Reconstructed global monthly land air temperature dataset (1880–2017)

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Abstract
Land surface air temperature is an essential climate variable for understanding rapid global environmental changes. Sparse network coverage prior to the 1950s is a significant source of uncertainty in global climate change evaluations. Recognizing the importance of spatial coverage, more stations are continually being added to global climate networks. A challenge is how to best use the information introduced by the new station observations to enhance our understanding and assessment of global climate states and changes, particularly for times prior to the mid-20th century. In this study, Data INterpolating Empirical Orthogonal Functions (DINEOF) were used to reconstruct mean monthly air temperatures from the Global Historical Climatology Network-monthly (GHCNm version 4) over the land surface from 1880 through 2017. The final reconstructed air temperature dataset covers about 95% of the global land surface area, improving the spatial coverage by ~80% during 1880–1900 and by 10%–20% since the 1950s. Validation tests show that the mean absolute error of the reconstructed data is less than 0.82°C. Comparison with the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model output shows that the reconstructed dataset substantially reduces the bias in global datasets caused by sparse station coverage, particularly before the 1950s.

KEYWORDS
DINEOF, GHCN, land air temperature, reconstruction

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1 | INTRODUCTION

Land air temperatures (1.5–2 m above the land surface) are one of the most fundamental climate variables for documenting and understanding rapid environmental changes (Stocker et al., 2013). However, there is increasing evidence that global air temperature datasets are biased due to the sparseness of observations prior to the 1950s, particularly in the Arctic where enhanced climate changes are expected (Cowtan and Way, 2014; Huang et al., 2017; Wang et al., 2017). The coverage bias is evident in the global dataset assembled by Karl et al. (2015), in the HadCRUT4 dataset (Cowtan and Way, 2014), the gridded Berkeley Earth temperature dataset (Way et al., 2017), and others. This bias has led to underestimates in both the Arctic and global temperature trends during the last several decades (Cowtan and Way, 2014; Huang et al., 2017).

There are several approaches for addressing data sparseness issues. Adding more stations to the datasets is the most effective approach for improving the spatial coverage (Wang et al., 2017b). Although it may be possible to fill in missing historical data with auxiliary in-situ measurements in some cases, this approach is unlikely to be successful everywhere, especially during the early historical period (prior to the 1950s). Thus, several mathematical and statistical methods have been developed to interpolate or reconstruct missing data values in historical temperature records. For example, Cowtan and Way (2014) used kriging to spatially interpolate the HadCRUT4 global temperature dataset, Huang et al. (2017) used Data INterpolating Empirical Orthogonal Functions (DINEOF) to improve coverage in the Arctic, while Wang et al. (2017a) used the Biased Sentinel Hospitals Areal Disease Estimation (BSHADE) method to improve global coverage over land.

Similar methodologies are currently used to produce the most widely used global temperature datasets such as HadCRU and Berkeley Earth. Briefly, the first step is to construct a baseline or background temperature map which is generally created from data over a 30 year period. Temperature anomalies are then produced by subtracting the baseline temperatures and the anomalies spatially interpolated to produce a map product. A variety of interpolation methods have been used and these are continually evolving. For the HadCRU products, triangulated linear interpolation (Harris et al., 2014) was used for the third version while Angular Distance Weighting has been used since version 4 (URL: https://crudata.uea.ac.uk/cru/data/hrg/cru_ts_4.03/Release_Notes_CRU_TS4.03.txt). Meanwhile, Berkeley Earth used kriging to implement spatial interpolation (Rohde et al., 2013). An important issue with these interpolation methods is that they rely on a distance relationship, which is problematic for the early period because of the sparse station coverage in the Arctic and elsewhere (examples will be shown in Figure 6).

For global air temperatures, spatial and temporal coverage issues are not independent, an issue that the DINEOF method (Beckers and Rixen, 2003) is designed to cope with. It determines the number of statistically significant empirical orthogonal functions (EOF) by a cross-validation procedure for incomplete datasets, as well as quantification of the noise level and interpolation errors. This method does not need prior information about the error covariance structure so it is self-consistent and parameter-free (Beckers and Rixen, 2003). By estimating both the spatial and temporal EOFs, it considers the spatiotemporal features in a set of available records. It has been applied successfully to incomplete spatial images, e.g., mapping changes in sea surface temperatures (Alvera-Azcárate et al., 2005) and salinity (Alvera-Azcárate et al., 2016). Huang et al. (2017) recently applied DINEOF to reconstruct missing data gaps in annual air temperature records for the Arctic.

In this study, we use the DINEOF method to produce a reconstructed mean monthly air temperature dataset for global land areas over the period 1880–2017. The raw dataset used in this study is the Global Historical Climatology Network (GHCN)-monthly temperature dataset Version 4 (GHCNm V4), which includes many more data sources than previous versions (Peterson and Vose, 1997; Lawrimore et al., 2011). The recent version (V4) provides mean monthly air temperature records from more than 27,000 stations (Menne et al., 2018). Two different validation methods are used to evaluate the accuracy of our reconstructed temperature data. Finally, the temporally extended station data significantly improve the spatial coverage during the period prior to the 1950s. This product is expected to be useful for global and regional climate analyses and provides a new perspective for improving global temperature products in the future.

2 | DATA PRODUCTION METHODS

A work-flow procedure was designed to prepare, reconstruct, and post-process station data from the GHCNm V4 network (Figure 1).

2.1 | Step 1: Input file preparation

In this step, raw GHCNm V4 data were filtered and converted to the format required by DINEOF software: (a) Stations with missing latitude, longitude, or elevation information were deleted. (b) To avoid short records, stations with <10 years of data for any month were removed. (c) Any records beyond the 1880–2017 time period were discarded. (d) Bad or questionable data were eliminated based on the quality flags in the GHCNm V4 raw files. (e) To improve the robustness of the reconstruction, a 5σ principle was used to detect and remove
any remaining outliers, i.e., any data points beyond ±5 standard deviations of the long-term mean were removed. (f) The preprocessed data were split into 12 monthly (binary) files to facilitate separate analysis with the DINEOF software. In the end, a total of 26,253 stations were used in this study, i.e., ~5% of the GHCNm V4 sites were removed because of insufficient record length or missing station location information.

2.2 | Step 2: Reconstruction of mean monthly temperature data using DINEOF

The reconstruction procedure follows that described by Beckers and Rixen (2003), although here we treat each month as an independent time series. Briefly, the procedure was: (i) Initial input monthly data were normalized by the temporal mean and variance at each station and the missing data values set to zero. This created a normalized spatiotemporal temperature matrix $X$. (ii) Missing data values were replaced by estimates obtained from the EOF analysis. This must be done iteratively because the calculated EOFs depend to some extent on the missing data values. In addition, the missing data estimates depend on the total number $N$ of EOFs retained in the analysis. In our analysis, we let $N$ range from 1 to 50 where the EOFs had been ordered according to their significance as measured by the magnitude of their associated singular values. For each $N$, a Singular Value Decomposition (SVD) was performed to decompose the temperature matrix $X$ into spatial and temporal EOFs. Utilizing the first $N$ EOFs, the missing data values were estimated and the EOFs reevaluated. This step was repeated until convergence occurred. Once convergence was obtained, the missing data/EOF evaluation was repeated using $N + 1$ EOFs. (iii) Once the spatial and temporal EOFs were known for each $N$, the cross-validation technique described by Beckers and Rixen (2003) was applied to determine the optimal number of EOFs to retain in the final reconstruction; the optimal number of EOFs occurs when the cross-validation error is minimized (Figure 2). For the GHCNm V4 dataset, we found that the

| Month  | $N$ | Month   | $N$ |
|--------|-----|---------|-----|
| January| 19  | July    | 12  |
| February| 18  | August  | 13  |
| March  | 18  | September| 17  |
| April  | 18  | October | 16  |
| May    | 14  | November| 16  |
| June   | 11  | December| 18  |
optimal number of EOF modes varied from 11 to 19, depending on month (Table 1); the optimal number of modes was generally higher during the northern hemisphere’s winter months. (iv) The first two steps (i and ii) were then repeated using only the optimal EOF modes. (v) A new normalized spatiotemporal temperature matrix $X_2$ was created using the optimal spatial and temporal EOF modes for each month. Missing data values in the original matrix $X$ are replaced by optimal EOF estimates in $X_2$. (vi) The temporal mean and variance were then added back to the reconstructed matrix $X_2$ to recover the actual temperature.

### 2.3 Step 3: Output file preparation

The 12 reconstructed monthly temperature matrices $X_2$ were merged into a single file. Details concerning the file format are described in Section 4.

### 3 VALIDATION

To validate the reconstructed dataset, we first randomly set ~10% of the total available data to missing data values and used the same method as Section 2 to reconstruct these artificial missing points. Comparing the reconstructed artificial missing data with the true observations, the mean absolute error

![Graphs showing overall accuracy and monthly biases for pure random missing value experiments.](image)

**FIGURE 3** Overall accuracy (a) and monthly biases (b) for pure random missing value experiments; (c) and (d) are same with (a) and (b), but for the block missing value experiments. Red dashed lines in (a) and (c) are 1:1 lines. MAE is the mean absolute error.
The estimated errors vary by month with the largest error occurring in January (~1.02 ± 0.99°C) and the smallest occurring in August (~0.65 ± 0.59°C) (Figure 3b, Table 2).

Second, we used block sampling to validate the case where continuous blocks of data 13 years long (about 10% out of the total 138 years) are missing. The first step was to randomly sample ~10% of the stations. For each of these stations we then artificially set a contiguous block of 13 years to missing data values. Reconstructing the artificial missing data as before and comparing with the true observations, we find the overall accuracy of the reconstruction (i.e., the average of MAEs between true observations and reconstructions) (Table 2).

### Table 2 Monthly mean absolute errors (unit: °C) in reconstructed temperature records

| Month | Random | Block |
|-------|--------|-------|
|       | Mean   | STDEV | N   | Mean | STDEV | N |
|       | 1.02   | 0.99  | 104,313 | 1.05 | 1.02  | 106,424 |
| Jan   | 0.99   | 0.95  | 106,236 | 1.02 | 0.99  | 108,056 |
| Feb   | 0.86   | 0.82  | 105,395 | 0.88 | 0.85  | 106,399 |
| Mar   | 0.76   | 0.74  | 106,057 | 0.79 | 0.76  | 107,870 |
| Apr   | 0.72   | 0.68  | 106,257 | 0.75 | 0.71  | 107,918 |
| May   | 0.69   | 0.64  | 105,964 | 0.72 | 0.66  | 109,150 |
| Jun   | 0.67   | 0.63  | 106,316 | 0.69 | 0.65  | 107,734 |
| Jul   | 0.65   | 0.59  | 106,471 | 0.67 | 0.61  | 108,400 |
| Aug   | 0.67   | 0.62  | 106,230 | 0.68 | 0.61  | 107,402 |
| Sep   | 0.71   | 0.66  | 105,815 | 0.73 | 0.69  | 109,588 |
| Oct   | 0.84   | 0.80  | 106,472 | 0.87 | 0.84  | 107,829 |
| Nov   | 0.96   | 0.92  | 105,366 | 0.98 | 0.94  | 107,990 |

aSTDEV: standard deviation of MAEs across grids.

bN is number of monthly temperature pairs between reconstructed and true record.

### Figure 4 Differences in mean monthly air temperature between the gridded raw (reconstructed) GHCNm V4 dataset and CMIP5 climate model output (a); Differences in temperature anomalies between the raw (reconstructed) GHCNm V4 data and CMIP5 output (b). Differences (absolute and anomaly) are represented by the mean absolute error (MAE), which is derived from raw GHCNm V4 dataset (blue curve) and reconstructed dataset (black curve).
is ~0.82 ± 0.80°C (Figure 3c), which is slightly larger than for the purely random sampling experiments. As before, MAEs vary by month with the maximum error occurring in January (~1.05 ± 1.02°C) while the minimum occurs during August (~0.67 ± 0.61°C) (Figure 3d, Table 2).

In summary, validation tests indicate the DINEOF reconstruction is reliable. The accuracy of the reconstruction during May – September is slightly better than during the other months. This is because the majority of the land stations are located in the Northern Hemisphere where larger mean absolute errors occur during the cold seasons.

An auxiliary way to evaluate the reconstructed dataset quality is to compare it with climate model output. Ordinarily, observations are used to evaluate climate model performance. However, climate model output can also be used to assess observational data quality as pointed out by Massonnet et al. (2016). The basic assumption is that observational data and climate model output play symmetrical roles so it is possible to use one to infer how close the other is from the true state, and vice versa. If observational data quality is consistent with time, the difference between the observations and the model outputs should remain relatively constant.

To reevaluate the observational data quality, we compared both the raw and reconstructed GHCNv4 mean monthly air temperatures in each 5° × 5° grid box with CMIP5 ensemble climate model output; CMIP5 ensemble outputs were obtained from http://climexp.knmi.nl/selectfield_cmip5.cgi. The algorithm used to grid the GHCNv4 temperatures was from Osborn and Jones (2014). We also implemented a similar comparison using temperature anomalies where the anomalies were calculated relative to the 1961–1990 climatological means. Mean absolute errors between the GHCNv4 datasets and CMIP5 output were calculated for each 5° × 5° grid cell and then averaged over the entire spatial domain. As indicated by the MAE trends, differences between the gridded raw GHCNv4 temperatures and CMIP5 output varies substantially with time (Figure 4a) with the differences being significantly larger prior to the 1920s. The maximum bias during the early part of the record exceeded 6.50°C. In contrast, the differences generally were around 5.60°C in recent time.
decades (since the 1950s). Similarly, temperature anomalies show a declining bias over time (Figure 4b).

In comparison with the raw GHCNv4 data, differences between the reconstructed GHCNv4 air temperatures and CMIP5 output were much more homogeneous over the entire period (Figure 4), i.e., differences between the reconstructed temperatures and the model output remain ~5.60°C over the entire period while differences in the temperature anomalies generally remain less than 1.25°C. This implies that the reconstructed data during the early period are as reliable as that in recent decades. Thus, the reconstructed dataset effectively overcomes the time-dependent coverage bias inherent in the raw dataset (Figure 5e).

Figure 5 provides a quick visualization of the gridded temperature anomalies from the raw GHCNv4 and our reconstructed datasets. Considering a regular 5° × 5° latitude-longitude grid (as it is widely used in existing global temperature products), the spatial coverage has increased to ~95%. The reconstruction improves the spatial coverage by about 80% during the earliest decades (1880–1900) and by 10%–20% since the 1950s.

To illustrate the improvement between our reconstruction and CRU TS4.02 (a widely used spatial interpolation product by Climate Research Units), the temperature anomalies for two locations (73.5°N, 110°E and 42.0°N, 110°E) are shown in Figure 6. As reported by Macias-Fauria et al. (2014), the CRU TS4.02 product has insufficient temporal variability during the early period (lower panels, Figure 6). This defect is likely due to how the CRU spatial interpolation method behaves with sparse data coverage. Our reconstructed temperature product significantly improves this aspect (middle panels, Figure 6).

4 | DATASET LOCATION AND FORMAT

The global monthly air temperature dataset is available at figshare, https://doi.org/10.6084/m9.figshare.7961120. Three files are available at this site:

1. List.dat: This file provides the GHCNv4 identification information for each climate station, including: alphanumeric station ID (column 1), numerical station ID code (column 2), longitude (column 3), latitude (column 4), and elevation (column 5).
2. Raw_GHCN4_Data.dat: This file contains all the raw data we used for the reconstruction after applying the quality control procedures.
control and reformatting procedures (Step 1, Section 2). The file consists of 14 columns: station ID code consistent with List.dat (column 1), year (column 2), and monthly air temperatures for January through December at 0.01°C resolution (columns 3–14). Missing data are flagged as −9999, a convention that is maintained throughout this study.

3. Reconstructed_GHCN4_Data.dat: This file provides all the reconstructed data. It has exactly same data structure as Raw_GHCN4_Data.dat.

5 | DATASET USE AND REUSE

The reconstructed global land air temperature dataset produced by this study can facilitate a variety of studies relevant to climatic and environmental research at regional, national, or continental scales. We caution that the reconstructed dataset may have several potential limitations.

1. Some studies using the previous version of the GHCNm (version 3) found the homogenized data may be significantly biased in regions where the station spatial coverage is sparse such as in the Arctic (e.g., Wang et al., 2017b). In GHCNm V4, the station data at high-latitudes (≥65°N, ≥65°S) has been separated during the data homogenization process to reduce biasing in these regions (Lawrimore, 2018). However, there may still be unknown issues for stations located in high-altitude regions such as the Qinghai-Tibet Plateau.

2. The DINEOF procedure used here fills gaps for all available stations, extending the limited data back to the late 19th century. The resulting reconstructed dataset substantially increases the spatial coverage, particularly during the early period. However, the procedure does not perform a spatial interpolation. Thus, the reconstructed dataset still contains blank areas where no station data exists.

3. The DINEOF method depends partly on the length and quality of input time-series. Thus, stations with records that are too short (<10 years) have been removed from this study. As data records are added in the future, these stations may be included in the analysis once the record duration criterion is satisfied. Although quality controls of raw station records were implemented by both this study and GHCNm V4, there may still be questionable values at a few sites.

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OPEN PRACTICES

This article has earned an Open Data badge for making publicly available the digitally-shareable data necessary to reproduce the reported results. The data is available at https://doi.org/10.6084/m9.figshare.7961120. Learn more about the Open Practices badges from the Center for Open Science: https://osf.io/tvyxz/wiki.

CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest.

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