, the restrictive climate factors for the growth of grain crops in Jixian County are insufficient heat conditions and possible low-temperature cold damage during the growth season. The county covers an area of 2227.5 km², a cultivated land area of 15.47×10^5 ha, a forest land area of 4.44×10^5 ha, and a total population of 285,000. In the past 20 years or so, the urbanization process of Jixian County has been relatively rapid. The built-up area increased from 10.13 km² in 2002 to 23.77 km² in 2023.

2.2 Meteorological data

This paper analyzed daily average temperature data from Jixian County National Station (after homogenization), 7 regional automatic stations, and 2 farm stations. When generating the spatial distribution map of accumulated temperature for Jixian County, neighboring data outside of the study were used. These include daily average temperatures (after homogenization) from 5 nearby national stations located in Fujin, Jiamusi, Huachuan, Huanan, and Shuangyashan. Homogenized daily average temperature data (Homogenized corrections were applied to station relocations, instrument replacements, and other factors, but urbanization biases remained uncorrected) from the 6 national stations were obtained from the National Meteorological Information Center, with the remaining data sourced from the Heilongjiang Provincial Meteorological Information Center. The specific information of the above-mentioned meteorological stations is shown in Table 1, and their locations are shown in Fig. 1.

Despite the fact that the 2 Farm Stations have been relocated, the relocation distances remain short, and the altitude changes are minimal. For example, the Erjiuyi Farm Station was relocated 7.8 km from its original site in 1973 and 3.1 km from the 1973 site in 2007. The altitude of the station was adjusted from 67.1 m at the time of establishment to 67.3 m and 69 m after the two re-locations. The Youyi Farm Station was relocated 5.6 km from its original site in 1966 and another 5.7 km in 1990, with an altitude change of merely 0.9 m before and after the re-locations. The observational environments of the two farm stations have changed little. They are all located within the farms both before and after the re-locations, and there are few buildings and a small population around the observation grounds. There are no significant relocation-induced inhomogeneities in the annual mean temperature series of the two farm meteorological stations (see Appendix). Therefore, the data of the farm stations after quality control are directly used in this paper. The data series of Regional Stations are short, and there are relatively many quality problems. This study conducts quality inspections and processing on them.

Table 1 Information of meteorological stations used in the study

Station	Longitude (°)	Latitude (°)	Altitude(m)	Type	Start and end years	Relocation year	Urban/Rural station	Role in drawing maps
Jixian	131.14	46.77	102	National Station	1961–2022	1958 1992	Urban	Core
Fujin	131.98	47.26	66		1991–2022	1969 1999	Urban	Auxiliary (out of Jixian)
Jiamusi	130.27	46.79	82		1991–2020	1955 2007	Urban	Auxiliary (out of Jixian)
Huachuan	130.75	47.02	78		1991–2022	1997	Urban	Auxiliary (out of Jixian)
Huanan	130.60	46.25	187		1991–2022	1960 2003	Urban	Auxiliary (out of Jixian)
Shuangyashan	131.18	46.68	175		1991–2022	1963	Urban	Auxiliary (out of Jixian)
Erjiuyi farm	131.38	46.91	69	Farm Station	1961–2022	1973 2007	Rural	Core (reference station)
Youyi farm	131.80	46.78	67		1961–2022	1966 1990	Rural	Core (reference station)
Xingan	131.05	46.84	80	Regional Station	2007–2022		Rural	Core
Fengle	130.89	46.84	112		2007–2022		Rural	Core
Taiping	130.74	46.78	96		2007–2022		Rural	Core
Yaotun	131.40	46.85	73		2007–2022		Rural	Core
Yongan	131.26	46.85	70		2007–2022		Urban	Abandon
Jixianzhen	131.26	46.83	95		2007–2022		Urban	Abandon
Shengchang	131.41	46.73	105		2007–2022		Urban	Abandon

The geographical information data adopt the 1:250,000 DEM. These data include administrative boundaries at the provincial, municipal, and county levels, along with elevation data. It is sourced from the China Meteorological Administration (CMA).

Regional station data processing. The 7 Regional Stations in Jixian County were all established in May 2007. Since these stations are unmanned, they can be affected by the surrounding environment, energy supply, communication transmission, etc., which results in insufficient data quality during the initial operation stage. It is necessary to check and handle issues such as data missing, outliers, inconsistency and duplication.

Missing data detection. This study mainly focuses on analyzing the accumulated temperature sequence of ≥ 10 ℃ in Jixian County. The initial day of ≥ 10 ℃ in Jixian County usually occurs at the end of April or the beginning of May, and the final day usually occurs at the end of September or the beginning of October. Therefore, the missing data of the daily mean temperature data during the crop growth season (from May to September) of the 7 regional weather stations were counted, as shown in Fig. 2. Overall, there were more missing records at each station during 2007–2011, and the data continuity and integrity have been good since 2012. Therefore, this study only uses data from 2012 onwards and mean imputation is adopted to minimize the impact of occasional missing data.

Outlier detection. In this study, the 5-times standard deviation method was selected for detection. After analyzing the dispersion degree of the data from May to September since 2012, no abnormal data were found.

Consistency and duplicate data check. Check the dataset for consistent formatting of dates, times, locations, etc., and also logical contradictions and duplicate records (such as reversed years/times and incorrect location info); check the relationship between hourly records and max/min values (e.g., Tmax < Tmin, hourly records exceeding Tmax or below Tmin); and check for duplicate year/time records. The checks show consistent and non-duplicate data across all regional station datasets.

Observational environment of Regional Stations. On-site inspections of the observational environment of each regional weather station revealed that the environments of three stations, namely Yongan, Jixian, and Shengchang, are poor. The Yongan station is only 12 m away from the township government's administrative building, which is about 13 m high. The Shengchang station is even closer, at a mere 2.6 m from the administrative building. The Jixian regional station is 14 m from the township government's administrative building, which is about 14 m high. Additionally, there is an 8-m-high auxiliary building just 8 m away. These three regional weather stations are too close to the buildings, which undermine the accuracy of meteorological data by blocking sunlight and altering wind direction and speed. Moreover, as the township government area is a hub for local offices and residences, the combination of buildings and human activities creates a more pronounced local urban heat-island effect, further diminishing the accuracy of the observation data. Therefore, this study discards the data from these three Regional Stations.

2.3 Calculation methods for determining the period and accumulated temperature of ≥10 °C

Calculation method for the period and accumulated temperature of ≥ 10 °C The 5-day moving average method is employed to determine the first day and the last day of the period with daily mean temperature ≥ 10 °C. Specifically,

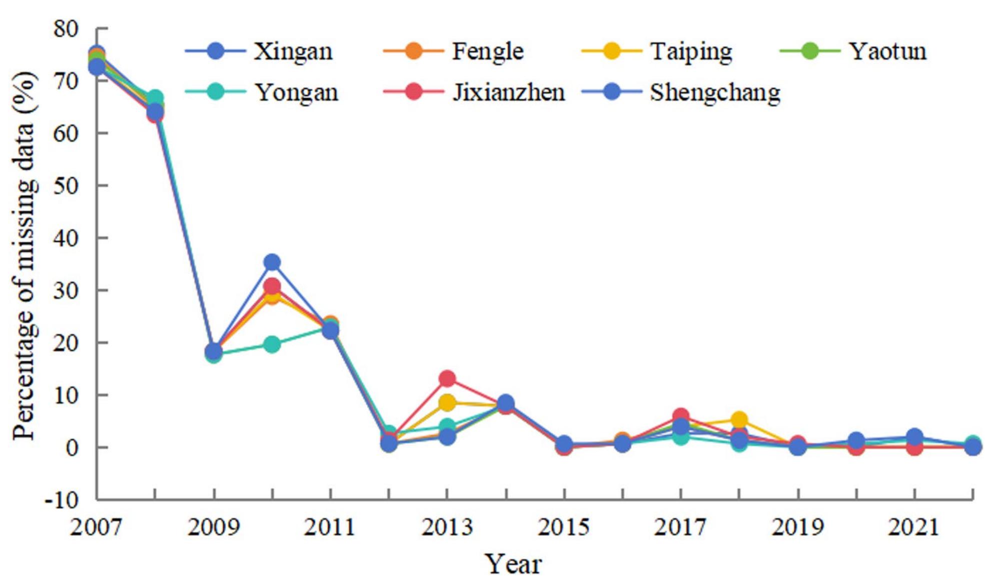

Fig. 2 Percentage of missing daily mean temperature records during the crop growth season of regional stations in Jixian County since their establishment

the first day is the date on which the daily mean temperature first reaches or exceeds 10 °C in the moving-average temperature series, and the last day is the date when the daily mean temperature first drops to or below 10 °C in the moving-average temperature series. The number of consecutive days is the duration between the first day and last day. The accumulated temperature is the sum of the daily mean temperatures that are greater than or equal to 10 °C during the period from the first day to the last day.

Calculation method for the 80% guarantee rate accumulated temperature The guarantee rate refers to the sum of the frequencies. Specifically, it refers to the frequencies of a certain meteorological element being above (or below) a certain threshold within a certain period of time (Zhao et al. 2015).

Considering the stability of heat resources, in agricultural production, the ≥10 °C accumulated temperature with an 80% guarantee rate is usually used as the indicator for dividing the accumulated temperature zones (Li et al. 2010; Zhao et al. 2015; Mo et al. 2016; Qi et al. 2017; Zhang et al. 2017; Liu et al. 2019; Shen et al. 2020). For instance, if a certain region has an accumulated temperature of 2600 °C with an 80% guarantee rate, this indicates that the heat resources in that area exceed 2600 °C in 80% of the years. Such a value of 2600 °C then serves as the basis for classifying the region into the second accumulated temperature zone (ranging from 2500 °C to 2700 °C).

The guarantee rate is calculated by the empirical frequency method (Agro-climatology Teaching Group of Beijing Agricultural University, 1987). First, sort the ≥10 °C accumulated temperature values in descending order; then, calculate the guarantee rate according to the following formula:

$$r = \frac{m}{n+1} \times 100\% \tag{1}$$

where r refers to the guarantee rate (%), n refers to the total number of samples, and m refers to the cumulative frequency. For example, with $n=30$ and $r=80\%$, m equals 24.8. Perform linear interpolation on the 24th and 25th data points (x_{24} and x_{25}) to get the 80% assurance value (x_80%), that is,

$$x\_80\% = x_{24} - (x_{24} - x_{25}) \times 0.8 \tag{2}$$

2.4 Trend analysis method

The least-squares method is employed to estimate the linear trend or change rate of the air temperature and accumulated temperature, and the Student's t-test method is utilized to evaluate the statistical significance of the trend. If the trend passes the test at the confidence level of $p<0.05$ (95% significance level), it is considered that the trend is statistically significant (Ma et al. 1993; Wei 2007).

2.5 Station classification and selection of reference stations

The 4 regional and 2 farm meteorological stations, situated in rural areas or farms with few surrounding buildings and sparse population (Fig. 3), are classified as rural stations in this study.

Most of the national stations in Heilongjiang Province are located in or near cities or towns. Based on the classification proposed by Tysa et al. (2019), the Jixian Station is classified as the U1 type, namely, the station with the least urbanization influence or a rural station. Evidently, this station is less impacted by urbanization. However, this classification

Fig. 3 Environment around meteorological stations of Erjiuyi farm (Top) and Youyi farm (Bottom) (Photographed by Li Chen on July 12, 2023)

is based on the 2015 satellite data and surrounding buildings have increased in the past decade. The county seat, with ~90,000 people, has the county's most concentrated buildings and population. Many buildings also have stood near the observation ground (Fig. 4). In comparison with the Regional Stations and Farm Stations in the county, its observation records are subject to a certain degree of urbanization influence. Given the small number of stations in the observation network, the deviation of the air temperature and accumulated temperature data of one station will impact the analysis of the accumulated temperature distribution and change in the whole county. Therefore, in this study, the urbanization bias in the accumulated temperature series of this station is assessed and corrected.

In order to assess and correct the urbanization bias of the air temperature and accumulated temperature data of Jixian Station, it is necessary to select reference meteorological stations. The maximum distance between the reference station and the target station is determined by the purpose of the research and the type of climate variables (Peterson et al. 1997; Janis et al. 2004; Ren et al. 2010; Wen et al. 2019b). Jixian is a small county, located in the Sanjiang Plain, with undulating hills over 100 km to its southeast. When choosing reference stations, priority is given to those also in plains. In this study, reference stations are stipulated to be within a circle centered at Jixian Station with a radius of 100 km. Erjiuyi Farm Station and Youyi Farm Station are rural stations with good representativeness. They are 39 km and 78 km away from Jixian Station, respectively. Moreover, the nearby urban built-up area around the two stations is very small, so the impact of urban development on the observation is limited. In addition, they also have long-term observation data series. Although there have been relocations, each relocation distance is quite short, and the altitude change is minimal. Therefore, these two Farm Stations, Erjiuyi Farm station and Youyi Farm station, are selected as reference stations. The daily mean temperature or accumulated temperature values of these two stations are used to establish a reference sequence, which is then used to assess and correct the urbanization bias of the accumulated temperature of Jixian Station.

2.6 Assessment and correction of urbanization bias of annual mean air temperature of Jixian station

Figure 5 shows that the annual mean air temperature of Jixian Station has generally been higher than that of the reference series. The average difference between the two temperature sequences from 1961 to 2022 is 0.73 °C. The difference must have been caused by the urban heat island effect in Jixianzhen, because the two reference stations are actually lower in altitude (34 m lower than Jixian). Specifically, the temperature change rate of Jixian Station is 0.42 °C/decade, while the average change rate of the annual mean temperature at the reference stations is 0.34 °C/decade. The difference between them, which represents the urbanization effect, is 0.08 °C/decade. This indicates that at least 18.8% of the upward trend of the annual mean air temperature at Jixian Station is caused by urbanization. Therefore, from both the perspective of the climatological means and the climate trend, Jixian Station shows obvious influence from urbanization, and there is a significant urbanization bias in the historical air temperature data series at the town station.

The changes in the ≥10 °C accumulated temperature of Jixian Station and the reference sequence from 1961 to 2022 are presented in Fig. 6. Both the ≥10 °C accumulated temperature of Jixian Station and the reference sequence exhibited a pronounced upward trend over the past 62

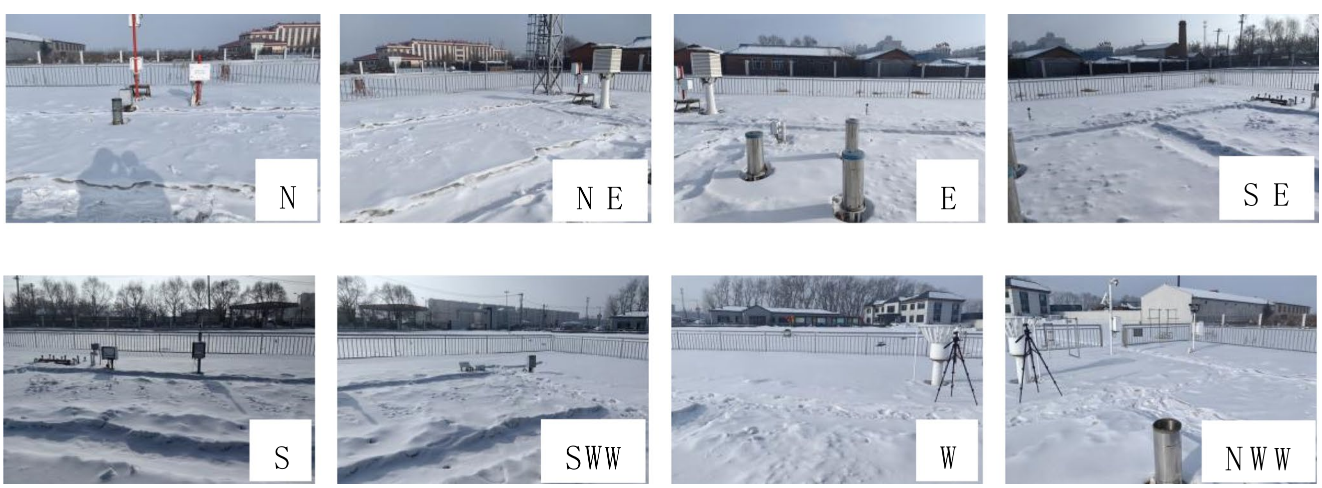

Fig. 4 Buildings around Jixian national station (Jixian station). There are many low-altitude buildings at each direction of the observation ground (Photographed by Chao Mu at 10:50 Beijing time, January 26, 2025)

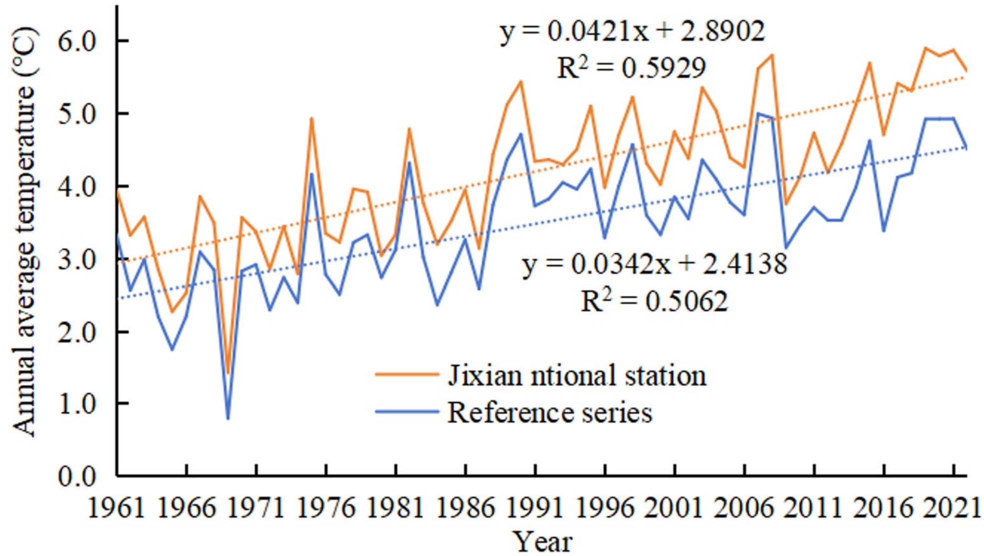

Fig. 5 Temporal changes in the annual mean air temperature of Jixian national station and the reference temperature sequence from 1961 to 2022

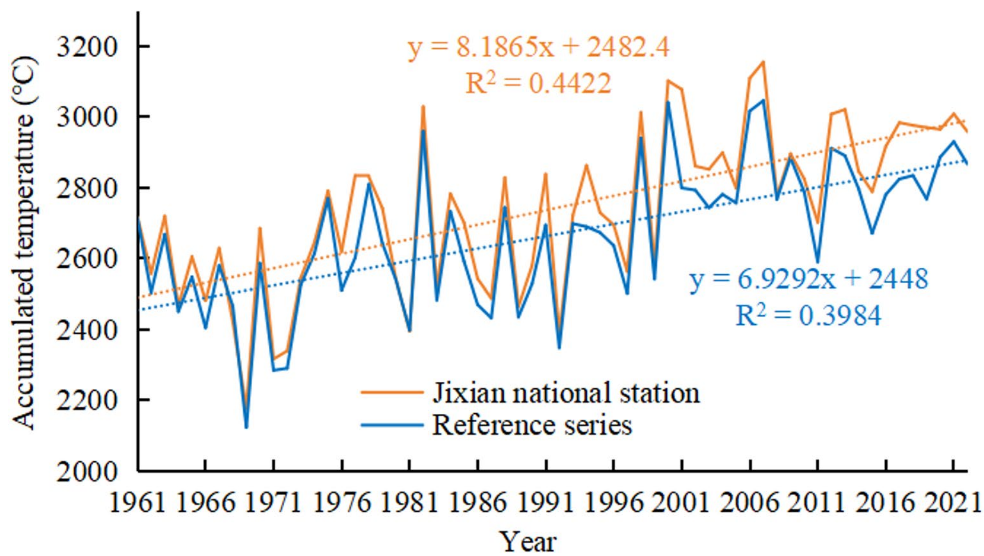

Fig. 6 Temporal changes in the ≥10 °C accumulated temperature of Jixian national station (Jixian Station) and the reference stations (average of the two farm stations) from 1961 to 2022

years. Their change rates are 81.9 °C/decade and 69.3 °C/decade, respectively. At least 18.0% of the upward trend of the ≥10 °C accumulated temperature at Jixian Station since 1961 is attributable to an urbanization effect, which is comparable to the contribution of urbanization to the upward trend of the annual mean air temperature. It can also be observed from Fig. 6 that before the 1980s, the difference in the ≥10 °C accumulated temperature between Jixian Station and the reference stations was not substantial. However, the gap became increasingly significant after 2000.

Therefore, the ≥10 °C accumulated temperature of Jixian Station is corrected directly for urbanization bias. Specifically, the correction method is to fully align it with the average accumulated temperature sequence of the two reference stations. In this way, not only is the change trend of the accumulated temperature rectified, but also the climatological mean of the accumulated temperature is adjusted. As a result, the corrected≥10 °C accumulated temperature of Jixian Station has largely eliminated the urbanization bias.

2.7 Temporal extension of the ≥ 10 ° C accumulated temperature series of regional stations

Taking the ≥10 °C accumulated temperature of Jixian Station from 2012 to 2022 as the independent variable, the accumulated temperature of each regional station is regressed and extended to 1991 using univariate linear regression. The slope, intercept, and fitting degree of the fitting equation are presented in Table 2. Moreover, the fitting equations of the four stations all passed the significance test at the $p<0.01$ level.

Table 2 Slope, intercept, and fitting degree of the ≥ 10 °C accumulated temperature fitting equation of each regional station

Regional Station	Slope	Intercept	Goodness of fit R^2	Root Mean Square Error RSME (°C)
Xingan	0.9418	107.19	0.9784	9.6
Fengle	0.7627	615.13	0.6031	42.6
Taiping	0.8171	407.33	0.8373	24.8
Yaotun	1.2776	−844.47	0.6393	66.1

2.8 Research scheme and steps for ≥10 °C accumulated temperature

Figure 7 illustrates the classification of the meteorological stations, and the functions of the stations in generating accumulated temperature maps. The maps were generated by using ArcGIS software with built-in Kriging interpolation method. The steps of calculation and analysis are summarized as follows.

1) Calculate the average numbers of days and mean temperature between the start and end dates of the periods with temperatures ≥ 10 °C for each station;
2) Convert the mean temperature of the ≥ 10 °C periods to the average sea-level temperature using stations' altitude and the annual average temperature lapse rate of 0.6 °C/100 meter;
3) Interpolate station-level sea-level temperatures and ≥10°C duration using ArcGIS Kriging to derive grid values;
4) Use elevation data and the 0.6°C/100-meter temperature lapse rate to derive each grid's average temperature for ≥10°C period, and then multiply this by the average days to get ≥10°C accumulated temperature for each grid;
5) Clip the accumulated temperature map to Jixian County's boundary to obtain the localized map of ≥10°C accumulated temperatures.

3 Results

3.1 Regional average ≥10°C accumulated temperature series in Jixian county

The regional average ≥ 10 °C accumulated temperature series in Jixian County from 1991 to 2022 was derived from the average values of 6 meteorological stations, including Jixian Station, Erjiuyi Farm Station, and 4 Regional Stations, as depicted in Fig. 8. The accumulated temperature at Jixian Station has been adjusted for urbanization bias. The average accumulated temperature in Jixian County from 1991 to 2022 is 2792.7 °C. The disparity between the maximum value (in 2007) and the minimum value (in 1992) reaches 693.6 °C. Since 1991, the average accumulated temperature has exhibited a significant upward trend ($p < 0.01$), with a change rate of 77 °C/decade. Nevertheless, the increase in

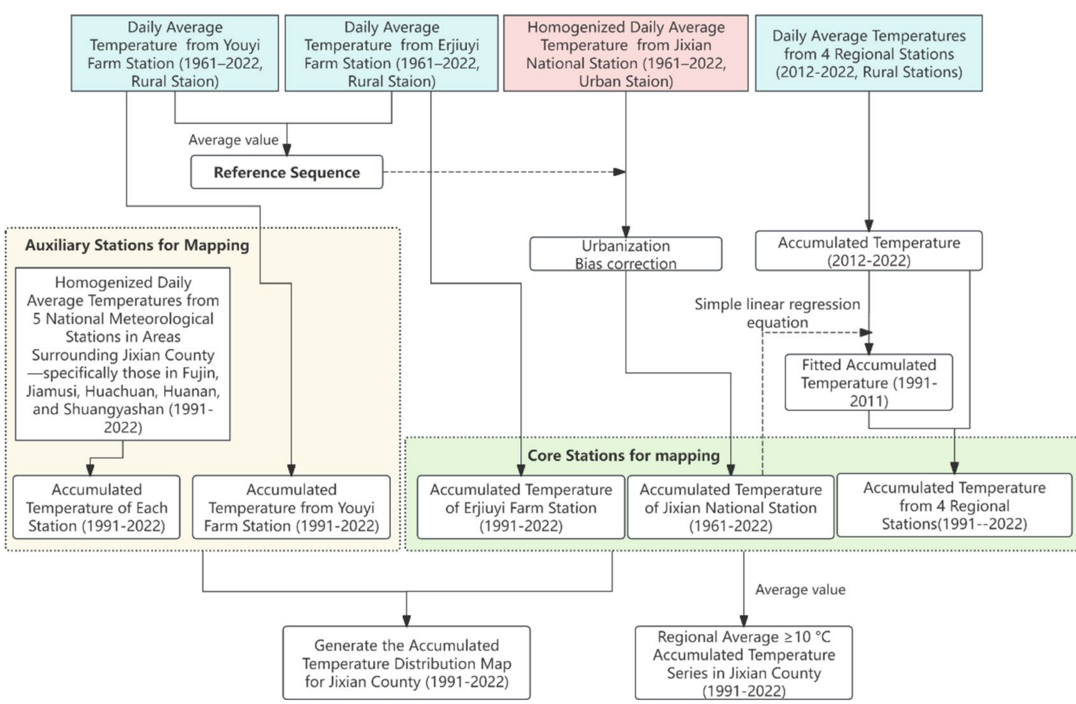

Fig. 7 Research workflow for ≥ 10 °C accumulated temperature in Jixian County, Heilongjiang Province, China

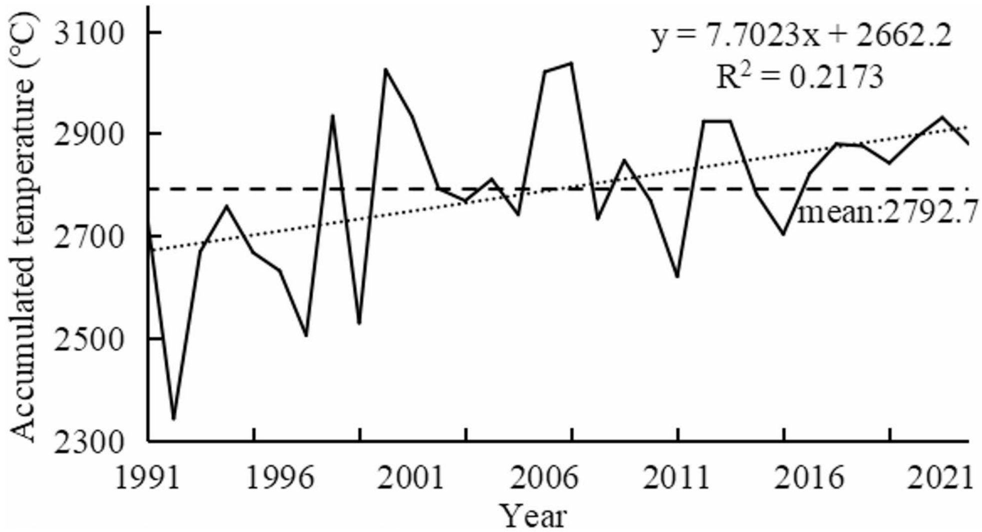

Fig. 8 The variation in the regional average ≥ 10 °C accumulated temperature in Jixian county from 1991 to 2022. Dashed line denotes average, and dotted line indicates linear trend

the average accumulated temperature mainly took place in the first 10 years of the sequence (The linear regression equations of accumulated temperature for 1991–2000 and 2001–2022: $y = 26.757x + 2534.2$, and $y = 1.4618x + 2826.5$, where x represents the number of years in the sequence). Since 2000, there has been no obvious change, and the county-wide average has even slightly declined, which is in line with the climate warming slow-down stage in Northeast China (Sun et al. 2018).

The largest average ≥ 10 °C accumulated temperature, 2822.9 °C, occurs at Yaotun Station, followed by Xingan Station (2810.6 °C), Fengle Station (2804.5 °C), Erjiuyi Station (2787.2 °C), Jixian Station (2778.0 °C), and Taiping Station (2752.8 °C), respectively. The standard deviations of the average ≥ 10 °C accumulated temperature range from 128.7 °C at Fengle station to 215.4 °C at Yaotun station (Fig. 9).

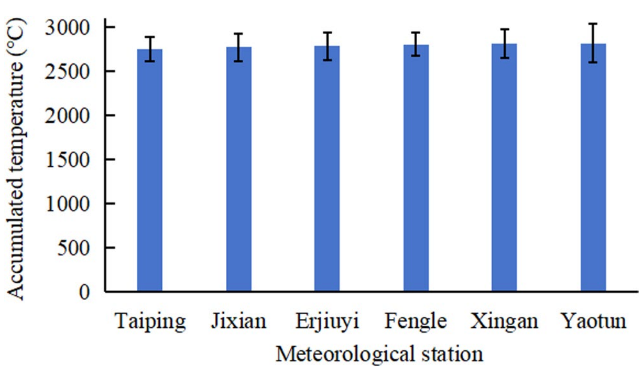

Fig. 9 The average value and standard deviation of ≥ 10 °C accumulated temperature from 1991 to 2022 at each meteorological station in Jixian county. The error bar denotes one standard deviation around the average

3.2 Distribution of ≥10 ℃ accumulated temperature zones before and after urbanization bias correction

In order to ensure that the accumulated temperature distribution at the boundary of Jixian County is relatively smooth, five nearby National Stations outside of Jixian County, namely Fujin, Jiamusi, Huachuan, Huanan, and Shuangyashan Stations, were included in the analysis.

The spatial distribution of ≥ 10 °C accumulated temperature zones was analyzed based on two sets of air temperature data. The first set is the homogenized air temperature data of Jixian county and the five surrounding National Stations; the second set is the data of Jixian County after urbanization bias was corrected for Jixian Station. According to the classification of Tysa et al. (2019), among the five nearby National Stations around Jixian, Fujin, Huachuan, Huanan, and Shuangyashan National Stations belong to the urbanization level U2 (The second lowest level of urbanization), while Jiamusi National Station belongs to the urbanization level U3 (Low to medium level of urbanization); urbanization has a more notable impact on five national meteorological stations than on Jixian, with Jiamusi Station (U3) being the most severely affected based on the classification using 2015 satellite data.

Although Shuangyashan Station is classified as U2, on-the-spot investigation found that this station is actually located in the city. Probably due to the relatively small size of the city, most of the areas outside the 16 buffer zones met the standards set at that time. Meanwhile, by comparing with nearby meteorological stations, it was found that the overall temperature was significantly higher, indicating the possible impact of urbanization. Therefore, this station should be classified as U3 or even higher-level urban station.

Thus, when drawing the spatial distribution map of accumulated temperature zones, the data from Jiamusi and Shuangyashan Stations were discarded, and the homogenized data from Fujin, Huachuan and Huanan Stations, which were less affected by urbanization, as well as the urbanization bias-corrected data from Jixian Station, two Farm Stations, and four Regional Stations, were adopted.

The distribution of ≥10 °C accumulated temperature from the first dataset (homogenized data without urbanization-bias correction) is shown in Fig. 10a. Specifically, except for some relatively high-altitude areas in the southwest that fall into the third and fourth accumulated temperature zones, most of Jixian County lies within the first and second accumulated temperature zones. Moreover, the first accumulated temperature zone is situated in the central and eastern parts of the county, while the second accumulated temperature zone is primarily located in the western part..

The distribution of ≥10 °C accumulated temperature from the second dataset (data after urbanization bias correction for Jixian Station) is presented in Fig. 10b. After the urbanization-bias correction, most areas of Jixian County fall into the second accumulated temperature zone, while the areas at relatively high altitudes in the southwest are in the third and fourth accumulated temperature zones. When compared with Fig. 8a, the most prominent change in the accumulated temperature zone distribution after the bias correction is the disappearance of the first accumulated temperature zone. All areas that were originally in the first accumulated temperature zone have now shifted to the second accumulated temperature zone.

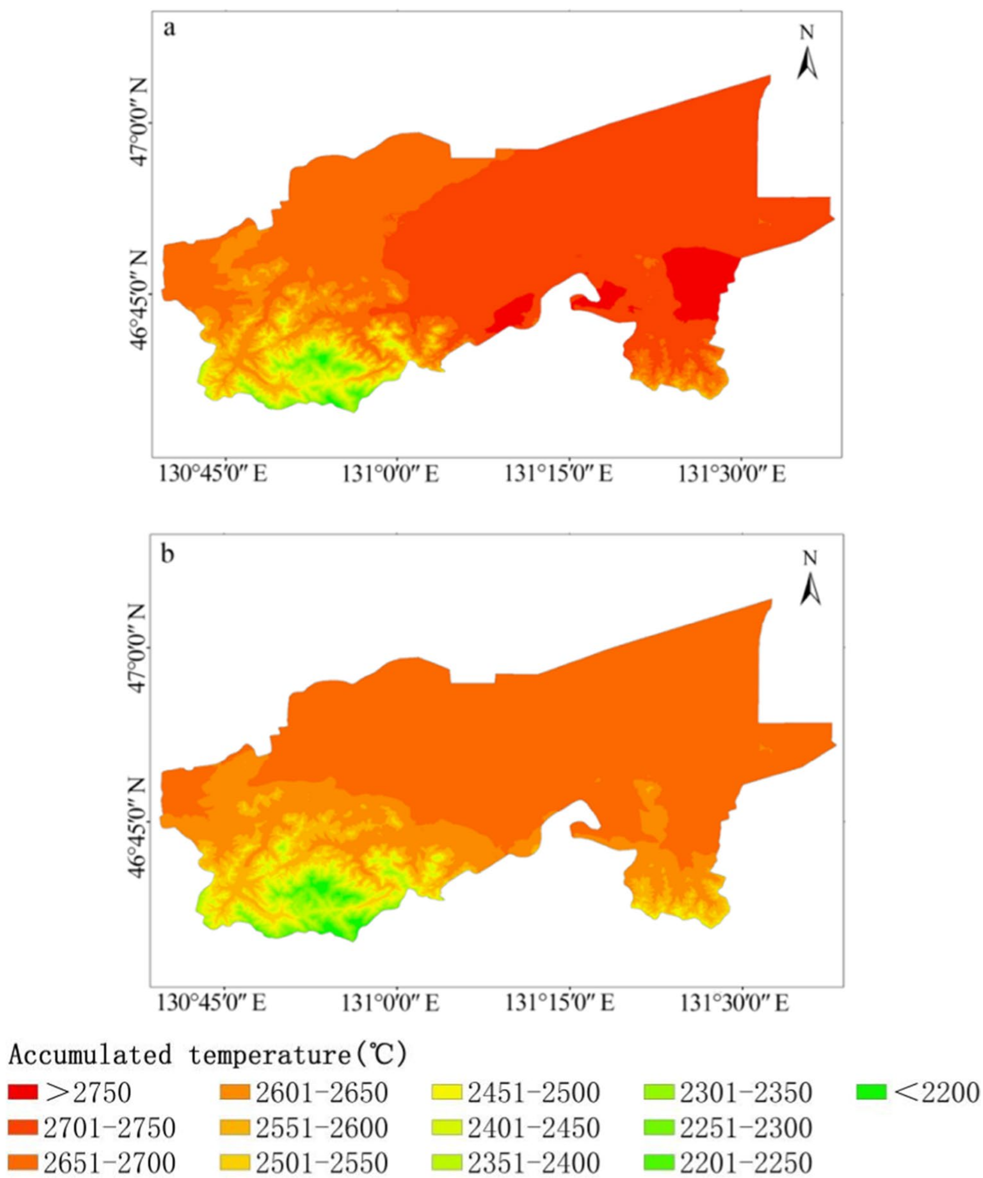

Fig. 10 Distribution maps of ≥10 °C accumulated temperature zones in Jixian County. a, based on homogenized data without urbanization-bias correction; b, based on homogenized data after urbanization-bias correction

4 Discussion

With the continuous deepening of the urbanization process in recent decades, the observational environment of China's National Stations has been significantly impacted by urban expansion. The rise in air temperature observed by these stations is attributable not only to global warming and the internal climate variability of the climate system, but also to the urbanization effect around the observational stations. Numerous studies have confirmed that there is a significant urbanization bias in the surface air temperature data observed by National Stations. For example, from 1961 to 2013, the surface air temperature in China rose by 1.44 °C, with the urbanization contribution reaching 33.3% (Sun et al. 2016). Between 1981 and 2007, the urbanization bias in the monthly average air temperature in eastern China was 24.2% (Yang et al. 2011). From 1961 to 2000, the urbanization bias in the surface air temperature series of national basic and reference stations in North China reached 37.9% (Zhou et al. 2005). From 1961 to 2004, the urbanization bias in the air temperature upward trends of large-and medium-sized city stations and national stations in Southwest China were 57.6% and 45.3% respectively (Tang et al. 2008). From 1961 to 2000, the contribution of urbanization to the upward trend of air temperature at Beijing National Stations was 71.0% (Chu et al. 2005). A recent study (Zhang et al. 2021) has revealed that, even in the global land area, there is an obvious urbanization bias in the existing homogenized surface air temperature data series, which calls for further attention.

Previously, researchers paid more attention to the imhomogeneity in long-series air temperature data. In regions like China, most meteorological stations were relocated because of the ever-growing urban constructions, leading to discontinuous observation series. However, when the discontinuity caused by station relocation is homogenized, the urbanization effect in the original observation data is restored in the corrected temperature data series (Zhang et al. 2014). Meanwhile, even if some stations are relocated to the suburbs, the rapid urbanization process means that they are surrounded by buildings a few years later, and the observational environment is still affected by the intensified local urbanization. In any case, regardless of whether the temperature series of the existing National Stations in China mainland are homogenized, the upward trend and the climatological mean of the surface air temperature will be significantly larger than those in the suburbs and vast farmlands.

The bias in the air temperature data series caused by urbanization hinders the detection and attribution of regional and global climate change, leading to a significant overestimation of the results of large-scale climate warming. To address this issue, some studies have started to correct the data of China's national stations, and obtained the monthly mean surface air temperature data after urbanization-bias correction (Wen et al. 2019a, b). The corrected data have largely eliminated the urbanization bias and have improved the reliability of regional climate change monitoring and assessment. However, in regional and global agro-climatic resource assessment, the possible impact of the urbanization bias in long-series observation data in the past has not been fully recognized. This situation may be attributed to two reasons: firstly, there is insufficient research in many regions, and the urbanization bias in large-scale observation network data has not been noticed; secondly, most agricultural areas in the world are in the mid-latitudes and tropical regions. These regions have sufficient heat resources, small temperature increases, and relatively small changes in accumulated temperature or heat condition. Even if there is a certain degree of urbanization bias in the temperature data of the mid- to low latitude regions, its impact on the assessment and zoning of agricultural heat resources is not significant.

In China, research has been carried out on the urbanization bias in surface air temperature data, rich results have been accumulated, and scientific understanding has been significantly improved. In Heilongjiang Province, which is located in the mid-high latitudes, heat resources are generally insufficient. The air temperature and accumulated temperature during the growth season are the key limiting factors for the adjustment of agricultural planting structure and variety layout. Whether to consider the systematic bias in observation data has a very obvious impact on the results of agro-climatic resource assessment. For example, if only the quality-controlled and homogenized air temperature data are used to calculate the distribution results of accumulated temperature zones and guide the adjustment of the agricultural structure and variety layout, problems such as out-of-zone planting and yield reduction will occur, putting the agricultural heat resources and crop demand conditions in a tight balance state and facing a greater risk of agricultural disasters.

This radical agricultural planning and variety layout expose food production to the risk of climate-induced cold damage, a risk that materializes due to large inter-annual climate variability. In the Sanjiang Plain, including Jixian County, the difference between the annual maximum and minimum values of the ≥10 °C accumulated temperature from 1991 to 2020 exceeded 600 °C. Moreover, with the slowdown of regional climate warming (Li et al. 2015; Sun et al. 2018), the low-temperature cold damage during the growing season in Heilongjiang Province has shown an upward trend in recent years. For example, from mid-May to the end of June 2024, Heilongjiang Province witnessed a rare continuous low-temperature event in nearly 40 years. During this period, the average temperature was merely 16.3 °C, 1.4 °C lower than normal. This not only set the lowest record for the same period since 1984 but also ranked as the 7th lowest for the same period since 1961. Notably, the top 6 low-temperature years (1969, 1972, 1974, 1976, 1981, and 1983) were all marked by low-temperature cold damage during the growth season. In these years, grain production in Heilongjiang Province suffered a severe decline. Specifically, in 1969, 1972, and 1974, the grain output decreased by 20% (Guo et al. 2009). Similarly, from June to the beginning of late July 2019, the daily average air temperature in most agricultural areas of Heilongjiang Province was remarkably lower. The ≥10 °C accumulated temperature was 50–100 °C less than normal, and the sunshine hours were 31–160 h fewer. Consequently, crop growth was sluggish, seedlings were small and weak, and the development period was delayed by 7–10 days. In some northern regions, soybean growth even halted, and in certain areas, rice failed to tiller.

Therefore, the urbanization bias in air temperature data used for heat resource zoning demands closer attention. When performing refined zoning of accumulated temperature zones or assessing heat resources, correcting the urbanization bias in air temperature data is especially crucial to minimize agricultural production risks arising from the overestimated regional warming and the resulting out-of-zone planting. In the study by Li et al. (2022), only 31 meteorological stations were available in Heilongjiang Province, and these stations were rather sparsely distributed. When analyzing county-level accumulated temperature changes and their urbanization effects using this dataset, the spatial resolution was insufficient to meet the research requirements. This paper is the first to utilize urbanization-bias-corrected data for county-level heat resource assessment in Heilongjiang Province.

The uncertainties of this study are primarily manifested in the following two aspects: Firstly, the surroundings of the two farm meteorological stations have long been dominated by field crops. While no inhomogeneity issues were identified through inspections, urbanization may still affect these two farm stations, due to the sparse residential buildings. As a result, the correction of urbanization bias for Jixian National Meteorological Station in this paper remains relatively conservative, and urbanization biases may still persist in the accumulated temperature distribution. Secondly, in the process of drawing the accumulated temperature distribution map, data from the 5 surrounding national meteorological stations were used as auxiliary references. As no urbanization bias correction was applied to these stations, this practice may have some impact on the accumulated temperature interpolation near the boundaries. However, these aforementioned issues will not significantly influence the key assessment conclusions of this paper. In future research, more rigorous corrections for urbanization bias will be applied to the data from the two farm stations once appropriate reference stations are identified. Additionally, the urbanization bias of the five surrounding national meteorological stations will be assessed and corrected to improve the reliability of auxiliary temperature data.

5 Conclusions

Based on the urbanization- bias-corrected data at Jixian National Meteorological Station, this paper has completed an analysis of accumulated temperature change in Jixian County, with data support from farm meteorological stations and regional meteorological stations within Jixian County. The main conclusions are as follows:

1) From 1961 to 2022, the annual mean air temperature of Jixian Station exhibited a significant upward trend, with a change rate of 0.42 °C/decade. The impact of urbanization on the temperature increase was more than 0.08 °C/decade, and the contribution of urbanization to the warming trend reached at least 18.8%. Similarly, during the same period, the ≥10 °C accumulated temperature of Jixian Station also showed a significant upward trend, with a change rate of 81.9 °C/decade, and the contribution of urbanization to the increase in the accumulated temperature was at least 18.0%.
2) After eliminating the urbanization bias, the regional average≥10 °C accumulated temperature in Jixian County from 1991 to 2022 was 2792.7 °C, which also showed a significant upward trend at a rate of 77 °C/decade. Nevertheless, since 2000, the regional average accumulated temperature has remained unchanged.
3) The distribution of ≥10 °C accumulated temperature zones in Jixian County is determined by the observation data used. In the accumulated temperature zone distribution derived from urbanization-bias-corrected data, the majority of the county's areas fall into the second accumulated temperature zone. The first accumulated temperature zone that was initially obtained from only homogenized data has disappeared.

The results of this study are more consistent with the actual growing-season heat condition, helping in reducing agricultural production risks caused by overestimated regional warming and the subsequent out-of-zone planting, and can provide a more reliable decision-making basis for local agricultural departments and farmers. Moreover, the fundamental ideas and methods presented in this research can serve as a reference for heat resource assessments under the background of global warming in other agricultural regions across the globe.

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Author contributions L. Chen: Conceptualization, methodology, investigation, Writing-original draft, field investigation; G. Ren: Conceptualization, methodology, supervision, field investigation, review & editing; C.M. Zhou: Methodology, investigation, visualization, field investigation; L. Wei: Visualization; Y. Li: Visualization, review & editing; H. Shi: Field investigation; S. Wu: Field investigation.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate No ethic issue involved. All the authors consented to the participation in the research.

Consent for publication The authors declare that they have no conflict of interest.

Competing interests The authors declare no competing interests.

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