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Regional Contrasts of the Warming Rate over Land Significantly Depend on the Calculation Methods of Mean Air Temperature

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Global analyses of surface mean air temperature (T_m) are key datasets for climate change studies and provide fundamental evidences for global warming. However, the causes of regional contrasts in the warming rate revealed by such datasets, i.e., enhanced warming rates over the northern high latitudes and the "warming hole" over the central U.S., are still under debate. Here we show these regional contrasts depend on the calculation methods of T_m. Existing global analyses calculate T_m from daily minimum and maximum temperatures (T_2). We found that T_2 has a significant standard deviation error of 0.23 °C/decade in depicting the regional warming rate from 2000 to 2013 but can be reduced by two-thirds using T_m calculated from observations at four specific times (T_4), which samples diurnal cycle of land surface air temperature more often. From 1973 to 1997, compared with T_4, T_2 significantly underestimated the warming rate over the central U.S. and overestimated the warming rate over the northern high latitudes. The ratio of the warming rate over China to that over the U.S. reduces from 2.3 by T_2 to 1.4 by T_4. This study shows that the studies of regional warming can be substantially improved by T_4 instead of T_2.

Near surface air temperature over land has a significant diurnal cycle, primarily determined by diurnal variation of surface net radiation, i.e., the sum of the net solar (incident minus reflected) and the net longwave (absorbed downwelling minus emitted upwelling) radiation at the surface. During the nighttime, surface net radiation is negative, and near surface air temperature decreases with time, reaching its minimum (T_{min}) in the early morning. Surface net radiation becomes positive during the daytime due to the absorption of incident solar radiation at the surface, and this surface net radiation is partitioned into latent heat and sensible heat fluxes. As the air above the surface is directly heated by the sensible heat flux, air temperature reaches its maximum (T_{max}) in the early afternoon[1].

T_{max} and T_{min} have been operationally observed at weather stations globally since the middle of the 19th century[2,3]. Their mathematical average $T_2 = (T_{max} + T_{min})/2$ has been taken as the standard method for calculating mean air temperature (T_m)[4] and has been the backbone of current global analyses of air temperature over land[5–7]. It is well known that T_2 is different from the true T_m, i.e., mean air temperature calculated from 24 hourly air temperature observations (T_{24})[8,9].

It has been assumed that T_2 can be used to accurately depict annual anomalies and trends in T_m[10,11]. However, recent studies have shown that T_2 trends can be significantly biased. It was found that T_2 trends have significant biases of 25% (one standard deviation) at a grid scale size of 5°×5°[12]. This is because T_2 only samples the diurnal cycle of air temperature twice daily, and $T_2 - T_{24}$ changes with the land surface conditions (e.g., wetness and vegetation coverage). Surface conditions dominate the partitioning of

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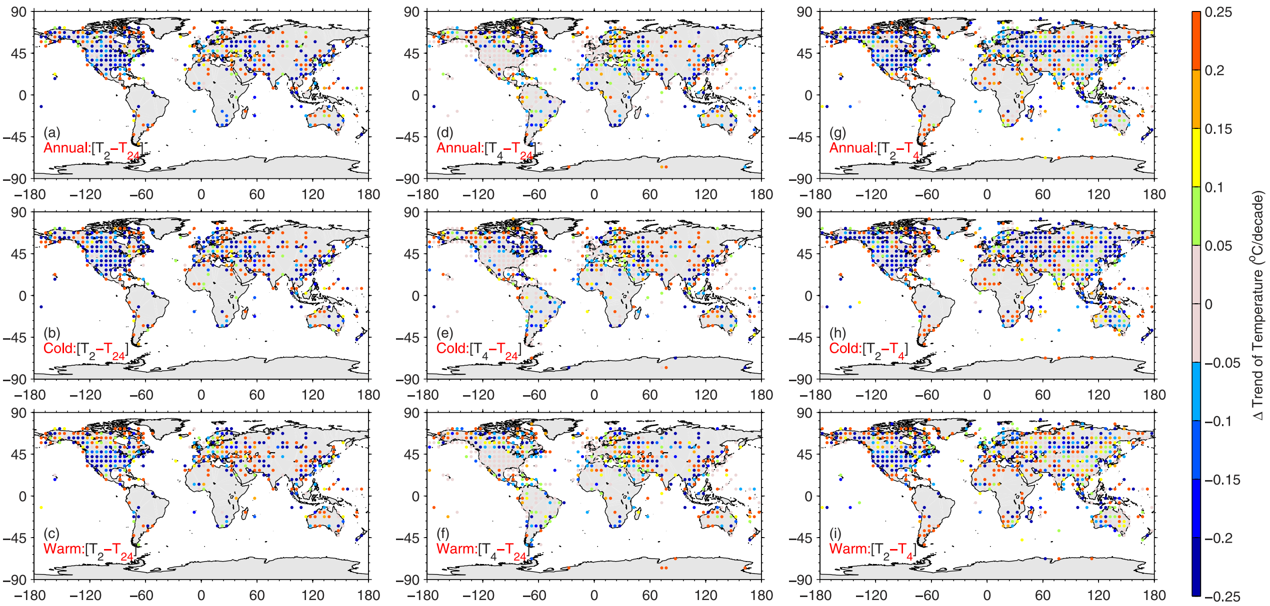

Figure 1. Trend biases in mean air temperatures (T_m) calculated from different methods: T_2, calculated from daily maximum and minimum temperature (T_2, left column), and T_4, calculated from four observations at 00:00, 06:00, 12:00, and 18:00 UTC (middle column). T_ms calculated from 24 hourly air temperatures (T_{24}) were used as reference data. Trend differences between T_2 and T_4 were also shown in the right column. The cold season is defined as November to April over the Northern Hemisphere and May to October over the Southern Hemisphere, and the warm season is defined as May to October over the Northern Hemisphere and November to April over the Southern Hemisphere. T_2 and T_4 at 6000 stations and T_{24} at 3000 stations from 2000 to 2013 from the Global Historical Climatology Network (GHCN) daily database and the Integrated hourly Surface Data (ISD) were used here. T_2 and T_{24} at identical time periods at a station were selected to calculate monthly anomalies. Monthly anomalies at the stations were aggregated into a 1°×1° grid and then into 5°×5° grid monthly anomalies, from which trends were calculated and shown in the left column. This is the same for the middle and right columns. The Figures were produced by MATLAB software.

surface net radiation into the latent heat and sensible heat fluxes. Sensible heat fluxes directly heat air above the surface and largely determine the diurnal curve of air temperature above land[13].

Air temperature has been measured more frequently at weather stations since the 1950 s, with the establishment of the World Meteorological Organization (WMO). Under the guidelines of the WMO, air temperature at 00:00, 06:00, 12:00 and 18:00 UTC (Coordinated Universal Time) has been measured operationally at weather stations. T_m can also be calculated from these four observations (T_4). We have accumulated more than 60 years of T_4 data at global weather stations. Since the 1990 s, hourly air temperature has been widely available at global weather stations with the development of automatic weather stations[3]. However, to remain homogenous, the century-long global analyses of T_m still rely on T_2[4,11].

In this study, we first evaluate and compare the uncertainty of T_2 and T_4 in depicting the trend in T_m from 2000 to 2013. We use T_{24} as the true T_m to serve as a comparison[8,9]. We calculate T_2, T_4 and T_{24} from hourly observations from the Integrated Surface Hourly Database (ISD)[14] and the Global Historical Climatology Network (GHCN) daily database[15] released by the National Climate Data Center (NCDC). In evaluating the trend bias of T_2 (or T_4), we select the exact same stations and time periods of T_2 (or T_4) and T_{24}. We found that there are more than 3000 globally distributed stations from which T_2, T_4, and T_{24} were available for more than 84 months during 2000 to 2013.

Results

Figures 1 and 2 show that T_2 demonstrates significant uncertainty in quantifying the trend in T_m. For the global average, T_2 underestimated the trend in global mean T_m by 0.03 °C/decade compared with T_{24} from 2000 to 2013. This indicates that the recent hiatus of warming was slightly overestimated by using current global analyses of T_2. This mean bias of T_2 can be reduced to 0.01 °C/decade by using T_4. This also partly explains the discrepancy between the observed and modelled warming hiatus during the most recent 15 years[16]. Current climate models run at a time step of approximately 30 minutes and calculate T_m from these calculations, which is nearly equal to T_{24}, whereas reference data provided by existing global analyses use T_2 over land.

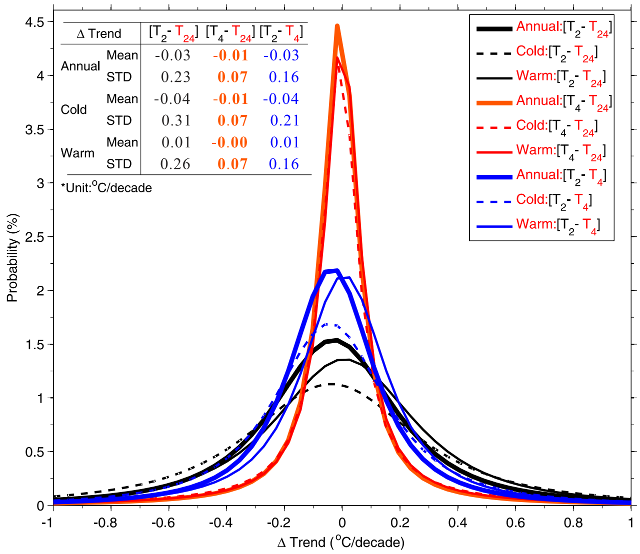

Figure 2. Fitted histograms of annual, cold season and warm season trend differences: T_2—T_{24} (black), T_4—T_{24} (red), and T_2—T_4 (blue) at 5°×5° grid as shown in Fig. 1. Statistical parameters of the trend differences, including mean and standard deviation (STD), are shown here. The data used here are the same as in Fig. 1. From 2000 to 2013, the global averaged trend in the mean air temperature over land is slightly underestimated by 0.03 °C/decade by T_2. At a 5°×5° grid scale, the trend in T_2 has a significant standard deviation error of 0.23 °C/decade. This error can be substantially reduced by more than two-thirds by using T_4.

At a 5°×5° grid scale, T_2 has a standard deviation error of 0.23 °C/decade in quantifying the trend in T_m (Fig. 2). This error is 0.31 °C/decade during cold seasons and is 0.26 °C/decade for warm seasons. This is because the diurnal cycle of air temperature changes with the surface conditions[12]. The error is higher during cold seasons because the impact of land-atmosphere interactions on diurnal variation in the surface air temperature is stronger during cold seasons. The surface is drier with lower vegetation coverage during cold seasons, and therefore, a higher fraction of surface net radiation is partitioned into the sensible heat flux, which directly heats the air above the surface.

This standard deviation error of the trend in T_2 can be substantially reduced by two-thirds using T_4 (Fig. 2). The primary reason for this is that T_4 samples the diurnal cycle of air temperatures four times a day, whereas T_2 only samples twice. Figures 1 and 2 indicate that T_4 is more suitable to study the trend in T_m than T_2.

We therefore compare the trends in T_m over land on a global scale from 1973 to 1997, the enhanced warming period. We select 1973 as the start year of the period because the T_4 data released by ISD have much better spatial coverage since 1973. On average, compared with T_4, T_2 overestimated the global mean warming rate by 0.02 °C/decade from 1973 to 1997, the enhanced warming period (Table 1).

Compared with T_4, T_2 overestimates the warming rate over the northern high latitudes, which is more obvious in cold seasons. In particular, the trend of T_2 is 0.06 °C/decade (27%) higher than that of T_4 over Northern Siberia (Table 1). The overestimation is stronger during cold seasons. The enhanced warming rate over these regions has been identified in the IPCC reports[17,18]. Different mechanisms have been proposed to explain the enhanced warming rate over these regions[19,20]. It still cannot be fully explained, and the state-of-the-art global climate models have not been able to fully reproduce the enhanced warming rate[21]. Figure 3 and Table 1 show that the use of T_2 at least partially explains the reported enhanced cold season warming over the northern high latitudes.

The regional warming rate over land significantly depends on the calculation methods of T_m. Compared with T_4, T_2 also substantially overestimates the warming rate by 0.06 °C/decade (25%) over China from 1973 to 1997. As a result, the ratio of the warming rate in China to that in the U.S. is 2.3 for T_2 and 1.4 for T_4. In the central U.S., T_2 has a negative trend of −0.05 °C/decade, whereas T_4 is 0.03 °C/decade. This partially explains the reported "warming hole" over the central U.S. during this period[22]. It is known that the variation in recording time has introduced a spurious negative trend in T_{max}, T_{min}, and T_2[23]. A homogenization method has been developed to homogenize monthly T_2[24,25]. Figure 3 shows that the homogenization has a negligible impact on the T_2 trend over the northern high latitudes. The homogenization only partly corrects the underestimation of T_m trend in T_2 over the U.S.

	Globe		North Hemisphere		South Hemisphere		North America		Europe		USA		China		Alaska		Central USA		North Siberia	
	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4	T_2	T_4
Annual	**0.14**	**0.13**	**0.16**	**0.14**	**0.06**	**0.06**	0.09	0.11	0.18	0.17	0.09	0.12	**0.21**	**0.17**	**0.20**	**0.18**	−0.05	0.03	**0.17**	0.15
Cold	**0.16**	**0.14**	**0.18**	**0.15**	**0.05**	**0.05**	0.10	0.09	0.14	0.14	0.16	0.21	**0.31**	**0.25**	0.17	0.19	0.01	0.10	**0.28**	0.22
Warm	**0.13**	**0.12**	**0.14**	**0.13**	**0.03**	**0.04**	0.06	0.09	**0.21**	**0.21**	0.04	0.06	**0.15**	0.11	0.14	0.13	−0.06	0.01	**0.14**	0.12

Table 1. This table summarizes the linear trends from 1973 to 1997 of mean air temperature (T_m) calculated from daily maximum and daily minimum temperature (T_2) and from four observations of temperature at 00:00, 06:00, 12:00, 18:00 UTC time (T_4). The trends in this table have the same unit of °C/decade. Three regional averages of Alaska ([180°W:130°W, 55°N:75°N]), central USA ([105°W:75°W, 30°N:50°N]), and North Siberia ([60°E:180°E,60°N:80°N]) were provided in this table. The numbers in bold black indicate the linear trend passes the $\alpha = 0.05$ level using a student's t confidence test. Compared with T_4, T_2 overestimated the warming trend in China and underestimated the warming rate in USA. The ratio of the warming rate in China to that in USA is 2.3 if T_2 was used to calculate the warming rates and 1.4 if T_4 is used instead. The difference between the trends in T_2 and T_4 partly accounts for the reported "warming hole" in the central USA.

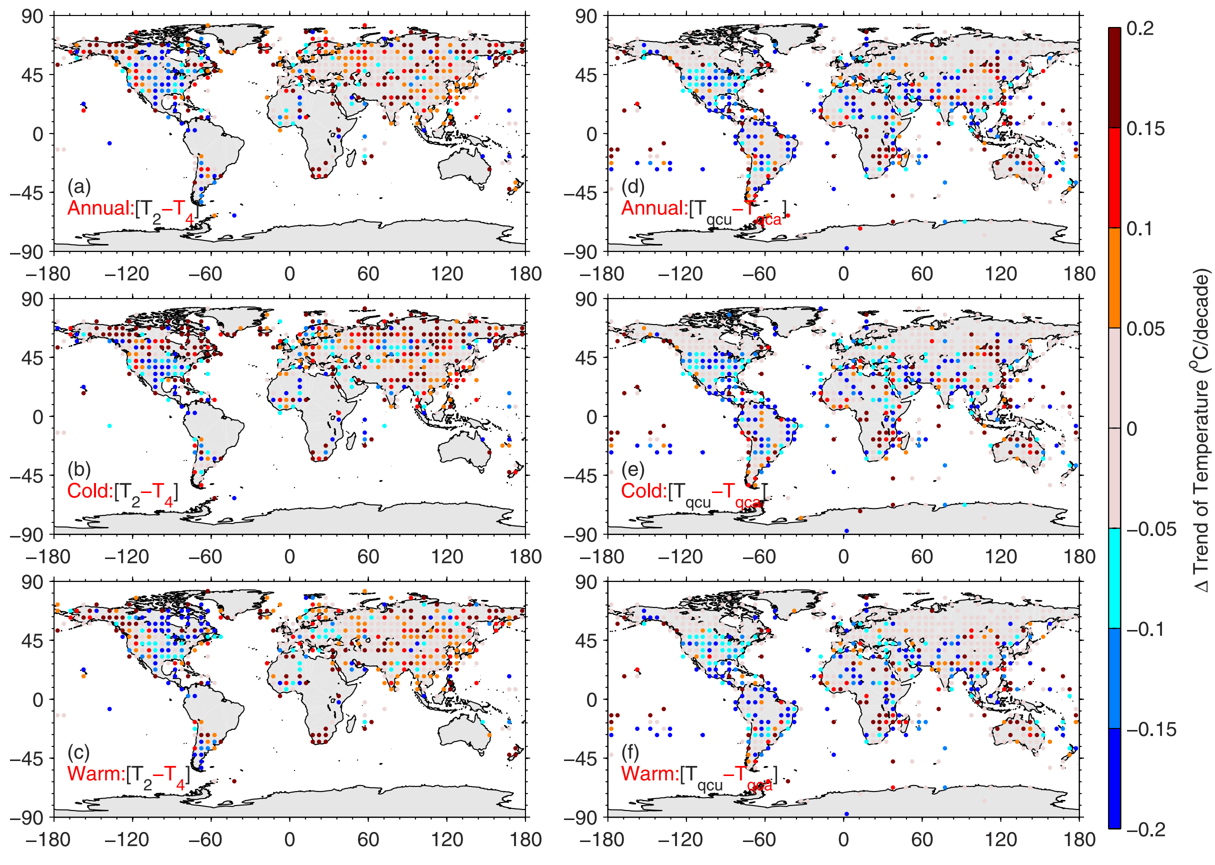

Figure 3. Differences in mean air temperature trends calculated using different methods (left column): T_2 was calculated from daily maximum and minimum temperature, and T_4 was calculated from four observations at 00:00, 06:00, 12:00, and 18:00 UTC. Definitions of the cold season and warm season can be found in the caption of Fig. 1. Hourly observations of air temperatures from 1973 to 1997 at 3300 stations were used here. T_2 and T_4 at identical time periods at a station were selected to calculate monthly anomalies. Monthly anomalies at the stations were aggregated into a 1°×1° grid and then into 5°×5° grid monthly anomalies, from which trends were calculated and shown. Compared with T_4, T_2 significantly underestimated the warming rate over the central U.S. and overestimated warming over the northern high latitudes and mainland China. For comparison, the differences in trends calculated from monthly raw T_2 (T_{qcu}) and monthly homogenized adjusted T_2 (T_{qca}) are shown in the right column. The Figures were produced by MATLAB software.

Discussion

This study shows that, compared with T_4, current widely used datasets based on T_2 overestimate the global mean warming rate by 0.02 °C/decade during the enhanced warming period (1973–1997) and underestimate the warming rate by 0.03 °C/decade during the hiatus period of warming (2000–2013). T_2 has difficulty in accurately reflecting the impact of land-atmosphere interactions on T_m[26,27]. The use of T_2 also partly explains the reported enhanced cold season warming rates in the northern high latitudes and the "warming hole" over the central U.S. The regional contrast in the warming rate between the U.S. and China is therefore substantially decreased if T_4 is used rather than T_2. The bias of T_2 also partly explains the discrepancy between the observed and modelled recent warming hiatus.

Because we have accumulated more than 60 years of T_4 data, it is essential to use T_4 to conduct a global analysis of T_m, which will substantially improve upon previous studies of regional climate change detection and attribution. This can be performed by calculating T_m using the recently available Integrated Surface Hourly Database[14] and the GHCN daily database[15], which are available at ftp://ftp.ncdc.noaa.gov/pub/data/. Both projects have collected hourly or daily data at tens of thousands of weather stations. However, these data sources have not been fully used in current global T_m analyses[5–7,11]. The new analyses of global mean T_m will substantially improve our understanding of spatial warming patterns and regional climate change.

Data and Method

This paper investigates T_m calculated by different methods. Mean air temperature (T_2) calculated from daily maximum (T_{max}) and minimum (T_{min}) air temperatures has been widely accepted. To calculate T_2, we use T_{max} and T_{min} from the Global Historical Climatology Network (GHCN) daily database[15], which has the best spatial and temporal coverage. Air temperature observations at specific times, i.e., 00:00, 06:00, 12:00, and 18:00, from the Integrated Surface Hourly Database (ISD)[14] are used to calculate T_4. Hourly air temperatures from ISD are used to calculate T_{24}, which is regarded as the true T_m[8,9], and to evaluate the uncertainty of T_2 and T_4.

Raw data of T_{max} and T_{min} have been known to be impaired by changes in recording time[3]. This is particularly important for the U.S.[23]. To address this issue, the pairwise comparison method has been used to homogenize the monthly T_m[25], which has been demonstrated to perform well over the U.S.[24]. However, homogenized and adjusted T_2 (*Tqca*) are available at fewer stations than the daily base[5,15]. To make comparisons between T_2, T_4, and T_{24} at exactly the same time and stations, we calculate these T_ms from raw hourly and daily data and then calculate their monthly values. In Fig. 3, we show the impact of homogenization is much less than that in different calculation methods.

Because T_{24} has only been widely available since 2000, we first evaluate the uncertainty of T_2 and T_4 in depicting T_m trend by comparison with T_{24} from 2000 to 2013. Our results show that T_4 can substantially reduce the uncertainty of T_2 in quantifying the T_m trend. We then compare the trends in T_2 and T_4 from 1973 to 1997 (the enhanced warming period), which shows that spatial contrasts in the warming rate over land significantly depends on the definitions of T_m, i.e., T_2 vs. T_4.

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Author Contributions

K.W. conceived the study and wrote the initial draft of the paper. C.Z. conducted the analysis. All authors interpreted the results and revised the paper.

Additional Information

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