Bias Analysis and Correction of Ground Surface Temperature Observations across China

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ABSTRACT

Based on the ground surface temperature (GST) and snow surface temperature (SST) measurements during the period of adjustment from manual to automatic observation systems in China, the influence of observation methods on GST and its relationship with snow cover is analyzed. GST is corrected by SST, and the correction effect is evaluated. The results show that, during the parallel observation period, the winter GSTs from automatic observations are generally higher than those from manual observations, with the automatically observed national daily GST 1.18°C higher. The adjustment has a greater impact on GSTs at 0200, 0800, and 2000 Beijing Time (BT) than at 1400 BT, and it has the greatest impact in Northeast and Northwest China, with deviations of 5.24 and 2.09°C, respectively.

Key words: ground surface temperature (GST) in winter, snow cover, correction, China

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1. Introduction

Ground surface temperature (GST) represents the temperature at the interface between the atmosphere and the land surface. It is not only an important climate resource, but also a key parameter in the land–atmosphere interaction and flux transfer processes, which plays an important role in the energy balance of the earth–atmosphere system (Liu and Avissar, 1999; Wen et al., 2003; Liu et al., 2014; Trigo et al., 2015; Liang et al., 2020). GST can reflect the spatial distribution characteristics and long-term evolution of the thermal equilibrium on the land surface, and it is also widely used in various fields of study including climate change and prediction, water cycle, vegetation monitoring, urban climate, and other environmental issues (Tang et al., 1988; Kogan, 2001; Su, 2002; Arnfield, 2003; Weng et al., 2004; Lu et al., 2006; Zhou and Huang, 2006; Kalma et al., 2008; Wang et al., 2016; Wang, C. et al., 2017; Li et al., 2018; Yang et al., 2020). In addition, it is one of the important performance parameters in the International Geosphere–Biosphere Program (Townshend et al., 1994), as an indispensable variable for estimating the evapotranspiration of soil moisture. By using the downscaled GST, Jiang and Weng (2017) established a model for estimating the hourly soil moisture and evapotranspiration. The response of evapotranspiration to precipitation under different underlying surface conditions has also been analyzed. By assimilating the GST and estimated soil moisture into hydrological models, the key parameters in land...
surface processes can be better identified (Wanders et al., 2014), and the accuracy of the models can be improved (Dumedah and Coulibaly, 2013). Applying the GST to urban climatic research improves understanding of the environmental impact of urban planning and can help to identify key areas where measures should be taken to implement sustainable development (Zullo et al., 2019).

In China, regular observation of the GST (including the underlying surface temperature and soil temperature at different depths) has been carried out since the 1950s, and there have been more than 800 national basic reference stations reliably recording GST data since 1960. According to China’s Specifications for Surface Meteorological Observation (CMA, 2003), the GST is observed by using a glass liquid thermometer or a platinum resistance temperature sensor placed on the horizontal ground and half buried in the soil, half exposed to the air. The buried part must be closely attached to the soil with no surrounding space, and the exposed part should be kept clean. When measuring the GST, the observer should step on a footplate placed 40 cm north of the thermometer and the value should be read directly from the above, avoiding removal of the thermometer under normal circumstances, with a recording accuracy of 0.1°C. If the thermometer is flooded, it should be taken out of the water and read quickly. If the thermometer is buried in snow, it should be carefully removed and then installed horizontally on the unbroken snow surface with half of it buried to continue the observation. The daily observations are taken at 0100, 0700, 1300, and 1900 Beijing Time (BT, UTC + 8 h) until about 1960, since then it has been changed to 0200, 0800, 1400, and 2000 BT. In addition, the observation instruments should be carefully checked to ensure proper operation every day after the 2000 BT recording, or following extreme weather events such as thunderstorms or strong winds.

Like most national meteorological services around the world, observation stations in China have gradually advanced from manual to automatic systems since 2000. The replacement of manual observational instruments is required to be done with great care. Based on China’s Specifications for Surface Meteorological Observation (CMA, 2003), manual and automatic GST observation systems differ mainly in three aspects. First, the observation instrument has changed from glass liquid thermometers during manual observations to platinum resistance temperature sensors during automatic observations. Second, the automatic observation site is 30 cm away from the manual observation site, which may have some minor effect on observational records. Third, their observation methods are different when the ground is covered with snow. For manual observations, the thermometer is taken out of the snow and installed on the snow surface to continue the observation, as described above. However, the platinum resistance temperature sensor used in automatic observations continues working when flooded or covered by snow. In other words, in this instance, manual observations measure the temperature above the snow surface, while automatic observations measure the temperature beneath the snow, which evidently cannot represent the real GST. Liu et al. (2008) analyzed the effects of these three factors on both types of observations, and found that when there was snow covering the ground, the GST from automatic observations was higher than that from manual observations. The obvious difference is mainly attributed to the different methods used by the two observation systems. Without the influence of snow, any difference is mainly caused by the type of instrument.

The deviation between the GST and air temperature during the winter in northern China has dramatically increased since 2005, which may be due to the increasing snow depth in northern regions (Wang Y. J. et al., 2017). The deviations from the daily average GST in China caused by the transition from manual to automatic observations have been analyzed, and the bias attributed to the different types of the recording instrument has been corrected at 686 stations. However, stations with larger GST deviations caused by different observational methods during periods of snow cover were not included in the previous research (Xu et al., 2019).

This paper will focus on the serious deviations of GST during the snow cover period. The main causes are investigated and reasonable corrections are made. The main goal is to remove significant system deviations caused by the transition from manual to automatic observations during periods of snow cover, thus helping to improve the accuracy of results for the analysis of long-term GST changes and providing more reliable data for the study of land–atmosphere interactions as well as for the evaluation of land surface reanalysis products.

In this paper, by using parallel observations of the GST, snow depth, and snow surface temperature (SST) at the fixed times of 0200, 0800, 1400, and 2000 BT during the period of the transition from manual to automatic observations, an analysis is conducted on the impact of the adjustment of observation systems on the winter GST in China. By comparing the differences between SST and GST from both automatic and manual observations during the snow cover period, the influence of snow depth on the winter GST across China is investigated. The possibilities of reliably correcting GST with SST data are
further explored. Finally, the climate change characteristics of winter GST in China before and after the correction of the GST deviation are evaluated.

2. Data and methods

The parallel observation data used in this study are derived from the dataset of manual and automatic weather station observations in China, collected by the National Meteorological Information Center. The dataset includes 823 stations in total; 35 stations have been excluded from this study because the effective length of their data is less than 10 days. The data used are the GST observed at fixed times (0200, 0800, 1400, and 2000 BT) during the parallel observation period from 788 national meteorological stations in China. To identify possible errors in the observations, quality control of the parallel observations is done by checking the climate threshold values and climate anomaly values. Anomalies in the GST data are found at 54 automatic weather stations, accounting for 0.043% of the observation data; and the error rates are 0.054% (0200 BT), 0.048% (0800 BT), 0.023% (1400 BT), and 0.045% (2000 BT). There are anomalies in the manually observed GST at 29 stations, accounting for 0.0014% of the observations; and the error rates are 0.0016% (0200 BT), 0.0011% (0800 BT), 0 (1400 BT), and 0.0029% (2000 BT).

The effective sample size (unit: day) is defined as the number of samples that are recorded in both manual and automatic observations in winter (December–February). Figure 1 shows the start time of the parallel observation data and effective sample sizes in winter at 788 stations. Since 2000, ground observation stations in China have been gradually changed from manual to automatic systems. This process began in the Yangtze River Delta, followed by areas of North and Southwest China, then in areas of Northeast, Northwest, and South China, and most recently in Tibet (Fig. 1). The effective sample sizes of parallel winter observations are more than 180 days (representing 2 yr) for stations in most parts of the country, 90–180 days (1–2 yr) for stations in the Yangtze River basin and Tibet, and less than 90 days (1 yr) for stations in parts of Yunnan and Shanxi provinces.

In addition to parallel observations of GST, the grass surface temperature (GRT)/SST observations are also used in this paper. With the adjustment of observation systems, the method of recording GST also changed (Fig. 2). During snow periods, automatic observations record GST under the snow, while manual observations record GST above the snow surface (CMA, 2003). Therefore, the change in the observation method leads to different meanings of the surface temperature. To solve this problem, GRT/SST observation has gradually been implemented at observation stations in China since 2005. This began in Shanxi Province, followed by Xinjiang Region and the Changbai Mountains area in 2006, and Tibet and Heilongjiang Province in 2007. The top and upper reaches of the Yangtze River and Yangtze River Delta region mostly started after 2013. GRT and SST are observed at the same place by using the same instrument but under different conditions. The GRT/SST sensor is positioned 6 cm above the ground. In the non-snow co-

![Fig. 1. The start time and length of GST data in winter during the parallel observation period.](image-url)
ver period, GRT is observed. In the snow cover period, when snow depth is less than 6 cm, GRT is still observed; but when the snow depth is more than or equal to 6 cm, SST is observed. The sensor is relocated to the original snow surface, which is the same as the manual observation of GST (Fig. 2). The data used in this paper include SST data observed at fixed times at 86 national basic reference stations in northern China since the observation records began.

3. Analysis of deviations in GST between manual and automatic observations

To analyze the differences between winter GST observations in different parts of China during the parallel observation period, the country is divided into eight regions according to the climate division of China proposed by Wang et al. (2004), combined with the geographical division. The divisions and the stations that they contain are shown in Fig. 3. The results show that during the parallel observation period, the national average deviation of the daily GST in winter is 1.18°C (Table 1)—the GST from automatic observations is 1.18°C higher than that from manual observations. The adjustment of observation systems has the greatest impact in Northeast and Northwest China, where the automatically observed daily GSTs is respectively 5.24 or 2.09°C higher than the manually observed one. The daily deviations in North China and the Tibetan Plateau are both below 1.0°C. The regions of central, East, South, and Southwest China are less affected by the change of observation methods, with all the deviations below 0.1°C.

From comparison of the daily GST observations at the four fixed times (Table 1), it can be seen that the adjustment of observation systems has a relatively small impact at 1400 BT, but a greater impact at 0200, 0800, and 2000 BT. In addition, the adjustment has a greater impact on the GST in the north regions than those in the south. In terms of national average, the GST deviation at 1400 BT is only 0.11°C, while those at the other three times are all above 1.0°C. The largest deviation is at 0800 BT (1.73°C), followed by 0200 BT (1.56°C). The deviation at 2000 BT is 1.31°C. For regional average, it can be seen that the GST deviation values are relatively small in low and southern most latitudes in the south (central, East, South, and Southwest China), ranging within 0.5°C. Meanwhile, the differences among the deviations at the four times are also small, especially in Southwest China with the smallest differences between −0.04 and 0.21°C, within a range of 0.3°C. There are obvious differences among the GST deviations at the four times in the northern most and high latitudes of northern areas (especially in Northeast and Northwest China), and the deviation range is significantly larger than that in the southern area. In Northeast China, the GST deviation is only 0.47°C at 1400 BT, significantly smaller than those at the other three times that exceed 5.5°C, leading to an overall difference of more than 5°C among these GST deviations. The nighttime GST deviation in Northwest China also reaches approximately 3°C. In summary, the
automatic observations of winter GST in Northeast China and Northwest China are significantly higher than those from manual observations.

From the distribution of winter GST deviations (Fig. 4), it can be seen that the deviation range of the daily average GST is between −2.0 and 15.7°C across the whole country. The largest variations lie in Northeast and Northwest China. The GST deviations are between −0.1 and 15.7°C in Northeast China, and a similar distribution (between −0.4 and 14.8°C) is found in Northwest China. The deviations are between −1.0 and 4.7°C in North China, and between −2 and 2°C in other regions. From the fixed four time results, it can be seen that the characteristics of the GST deviations are largely consistent with those of the daily average. The variations in Northeast China are greater at 0200, 0800, and 2000 BT, with an average deviation of more than 5°C, indicating that the automatic GST observations are significantly higher than those from manual observations. Although the regional average deviations at 0200, 0800, and 2000 BT in Northwest and North China are smaller than those in Northeast China, extreme values of the deviations all tend to be positive, suggesting that positive deviations exist at most stations in these areas. At 1400 BT, the average deviation in each region is close to 0. At that time, the absolute value of the average deviation is the largest over the Tibetan Plateau with the value of only about 0.96°C, showing that the data at 1400 BT are the least affected by the adjustment in observation systems.

4. Effects of different snow depths on GST observation deviations

As described above, the most obvious GST deviations between manual and automatic observations lie in Northeast and Northwest China, where snow is prone to accumulating in winter. To help to analyze the impact of system changes on GST observations in China during the snow cover period, Fig. 5 shows the variation of average GST deviations with different snow depths. The average daily GST deviation increases at the rate of 0.66°C cm⁻¹ with the increase of snow depth when it is less than 15 cm,
and after that it tends to be stable and remains at about 10°C. When the snow depth is less than 6 cm, the daily GST deviation is generally within 5°C. When the snow depth is greater than 35 cm, the fluctuation of GST deviation becomes greater, due to the reduction in meeting the sampling requirements, although the mean GST deviation remains at about 10°C. Variations of the average GST deviation at 0200, 0800, and 2000 BT are consistent with the average daily GST deviation, and the deviation amplitude at 0200 and 0800 BT is greater than that at 2000 BT. The snow depth has less effect on the mean GST deviation at 1400 BT and there is no obvious characteristic of the positive deviation. As with the daily GST, the fluctuation of GST deviation at 1400 BT increases when the snow depth is greater than 35 cm for the reason stated.

To further investigate the relationship between the GST deviation and snow depth, a scatterplot of the average annual snow totals and daily GST deviation at 788 stations during the parallel observation period is shown in Fig. 6. The results show that the average daily GST deviation is affected by a station’s winter snow totals—generally, the greater the snow total, the greater the GST deviation. The GST deviations are mostly within 2°C when snow totals are less than 200 cm (about 2 cm day$^{-1}$), and they are within 5°C when snow totals are between 200 and 500 cm, with the exception of three stations that surpass 5°C. The GST deviations at 83% of the
stations whose snow totals are more than 500 cm exceed 5°C. Stations with GST deviations greater than 10°C all have snow totals above 1000 cm, and they are all located in Northeast and Northwest China.

5. Correction to GST with SST during the snow cover period

The results above show that GST differences between the automatic and manual observations are closely related to snow depths and annual snow totals, which can be mainly attributed to different methods used by the two kinds of observation systems during the snow cover period. As described in the introduction, when there is snow on the ground, the manual GST observation is actually the temperature above the snow surface while that from the automatic observation is the temperature under the snow. Therefore, in order to solve the problem that GST cannot be realistically represented by the automatic observation method when there is snow cover, since 2005, GRT/SST observations have been added to the surface meteorological observations in China. According to the Specifications for Surface Meteorological Observation, the sensor is positioned 6 cm above the ground. The temperature is documented as GRT when the snow depth is between 0.1 and 6 cm; and when the temperature sensor is covered by snow, it is relocated to the original snow surface to measure the SST (Fig. 2).

To investigate the possibility and reliability of replacing the GST from automatic measurements with SST during the snow cover period, Erdao Station (54285) and Beita Mountain Station (51288) are selected for further analyses by using parallel observation data from 1 November to 31 December 2006. Annual snow totals at the two chosen stations are respectively 801.5 and 1551 cm. During the parallel observation period, the average GST from manual and automatic observations at Erdao Station are −8.2 and −2.6°C, respectively; and the SST is −7.3°C. The difference between the SST and manual observation is 4.7°C less than that between the automatic and manual observations. When the snow depth is below 6 cm, there is no significant difference between automatically and manually observed GST. However, when the snow depth is greater than or equal to 6 cm, the SST is much closer to the GST from manual observations, and the mean difference between the SST and manually observed GST is 7.1°C smaller than that between automatic and manual observations. This indicates that GST observations can be significantly improved by using the SST (Fig. 7a). Similar to Erdao Station, the SST at Beita Mountain Station also represents a significant improve-

![Fig. 7. Temporal variation of the deviations between SST and automatically observed GST (AWS) with the manually observed GST (HUMAN) during the parallel observation period at (a) Erdao Station and (b) Beita Mountain Station.](image-url)
average values of both the GST measured by automatic observations and SST after the adjustment of observation systems. The results show that the differences between the average values of the automatically observed GST and SST are not significant at 16% of the stations (16), which indicates that the improvement effect of correcting the automatically observed GST by using SST at these stations is limited, and effective samples of GST may be reduced instead. However, significant differences at 61% of the stations (86) are found, meaning that corrections can effectively reduce the deviations caused by the adjustment. Therefore, 86 stations are selected for the correction to winter GST. The correction to GST follows the following principles. (1) During the parallel observation period, GST from automatic observations at the four fixed times are replaced by manual observations taken at the same time. (2) After the adjustment of observation systems, when the snow depth is greater than or equal to 6 cm, the automatically observed GST is replaced by the SST. (3) To reduce the inhomogeneity, GST data are assigned as missing values when the daily snow depth or SST is missing after the adjustment of the observation system.

To further investigate the reliability of the correction process, the trend of GST before and after the correction at stations of Mohe and Altay are analyzed (Fig. 8). It can be seen that the sharp rise of winter GST in 2005, caused by the adjustment of observation systems, has been effectively improved after the correction, and the continuity and consistency of the GST series have also been greatly improved, thus leading to more reasonable GST series after the correction. Before the correction, the winter GST increases significantly at Mohe, with a rising trend of 3.21°C decade⁻¹. After the correction, the rising trend of the temperature decreases to 0.55°C decade⁻¹. The rising trend of winter GST at Altay is consistent with that at Mohe, which also decreases from 2.26 to 0.37°C decade⁻¹. This indicates that the adjustment of observation systems has led to an overestimation of the rising trend of GST, while the correction by using the SST can effectively reduce the false variation trend caused by this.

6. Evaluation of the correction effect on GST in northern China

The GST at 86 stations in northern China during the snow cover period are corrected according to the principles given in the previous section, and the correction effect is evaluated. Figure 9 shows a box plot of the average deviations of GST between automatic and manual observations before and after the correction. After the correction to GST by using SST following the transition of observation systems, the GST deviation between automatic and manual observations is significantly reduced. Before the correction, the average deviation of the daily average GST between automatic and manual observations is 8.19°C. Deviations of above 10 and 5°C are found at 30% (26%) and 83% (71%) of the stations, re-
spectively. After the correction, the deviations are obviously reduced, with an average value of 2.39°C. Deviations within 3 and 5°C are found at 70% (60%) and 97% (83%) of the stations, respectively. Similar to the daily average GST, the correction has significantly improved the observed GST at 0200, 0800, and 2000 BT. The average deviations between the GST after the adjustment and the manually observed GST at these times have been reduced from 11.36, 10.92, and 10.18°C to 2.95, 3.18, and 2.73°C, respectively; that is, the average deviations are reduced by 8.41°C (0200 BT), 7.74°C (0800 BT), and 7.45°C (2000 BT). At 1400 BT, the improvement effect on the GST is not so significant as that at the other three times, but it is still slightly better after the correction, with the average deviation reduced from 0.92 to 0.71°C.

From the temporal variation of GST anomalies before and after the correction (Fig. 10), it can be seen that the GST anomaly in northern China shows significant rising trends both before and after the correction. Before the correction, the rising trend of GST in winter is 1.87°C decade\(^{-1}\). After 2005, a sharp rise is found in the GST series with all the anomalies above 5°C and the highest reaching 10.76°C (2016). After the correction, the GST series is more gentle in those parts with abrupt changes in the original series, the rising trend is reduced to 0.65°C decade\(^{-1}\), and the GST anomaly in 2016 decreases to 3.44°C. Therefore, the GST series tend to be more reasonable after the correction.

In terms of the spatial distribution, the decrease in the rising trends of winter GST after the correction have been found at all the selected stations (Fig. 11). The winter GSTs before the correction all show significant increasing trends, which are the most obvious in the northern Greater Khingan Mountains, Lesser Khingan Mountains, Changbai Mountains, and the Altay regions of Xinjiang Region, with all the ascending trends above 2°C decade\(^{-1}\). The largest value of the increasing trend lies in Sunwu of the Greater Khingan Mountains, at 3.55°C decade\(^{-1}\) before the correction; the smallest is in Suolun of Hinggan League, with the increasing trend of 0.66°C decade\(^{-1}\). After the correction, the increasing trends in GST at all stations are significantly reduced, and the trends decrease to below 1°C decade\(^{-1}\) at 88% (76) of the stations, indicating that the increasing trends in GST are overestimated due to the transition of observation systems. The stations with significant differences in trend reduction before and after the correction are mainly located in the northern part of the Greater Khingan Mountains and Altay region of Xinjiang Region, as well as in the areas with long snow cover durations and deep snow depths.

![Fig. 10.](image) The average temporal variation of GST anomalies in winter in northern China.

![Fig. 11.](image) Distributions of the trend of GST anomaly series in winter (a) before and (b) after the adjustment in northern China.
7. Conclusions and discussion

Based on the GST data from the parallel observations and SST data from automatic observations during the adjustment period of observation systems, the impact of the system changes on winter GST observation in China is analyzed. The causes of differences in winter GST observations and effect of snow cover on these deviations are investigated. Finally, the SST from automatic observations are used to correct the automatically observed GST, and an evaluation is conducted on the correction results and effects. The main conclusions are as follows.

1) During the parallel observation period, winter GST from automatic observations are generally higher than those from manual observations. The deviation of the daily average GST between automatic and manual observations is 1.18°C, while the deviations at the four fixed times are 1.56°C (0200 BT), 1.73°C (0800 BT), 0.11°C (1400 BT), and 1.31°C (2000 BT). The distribution of deviations of daily average GST has obvious regional characteristics, with larger deviations in Northeast and Northwest China than those in the central and southern regions. The deviations at 0200, 0800, and 2000 BT have positive deviations at most stations, are significantly larger than those recorded at 1400 BT. Northeast and Northwest China, with the average daily GST deviations of 5.24 and 2.09°C, are affected the most by the transition of observation systems.

2) The GST difference between automatic and manual observations is closely related to snow depth and annual snow totals. The average daily GST deviation increases at the rate of 0.66°C cm⁻¹ with the increase of snow depth when it is less than 15 cm, and then the deviation tends to be stable at around 10°C. The influence of snow depth is greater at 0200, 0800, and 2000 BT than that at 1400 BT, consistent with the daily GST deviation. The GST deviation is affected by a station’s winter snow totals, which becomes greater with more snow. Snow totals of stations with GST deviations greater than 10°C are all above 1000 cm, and these are located in Northeast and Northwest China.

3) The SST can effectively reduce the impact of observation system changes on GST observations. The inhomogeneity and discontinuity of the GST data can be effectively improved by using SST for the correction to GST. For the daily average GST, the average deviation between automatic and manual observations decreases from 8.19 to 2.39°C after the correction, reduced by 5.8°C. For the GST at 0200, 0800, and 2000 BT, after the correction, the deviations between automatic and manual observations decrease by 8.41, 7.74, and 7.45°C, respectively. The correction can effectively reduce the false variation trends of GST caused by the transition of observation systems. The increasing trends of GST at Mohe and Altay stations have reduced from 3.21 and 2.26 to 0.55 and 0.37°C decade⁻¹, respectively. The rising trend of GST in winter averaged at the corrected stations decreases from 1.87 to 0.65°C decade⁻¹. The increasing trends of winter GST at all the corrected stations decrease significantly after the correction, and the rising trends that have decreased to below 1.0°C decade⁻¹ are found at 88% of the stations.

This paper analyzes the impact of the transition of observation systems on winter GST across China, and conducts the correction to GST with SST. Although the correction can effectively reduce the observation errors in winter GST in the northern region, the inhomogeneity of GST data has not yet been objectively evaluated, and the causes of the minimal differences observed at 1400 BT have not been quantitatively analyzed in this paper. Future detailed and objective investigation, combined with the metadata information and solar radiation data, will be conducted on the homogeneity of winter GST and the reasons for different characteristics at different moments, especially at 1400 BT in northern China, thus establishing a more comprehensive GST dataset and providing more reliable information for climate change studies of GST in China.

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