Assessment of Temperature Changes on the Tibetan Plateau During 1980–2018

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Key Points:
- Out of 10 assessed gridded products, the China meteorological forcing data set compares best with temperature observations.
- Tibetan Plateau temperatures increase significantly during 1980–2018, with winter dominating the warming rate.
- The limitations related to the irregular spatial distribution of in-situ sites in this complex terrain, especially elevation biases result in uncertainties.

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Abstract
Surface air temperatures affect a diverse set of physical and biological systems in many parts of the world. For regional-scale studies, gridded surface air temperature data sets are frequently used as input variables. Here we evaluate 10 commonly used gridded air temperature products with spatial resolutions ranging from 0.1° × 0.1° to 5.0° × 5.0°, relative to observations from in situ weather stations on the Tibetan Plateau. Gridded temperatures are consistently lower, with mean annual air temperature biases ranging from −4.68 °C to −1.72 °C, and root mean square error (RMSE) from 3.24 °C to 6.11 °C. The mean biases of mean seasonal air temperatures for spring, summer, autumn, and winter are −3.21 °C, −2.98 °C, −2.89 °C, and −2.98 °C, respectively, and RMSEs of 4.81 °C, 4.39 °C, 4.3 °C, and 4.7 °C. Of all 10 products, the China meteorological forcing data set compares best with observations. Annual and season temperatures all increase significantly during 1980–2018 on the Tibetan Plateau, with winter dominating the warming rate.

1. Introduction
The Tibetan plateau has been called the roof of the world and the third pole of the Earth. Comprised of the Earth's highest mountains, it represents some of the most complex terrain of the globe (Frauenfeld et al., 2005). Yao et al. (2017) report some of the strongest warming and large uncertainties about the impact of future global climate change in this region. With its numerous glaciers and lakes, the Tibetan Plateau is the source region for many large rivers that represent an important water resource for south and central Asia, and is therefore also known as Asia's water tower (Immerzeel et al., 2013; Pritchard, 2017). Due to its high elevation, the Tibetan Plateau contains the Earth's largest solid water reservoir outside the Polar regions (Guo, Sun, Yang, Pepin, & Xu, 2019; Guo, Sun, Yang, Pepin, Xu, Xu, & Wang, 2019). The Tibetan cryosphere consists of glaciers with an area extent of about 1.0 × 106 km² (Yao et al., 2012), 41.9 × 106 m³/year water equivalent of snow (X. Li et al., 2008), and 1.17 × 108 km² of permafrost (Cao, Zhang, Wu, Sheng, Zhao, & Zou, 2019; Cao, Zhang, Wu, Sheng, & Zou, 2019).

According to ongoing analyses, the average global temperature on Earth has increased by slightly more than 1 °C since 1880, two-thirds of which has occurred since 1975 at a rate of roughly 0.15 °C–0.20 °C per decade (NASA GISS, 2020). As part of this global warming, high-altitude environments have been shown to experience more rapid changes in temperature than environments at lower elevations (Pepin et al., 2015; Yan & Liu, 2014). However, air temperature warming rates have been shown to again decrease above 4,500 m, and the reported increases are perhaps confined to 2,000 to 4,500 m (Guo, Sun, Yang, Pepin, & Xu, 2019). This suggests a reversal in elevation-dependent warming at the highest elevations on the Tibetan Plateau, which is in contrast to the elevational warming derived from short-term land surface temperatures presented in earlier research (Guo, Sun, Yang, Pepin, & Xu, 2019; Guo, Sun, Yang, Pepin, Xu, Xu, & Wang, 2019). Thus, there are remaining uncertainties in temperature changes on the Tibetan Plateau. Given the Tibetan cryosphere's sensitivity to climate warming including frozen ground, accurate temperature records are crucial for gauging, for example, permafrost area extent decreases (Guo & Wang, 2013, 2017), active layer deepening (Peng et al., 2018), soil freeze depth decreases (Peng et al., 2017), the general decline in area extent of frozen ground (Guo & Wang, 2016), and soil temperature increases (Cao et al., 2020).

Limited observational records and an uneven station distribution represent a major difficulty for accurately quantifying climate change on the Tibetan Plateau. On the other hand, many temperatures products have...
been created at the global or regional scale, which have laid a solid foundation for an improved understanding of the overall changes in surface air temperature. Previous assessments of temperature data sets on the Tibetan Plateau focused on comparing only one or two reanalysis products (e.g., Frauenfeld et al., 2005; Ma et al., 2008), or on particular applications such as the dynamics of amplified warming based on different data sets (e.g., Guo, Sun, Yang, Pepin, & Xu, 2019; Pepin et al., 2015; Yan & Liu, 2014). However, there has not been a comprehensive evaluation that focuses on assessing many gridded temperature data sets ranging from interpolated, to blended, and modeled (reanalysis) products with different spatial resolutions, to quantify temperature changes in this region. Thus, the objective of this study is to compare 10 commonly used global gridded products to in situ observations on the Tibetan Plateau during 1980–2018. The product that compares most favorably to in situ observations will thus be determined, and to provide an application and showcase its utility, the temperature product will be used to estimate the permafrost distribution on the Tibetan Plateau.

2. Data and Methods

2.1. Data

2.1.1. Air Temperature

We obtained monthly surface air temperature measurements for 86 stations located throughout the Tibetan Plateau from the China Meteorological Administration (CMA) (Figure 1). These observations form the basis for our evaluation of 10 gridded products (Table 1). The Berkeley Earth surface air temperatures (1° × 1°) were obtained from http://berkeleyearth.org/, available from 1880 to 2018 (Rohde et al., 2013). The Climatic Research Unit (CRU) time-series (TS) v. 4.03 data set, developed by the University of East Anglia (http://www.cru.uea.ac.uk/), is composed of 1901–2018 monthly grids of observed climate data. It is provided at a horizontal latitude × longitude resolution of 0.5° × 0.5° and consists of surface air temperatures interpolated from meteorological stations across global land areas (Harris et al., 2014). The European Center for Medium-Range Weather Forecasts (ECMWF) fifth generation reanalysis (ERA5) monthly air temperatures are collected from https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview, with a resolution of 63 km (0.25°), available from 1979 to 2018 (Service, 2017). The 1948–present Global Historical Climatology Network version 2 and Climate Anomaly Monitoring System (GHCN_CAMS) data set at a 0.5° × 0.5° resolution represents a combination of two individual station observation products, GHCN and CAMS, which are regularly updated in near-real time with many stations and a unique interpolation method (Fan

![Figure 1. The locations of in situ sites (black circles) on the Tibetan Plateau and elevation.](image)

| Product name    | Time span       | Spatial resolution | Source                                                                 |
|-----------------|-----------------|--------------------|----------------------------------------------------------------------|
| Berkeley Earth  | 1880–2018       | 1° × 1°            | http://berkeleyearth.org/data-new/                                  |
| CRU             | 1901–2018       | 0.5° × 0.5°        | http://www.cru.uea.ac.uk/                                           |
| ERA5            | 1979–2018       | 0.25° × 0.25°      | https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels-monthly-means?tab=overview |
| GHCN_CAMS       | 1948–2018       | 0.5° × 0.5°        | https://www.esrl.noaa.gov/psd/data/gridded/data.ghcncams.html        |
| JRA55           | 1958–2018       | 1.25° × 1.25°      | https://jra.kishou.go.jp/JRA-55/index_en.html                       |
| MERRA2          | 1980–2018       | 0.3° × 0.625°      | https://gmao.gsfc.nasa.gov/reanalysis/MERRA-2/data_access/           |
| NOAA V5         | 1880–2018       | 5.0° × 5.0°        | https://www.esrl.noaa.gov/psd/data/gridded/data.noaaglobaltemp.html   |
| UDEL            | 1900–2017       | 0.5° × 0.5°        | http://climate.geog.udel.edu/~climate/                               |
| CMFD            | 1979–2018       | 0.1° × 0.1°        | http://westdc.westgis.ac.cn/                                        |
| CMA             | 1961–2018       | 0.5° × 0.5°        | http://data.cma.cn/                                                 |
& Van den Dool, 2008). The Japanese 55-year reanalysis (JRA-55) project from the Japan Meteorological Agency for 1958–2018 (Kobayashi et al., 2015) is available at a resolution of 1.25° × 1.25°. The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA2), is an atmospheric reanalysis produced by NASA’s Global Modeling and Assimilation Office, providing data starting in 1980. It represents an improvement over the original MERRA product that also assimilates hyperspectral radiance and microwave observations, along with GPS-radio occultation data (Gelaro et al., 2017). The spatial resolution is about 0.5° × 0.625°. NOAA’s Merged Land Ocean Global Surface Temperature Analysis version 5 (NOAA V5) is a merged land-ocean surface temperature analysis with a 5° × 5° spatial resolution from January 1880 to present, available from https://www.esrl.noaa.gov/psd/data/gridded/data.noaaglobaltemp.html (Vose et al., 2012). We obtained the University of Delaware’s 1900–2017 terrestrial air temperature gridded monthly time series (http://climate.geog.udel.edu/~climate/) (UDEL) at a 0.5° × 0.5° spatial resolution. This product combines station records across the world, using a digital elevation model-assisted interpolation and spatial cross-validation procedures (Legates & Willmott, 1995; Willmott et al., 1995). The China meteorological forcing data set (CMFD) combines reanalysis data, Global Land Data Assimilation System forcing data, the World Climate Research Programme’s Global Energy and Water Exchanges Surface Radiation Budget data, the Tropical Rainfall Measuring Mission 3B42 precipitation product, and observational data from the CMA (Chen et al., 2011). CMFD is available from http://westdc.westgis.ac.cn/ with a resolution 0.1° × 0.1° for 1979–2018. The last data set also comes from CMA and is based on observations across China, interpolated with a thin plate spline method and digital elevation model data. Here we refer to it as the CMA data set, with a resolution 0.5° × 0.5°, available for 1961–2018 from http://data.cma.cn/ Our study is based on monthly values for 1980 to 2018, the period common to all 10 products and the in situ station observations. We also obtained five elevation data sets from CRU, ERA5, JRA55, MERRA2, and CMA. These data are used to evaluate the elevation differences between grid cells and observation sites. For the other five data products, we were unable to obtain elevation values.

2.1.2. Snow Depth
Snow depths are used as the forcing data for a surface frost number model, which estimates the snow damping effect between the ground surface and air temperature. We chose a 1979–2018 snow depth data set developed by Che et al. (2008), obtained from the National Tibetan Plateau Data Center (http://www.tpdc.ac.cn/en/). The daily snow depths at 25 km resolution use an algorithm that combines brightness temperature data from passive microwave sensors (SMMR, SSM/I, and AMSR-E) based on a modified Chang’s algorithm (Chang et al., 1987). Results suggest that this product is better than other snow depth datasets on the Tibetan Plateau (Y. Wang et al., 2019).

2.2. Methods
2.2.1. Temperature Comparisons
For the in situ air temperature data, mean seasonal air temperatures (MSAT) and mean annual air temperatures (MAAT) were averaged for all years without any missing values. Using the monthly surface air temperatures, we calculated MAAT based on the calendar year, and MSAT for the four seasons, that is, spring (March–May), summer (June–August), autumn (September–November), and winter (December–February) (Peng et al., 2019). Anomalies of MAAT or MSAT are all based on a climate normal period, generally 30 years. Because this study focuses on 1980–2018, we define a climate normal period of 1981–2010. To create regional anomalies, we average all grid cells located in a region of interest using an area-weighted method (Harris et al., 2014; K. Wang et al., 2017):

\[
T = \frac{\sum_{i=1}^{N} \cos(\text{lat}_i) \frac{\pi}{180} \Delta T_i}{\sum_{i=1}^{N} \cos(\text{lat}_i) \frac{\pi}{180}}
\]
where $N$ is the number of grid cells in the region, $\text{lat}_i$ is the latitude of the grid cell $i$, and $\Delta T_i$ is anomaly temperature of grid cell $i$.

We estimated the regional anomalies of MAAT and MSAT based not only on the gridded products but also on the observations, and the temperatures extracted from the gridded products corresponding to the locations of observational sites.

We use basic statistical methods and error analysis to compare the gridded air temperatures to observations. We calculate bias, root mean square error (RMSE), and correlations ($R^2$). Linear trends are compared for seasonal and annual temperatures for 1980–2018. The confidence interval we use for all statistical tests is 95%.

### 2.2.2. Surface Frost Number

As an application and to showcase the utility of the most accurate air temperature data set to be determined, we simulate permafrost distribution on the Tibetan Plateau based on the surface frost number model, defined by Nelson and Outcalt (1987) as

$$F_s = \frac{\text{DDF}_s^{1/2}}{\text{DDF}_s^{1/2} + \text{DDT}^{1/2}}$$

(2)

where DDF$_s$ (°C·day) is the sum of freezing degree days modified for snow insulation, and DDT (°C·day) is the sum of thawing degree days. More detail can be found in Nelson and Outcalt (1987). This model requires inputs consisting mainly of air temperature and snow parameters, which are readily available. Although the surface frost number model is a simple estimation, it has been found to provide better assessments of permafrost change than estimates based on soil temperatures from climate models (Guo & Wang, 2016).

### 3. Results

#### 3.1. Comparisons Between In Situ and Gridded Data

To evaluate MAAT derived from gridded data, 86 observational sites are used and comparisons are based on temporal agreement (Figure 2) and the spatial patterns of biases and RMSEs (Figures 3 and 4).

Assessing the long-term grid cell MAAT indicates that gridded temperatures are consistently lower than station observations, with few exceptions (Figure 2). The MAAT bias ranges from $-4.68$ °C to $-1.72$ °C, all statistically significantly different. The RMSE of MAAT ranges from 3.24 °C to 6.11 °C. The largest biases and RMSEs are for GHCN_CAMS, and the smallest for CMFD. The correlations range from 0.43 to 0.76, all statistically significant with observations except for the NOAA V5 reanalysis data. To further evaluate the applicability of the gridded data, the spatial pattern of bias and RMSE is determined (Figures 3 and 4).

There is a negative bias at most sites. The largest biases are mostly located in the southeast, while the few positive biases are mostly in the center and southern portion of the Tibetan Plateau. Of all observation sites, the number of sites with bias less than 0 °C is greater than 80%, except for UDEL, CMFD, and CMA. The spatial pattern of RMSE shows relatively larger values mostly in the southeast and south, and most ranged 0–5.0 °C. RMSEs are smaller than 7.5 °C at more than 85% of sites. However, 10 sites show more than 10 °C RMSE with GHCN_CAMS. In summary, CMFD has the lowest bias and strongest correlations with observed MAAT.

We next evaluate the seasonal air temperature correspondence between gridded values and observation sites (Table 2). All biases are negative except for NOAA V5 in winter. Bias ranges $-1.64$ °C to $-5.12$ °C in spring, $-1.80$ °C to $-3.52$ °C in summer, $-1.69$ °C to $-4.40$ °C in autumn, and $-1.56$ °C to $-5.66$ °C in winter. The mean biases are $-3.21$ °C, $-2.98$ °C, $-2.89$ °C, and $-2.98$ °C from spring to winter. RMSE varies 3.22–6.30 °C in spring, 3.30–5.93 °C in summer, 2.26–5.43 °C in autumn, and 3.19–7.20 °C in winter. The mean RMSEs are 4.81 °C, 4.39 °C, 4.3 °C, and 4.7 °C from spring to winter. The correlations mainly range between 0.60 and 0.75. Based on the combination of bias, RMSE, and $R^2$, the CMFD data compares most favorably with MSAT observations. Bias and RMSE further suggest that the gridded products perform best in autumn, then summer, and worst in spring.
Annual and individual seasonal analyses show that the CMFD data agrees best with temperature observations.

### 3.2. Temperature Trends

To further evaluate the agreement between gridded products and observations on the Tibetan Plateau, we compared the time-series and trends in annual (Figures 5 and 6) and seasonal (Figures 7 and 8) temperatures.

Time series of plateau-averaged MAAT show increasing temperatures during 1980–2018 for all gridded products and observations (Figure 5a). Further, the observations’ MAAT trends are greater than those for most of the gridded products. Observed MAATs increase statistically significantly by $0.45 \pm 0.09 \, ^\circ$C/decade, while MAAT trends from the gridded products range from $0.24 \pm 0.10 \, ^\circ$C/decade to $0.48 \pm 0.10 \, ^\circ$C/decade and are all also statistically significant (Figure 5b). The three gridded products with the smallest MAAT trend differences with observed trends are CMA, CMFD, and GHCN_CAMS, at $0.026$, $0.032$, and $0.032 \, ^\circ$C/decade, respectively. However, the largest differences are with MERRA2, at $-0.20 \, ^\circ$C/decade. In addition to comparing the plateau-wide temperature trends, we averaged just those grid cells that contain...
observing stations, and also compared those MAAT trends (Figure 6). The MAAT time-series anomalies are very similar to those averaged for the entire Tibetan Plateau (Figure 5a). The MAAT trends range from $0.22 \pm 0.12 \, ^\circ C$ per decade (UDEL) to $0.53 \pm 0.10 \, ^\circ C$ per decade (CMFD), all again being statistically significant during 1980–2018.

Seasonally, 1980–2018 plateau-averaged temperatures increased $0.39 \pm 0.14 \, ^\circ C$ per decade in spring, $0.39 \pm 0.11 \, ^\circ C$ per decade in summer, $0.41 \pm 0.14 \, ^\circ C$ per decade in autumn, and $0.60 \pm 0.22 \, ^\circ C$ per decade in winter based on the observations (Figure 7). This suggests that winter and autumn dominate the main warming trend. Based on the gridded products, MSAT trends vary $0.29 \pm 0.16–0.48 \pm 0.13 \, ^\circ C$ per decade in spring, $0.23 \pm 0.11–0.42 \pm 0.09 \, ^\circ C$ per decade in summer, $0.22 \pm 0.13–0.47 \pm 0.14 \, ^\circ C$ per decade in autumn, and $0.29 \pm 0.18–0.69 \pm 0.23 \, ^\circ C$ per decade in winter. Comparing these MSAT trends to those from observations, the smallest differences are with CMA in both spring and summer ($0.42 \pm 0.15 \, ^\circ C$ per decade and $0.38 \pm 0.10 \, ^\circ C$ per decade, respectively), with CMFD in autumn ($0.43 \pm 0.14 \, ^\circ C$ per decade), and with JRA55 during winter ($0.57 \pm 0.21 \, ^\circ C$ per decade). We also again estimated the MSAT trends based on just grid cells with observations, and the results are again very similar (Figure 8).

Both observations and gridded products show increasing trends in MAAT and MSAT during 1980–2018, with winter dominating the warming rate. The observed temperature trends are best captured by the gridded CMFD and CMA products.

4. Discussion
The Tibetan Plateau is experiencing amplified warming due to global climate change (Pepin et al., 2015). Accurate estimation of long-term temperature trends in this part of the world is crucial for the detection and attribution of impacts, and the projection of climate change (Q. Li et al., 2019). There are countless
Figure 4. RMSE of MAAT between gridded data and observations at each site on the Tibetan Plateau. MAAT, mean annual air temperatures; RMSE, root mean square error.

Table 2
Seasonal Temperature Bias, RMSE, and Correlations Between Gridded Data and Stations on the Tibetan Plateau

|               | Berkeley Earth | CRU | ERA5 | GHCN_CAMS | JRA55 | MERRA2 | NOAA V5 | UDEL | CMFD | CMA |
|---------------|----------------|-----|------|-----------|-------|--------|---------|------|------|-----|
| Bias (°C)     |                |     |      |           |       |        |         |      |      |     |
| Spring        | −2.74          | −3.32 | −5.12 | −3.59     | −3.48 | −3.68  | −4.03   | −1.89 | −1.64 | −3.46 |
| Summer        | −3.04          | −3.09 | −3.26 | −3.52     | −3.32 | −3.37  | −12.45  | −2.04 | −1.80 | −3.40 |
| Autumn        | −2.64          | −2.80 | −4.40 | −3.02     | −3.34 | −3.50  | −3.86   | −1.80 | −1.69 | −2.85 |
| Winter        | −2.70          | −2.70 | −5.66 | −2.96     | −3.36 | −3.54  | 6.03    | −1.83 | −1.56 | −2.57 |
| RMSE (°C)     |                |     |      |           |       |        |         |      |      |     |
| Spring        | 4.56           | 4.88 | 6.29  | 4.67      | 4.6   | 4.77   | 5.97    | 4.05  | 3.22  | 6.30 |
| Summer        | 4.58           | 4.41 | 4.11  | 4.54      | 4.26  | 4.31   | 12.9    | 4.02  | 3.30  | 5.93 |
| Autumn        | 4.34           | 4.30 | 5.43  | 4.16      | 4.33  | 4.53   | 5.74    | 4.00  | 2.26  | 5.35 |
| Winter        | 4.55           | 4.42 | 7.20  | 4.18      | 4.57  | 4.89   | 8.27    | 4.24  | 3.19  | 5.13 |
| R             |                |     |      |           |       |        |         |      |      |     |
| Spring        | 0.63           | 0.64 | 0.63  | 0.78      | 0.71  | 0.71   | −0.02   | 0.63  | 0.78  | 0.37 |
| Summer        | 0.55           | 0.59 | 0.71  | 0.71      | 0.65  | 0.65   | 0.03    | 0.55  | 0.69  | 0.29 |
| Autumn        | 0.65           | 0.67 | 0.69  | 0.79      | 0.75  | 0.72   | −0.01   | 0.61  | 0.76  | 0.48 |
| Winter        | 0.76           | 0.77 | 0.62  | 0.86      | 0.82  | 0.79   | −0.11   | 0.73  | 0.86  | 0.66 |
Therefore, choosing the most appropriate data for the area in question is critical for quantifying climate changes and their impacts. Here, we evaluated a suite of 10 gridded data sets relative to observations on the Tibetan Plateau and find that the gridded CMFD product best represents the temperature variability. However, there are of course uncertainties and limitations that contribute to the differences between interpolated, modeled (reanalysis), and blended data products relative to observations.

4.1. Irregular Spatial Distribution of In Situ Sites

The station observations are considered the standard against which to evaluate other data sets. However, in situ station observations have their own limitations, including their nonrepresentative spatial distribution at the regional scale. Figure 1 shows the distribution of in situ sites on the Tibetan Plateau, indicating that most are located in the east and south, with only a few stations in the west. Therefore, this affects the accuracy of evaluating the plateau-wide temperature variability based on in situ sites. However, to alleviate this issue we separately compare only those grid cells where the stations are located.

4.2. Spatial Resolution

The comparisons between gridded data and observations are based on the point-locations of in situ sites. Therefore, one grid cell’s temperature is compared to one or several in situ sites, with the gridded spatial resolution ranging from 0.1° to 5° (Table 1). The area extent of one grid cell includes many different, heterogeneous environmental variables, for example, land cover, elevation, population, snow cover, permafrost, and so on. To reduce this uncertainty of the spatial resolution, we applied area-weighting when estimating MAAT and MSAT at the regional scale.
4.3. Elevation Error

Although Pepin et al. (2015) reported amplified climate change on the Tibetan Plateau due to elevation-dependent warming, Guo, Sun, Yang, Pepin, and Xu (2019) and Guo, Sun, Yang, Pepin, Xu, Xu, and Wang (2019) more recently found that the warming rate decreases above 4,500 m. Both studies indicated that elevation is important for estimating temperature change in complex, rugged mountain topography. To quantify this uncertainty, we estimate the elevation differences between the gridded data and in situ sites (Figure 9). The spatial patterns of elevation differences are similar among the five data sets for which we were able to obtain elevations, ranging between 0–1,200 m, with larger differences in the southeastern plateau. Elevation differences less than 0 m occurred in less than 9% of the CMA data set. Approximately 68%–74% stations have elevation differences between 0–900 m, and less than 8% of stations have elevation differences greater than 1500 m. Among the 5 gridded data sets, the largest elevation differences (0–900 m) are in ERA5, CMA, and CRU, respectively. Assuming the standard atmospheric lapse rate of 0.65 °C/100 m, the uncertainties resulting from elevation are mostly between 0–5.9 °C. While we use the standard lapse rate of 0.65 °C/100 m to estimate the general impact of elevation differences, the lapse rate is not the same across the region. Using spatially and temporally variable lapse rates derived from different pressure levels of each reanalysis data set could be used for more precise estimates and to decrease the uncertainties (Cao et al., 2017; Gao et al., 2012).

4.4. Other Aspects

In addition to the above factors impacting the uncertainties, other issues include, for example, the urban heat island effect, land use and land cover change, and assimilation. Urbanization, agriculture and animal husbandry, tourism, and transportation development are examples of human activities occurring at various temporal and spatial scales on the Tibetan Plateau (Fan & Van den Dool, 2008). Growing cities and concurrent human activities contribute to the urban heating, which impacts temperature changes in situ sites.
located in urban areas (Q. Li et al., 2004; Liu & Chen, 2000; Wen et al., 2019). The cities are mostly located in the eastern portion of the plateau, as are the observing stations. Such land cover changes have the potential to impact the land surface and air temperatures (Frauenfeld et al., 2005; Ma et al., 2008). However, previous studies indicated that land use and land cover change on the Tibetan Plateau is relatively stable, and the proportion of first-level land use type change was less than 7% from 1992 to 2015. Most of these changes are a result of single disturbances, with repeated land change occurring in only 1.85% of the total area. The quality of land cover has been improving in areas where no land type change occurred (Zhang et al., 2019).

Additional uncertainty may arise because some of the station observations used to assess the gridded products may have been assimilated into the gridded products. While the degree to which this impacts our comparisons is unclear, it is important to acknowledge that our comparisons are not necessarily independent.

Having evaluated 10 commonly used gridded data products against station observations, we find that the CMFD data best represents observed temperature variability on the Tibetan Plateau. Surface air temperature variability is important not only for assessing climate change, but also for quantifying changes in other parts of the environment, for example, frozen ground. Air temperature is an important input for modeling frozen ground changes (Luo et al., 2018, 2020), including its distribution (Cao, Zhang, Wu, Sheng, Zhao, & Zou, 2019; Cao, Zhang, Wu, Sheng, & Zou, 2019; Guo et al., 2012; Zou et al., 2017), soil freeze/thaw status (Jin et al., 2015; Peng et al., 2016), soil freeze depth (Peng et al., 2017), and active layer thickness (Peng et al., 2018; Xu et al., 2017). Therefore, to illustrate the utility of the CMFD data, we used the surface frost number method to estimate permafrost distribution on the Tibetan Plateau. The spatial pattern of permafrost distribution is similar with previous estimates (Cao, Zhang, Wu, Sheng, Zhao, & Zou, 2019; Cao, Zhang, Wu, Sheng, & Zou, 2019; Zou et al., 2017). The time series characterizing the change in area extent of permafrost demonstrates a statistically significant annual decrease in permafrost area of 11,300 km² during 1979–2018 (Figure 10).
Figure 8. Comparisons of observed MSAT trends and those from grid cells containing stations on the Tibetan Plateau for 1980–2018. MSAT, mean seasonal air temperatures.

Figure 9. Elevation differences between five gridded products and observations: (a) CRU, (b) ERA5, (c) JRA55, (d) MERRA2, (e) CMA, and (f) the distribution of elevation differences. CMA, China Meteorological Administration; CRU, Climatic Research Unit; ERA5, ECMWF fifth generation reanalysis; JRA55, Japanese 55-year reanalysis; MERRA2, Modern-Era Retrospective Analysis for Research and Applications, version 2.
5. Conclusion

Gridded air temperature products, including interpolated, modeled (reanalysis), and blended data, are widely used in climate and associated studies at the regional and global scale. However, choosing an appropriate data set that properly represents temperature variability is critical. Based on comparisons with observations from 86 stations, we conclude that the CMFD data best represent air temperatures on the Tibetan Plateau. The MAAT bias is −1.72 °C, RMSE is 3.24 °C, and best agreement found during autumn. To capture the observed air temperature trends, most gridded data sets reproduce the general warming trend, while again CMFD (and CMA) trends compare best to those from observations. Given the limitations related to the irregular spatial distribution of in situ sites in this complex terrain, especially elevation biases result in uncertainties. Thus, to improve the accuracy of estimating climate change on the Tibetan Plateau, Earth’s third pole, more in situ observing sites should be added, especially in the central and western portions and in the high-altitude regions of the plateau.

Data Availability Statement

The 10 gridded data sets were provided by the respective institutes, detailed in Table 1.

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