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Short communication

A new interpolation method for Antarctic surface temperature

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Abstract

We propose a new methodology for the spatial interpolation of annual mean temperature into a regular grid with a geographic resolution of 0.01° for Antarctica by applying a recent compilation of the Antarctic temperature data. A multiple linear regression model of the dependence of temperature on some geographic parameters (i.e., latitude, longitude, and elevation) is proposed empirically, and the kriging method is used to determine the spatial distribution of regional and local deviations from the temperature calculated from the multiple linear regression model. The modeled value and residual grids are combined to derive a high-resolution map of surface air temperature. The performance of our new methodology is superior to a variety of benchmark methods (e.g., inverse distance weighting, kriging, and spline methods) via cross-validation techniques. Our simulation resembles well with those distinct spatial features of surface temperature, such as the decrease in annual mean surface temperature with increasing latitude and the distance away from the coast line; and it also reveals the complex topographic effects on the spatial distribution of surface temperature.

Keywords: Surface temperature; DEM; Antarctica

1. Introduction

Over the past few decades, great effort has been made for temperature reconstruction through stable water isotopic composition as recorded in Antarctic ice cores. The prominent empirical relationship between annual mean temperature and the isotopic composition of snow (i.e., the isotope–temperature slope) [1,2] forms the basis of the application of stable water isotopes as a climate proxy. However, some controversy does exist as to the extent this proxy can be used as a temperature indicator, because the isotope–temperature slope varies in space and time [3–8]. To quantify the spatial variations of the isotope–temperature slope, it is necessary to generate a spatial framework of Antarctic surface temperature. Additionally, such a framework is useful to estimate Antarctic ice sheet mass-balance and to force Antarctic ice sheet models. It is also beneficial for logistics management, especially under the harsh conditions of Antarctica. However, little information on surface temperature is available for most Antarctic areas due to the lack of *in situ* measurements. Spatial interpolation provides a method to explore the places where data are not available by generating a smooth trend from the existing data. Nevertheless, errors from interpolation are usually large for mountainous areas because of large elevation variability. This parameter pertaining to topography should be taken into account when developing a reliable climate model for Antarctica.

Numerous spatial interpolation techniques, such as inverse distance weighting (IDW), kriging, and spline, have been widely applied to estimate the spatial distribution of surface temperature during recent years [9–13]. However, these routine interpolation methods yield less satisfactory

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results due to limited observations. Here, we attempt to establish a statistical approach by applying regression techniques [14–16]. This new interpolation method is based on a multiple linear regression model incorporating the kriging interpolation technique. A spatial distribution map of Antarctic surface temperature is generated by combining the interpolation method with a high-resolution digital elevation model (DEM).

2. Data

Antarctic annual mean surface temperature data are from THERMAP Antarctic ice sheet temperature data [17] and the updated compilation of 10-m borehole temperature and automatic weather station (AWS) data at 1175 sites [18]. Among them, temperature data at 1024 sites were used in this study due to the available limitation of latitudes, longitudes, or elevations at sites elsewhere (Fig. 1). The 10-m borehole temperature is commonly regarded as a close estimate of annual mean surface air temperature at the snow surface [19,20]. The accuracy of this estimate depends on the snow structure, the pattern of air temperature variation within the year, and possible long-term temperature change [21]. The estimate error is about ±1.2% for Antarctica [22]. The error of annual mean temperature from AWS was not calculated due to lack of consistent methodologies [18].

A continuous grid map of annual mean surface temperature was generated using the National Snow and Ice Data Center Radarsat Antarctic Mapping Project digital elevation model version 2 (RAMP/DEM) [23]. This DEM incorporates topographic data from satellite radar altimetry, airborne radar surveys, the recently updated Antarctic Digital Database (version 2), and large-scale topographic maps from the U.S. Geological Survey and the Australian Antarctic Division. Data were collected from the 1940s to the present, but mostly during the period from the 1970s to the 1990s. Version 2 improves the first version by incorporating new topographic data, error corrections, extended coverage, etc. The vertical accuracy of the DEM is ±100 m for the rugged mountainous areas, ±15 m for the steeply sloped coastal regions, ±1 m for the ice shelves, ±7.5 m for the relatively flat interior ice sheet, ±17.5 m for the relatively steep portions of the ice sheet perimeter, and ±50 m for the interior of East Antarctica south of 81.5°S excluding the mountainous areas.

3. Method

The spatial distribution of temperature at the continental scales is controlled by geographic factors such as latitude, longitude, and elevation. A study of the linear relationships between mean annual surface temperature and geographic parameters (Table 1) yields a multiple linear regression model.

$$T_\chi = aLAT_\chi + bLON_\chi + cELEV_\chi + d \tag{1}$$

where T_χ stands for the initial estimate of temperature (°C), LAT for latitude (°), LON for longitude (°), $ELEV$ is elevation (m), and a, b, c, and d are the empirical parameters. In the model, the latitude, longitude, and elevation reflect the change in surface temperature from low- or mid-latitude to the South Pole, from ocean to inland, and from sea level to high elevation, respectively. The best-fit parameters for all

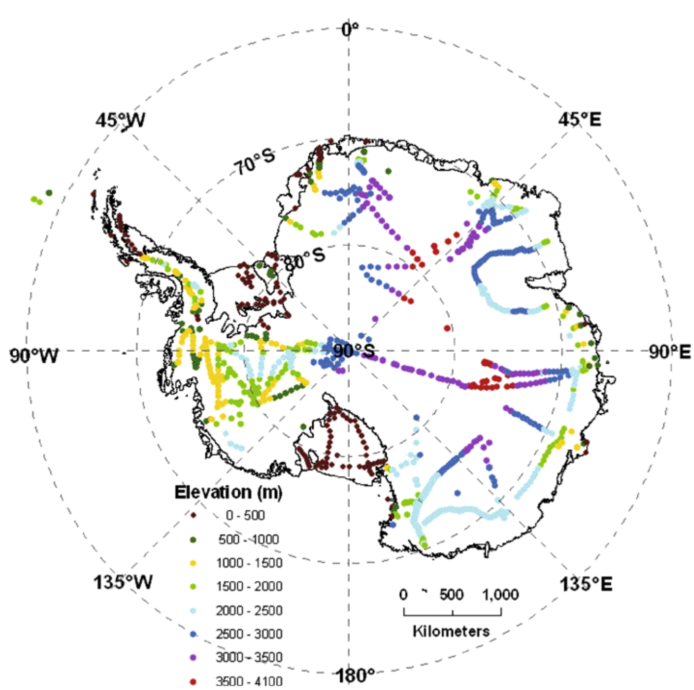

Fig. 1. A map of Antarctica showing the sites where surface temperature values are available together with their corresponding elevations.

Table 1
Correlation matrices.

	Latitude (°)	Longitude (°)	Elevation (m)	Temperature (°C)
The whole of Antarctica				
Latitude	1.00	0.44	−0.03	0.26
Longitude		1.00	0.40	−0.44
Elevation			1.00	−0.87
Temperature				1.00
Region 1 of East Antarctica				
Latitude	1.00	−0.67	−0.54	0.68
Longitude		1.00	0.67	−0.74
Elevation			1.00	−0.96
Temperature				1.00
Region 2 of East Antarctica				
Latitude	1.00	−0.11	−0.72	0.76
Longitude		1.00	−0.14	0.20
Elevation			1.00	−0.97
Temperature				1.00
Region 3 of East Antarctica				
Latitude	1.00	0.48	−0.88	0.93
Longitude		1.00	−0.62	0.44
Elevation			1.00	−0.94
Temperature				1.00
Region 4 of East Antarctica				
Latitude	1.00	0.40	0.02	0.19
Longitude		1.00	−0.71	0.71
Elevation			1.00	−0.90
Temperature				1.00
West Antarctica (including the Ross shelf)				
Latitude	1.00	0.13	−0.32	0.84
Longitude		1.00	−0.15	0.12
Elevation			1.00	−0.62
Temperature				1.00

the temperature data are described by the following polynomial, which accounts for 88% of the total variance.

$$T_\chi = 0.815LAT_\chi - 0.033LON_\chi - 0.008ELEV_\chi + 42.74 \quad (r^2 = 0.88) \tag{2}$$

According to this polynomial, elevation acts as the first driver for the spatial variations of annual mean surface temperature across the continent. But for West Antarctica, latitude plays a more important role than the other two parameters. Differences between the estimated and measured temperature values range from −11.06 to +13.29 °C, with a standard deviation of 3.83 °C and a mean absolute residual of 3.3 °C.

To improve the estimate accuracy, we estimated additionally temperature as a function of latitude, longitude, and elevation for West Antarctica (including the Ross shelf) and four regions of East Antarctica (Fig. 2), respectively, with the following equations.

For West Antarctica:

$$T_\chi = 1.029LAT_\chi - 0.004LON_\chi - 0.004ELEV_\chi + 56.872 \ (r^2 = 0.85) \tag{3}$$

For region 1 of East Antarctica:

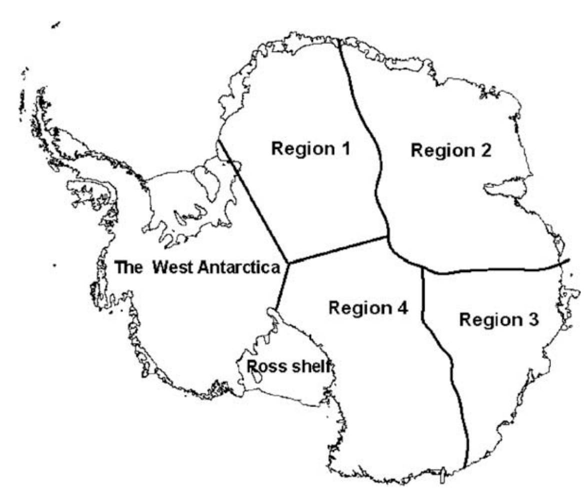

Fig. 2. The subsets and the divided regions in Antarctica.

$$T_\chi = 0.687LAT_\chi - 0.053LON_\chi - 0.009ELEV_\chi + 34.526 \quad (r^2 = 0.95) \tag{4}$$

For region 2 of East Antarctica:

$$T_\chi = 0.578LAT_\chi + 0.069LON_\chi - 0.012ELEV_\chi + 28.975 \quad (r^2 = 0.97) \tag{5}$$

For region 3 of East Antarctica:

$$T_\chi = 1.343LAT_\chi - 0.083LON_\chi - 0.01ELEV_\chi + 89.004 \quad (r^2 = 0.86) \tag{6}$$

For region 4 of East Antarctica:

$$T_\chi = 0.474LAT_\chi - 0.027LON_\chi - 0.01ELEV_\chi + 19.017 \quad (r^2 = 0.85) \tag{7}$$

In comparison to the result of Eq. (2), the difference between the estimated and measured temperature values by Eqs. (3)–(7) yields a smaller range (−6 to 10.6 °C) and exhibits a smaller standard deviation of 2.6 °C and a mean absolute residual of 2.0 °C. The estimated improvement may reflect the importance of the other factors, e.g., atmospheric circulation (penetration of synoptic cyclonic systems), strength of the inversion layer, and the distance away from the coast on the Antarctic surface temperature. Therefore, we interpolated the spatial temperature variability that is not accounted for by Eqs. (3)–(7), by the kriging interpolation technique. The kriging interpolation approach was applied due to the great coverage in spatial data density with which kriging copes well. The kriging is a form of weighted average estimator. The weights are assigned on the basis of the form of a model fitted to a function. In this case, the variogram represents the spatial variability of the data. The semi-variogram is an essential step for determining the spatial variation of the sampled variables.

The semi-variogram is:

$$\gamma(h) = \frac{1}{2}E(y(x) - y(x+h))^2$$

where $\gamma(h)$ is a semi-variogram, depending on the distance vector h; $(x, x + h)$ is the pair of points with distance vector h; $y(x)$ is the regionalized variable y at point x; $y(x) - y(x + h)$ is the difference of the variable at two points separated by h; and E is mathematical expectation.

This interpolation combined with Eq. (1) gives the composite model equation:

$$T'_\chi = \sum_{i=1}^{n} \lambda_i (T'_i - T_i) + T_\chi \tag{8}$$

where λ_i is the kriging weight.

Eq. (8) makes it possible to estimate annual mean temperature at any point where the three independent variables are available. Then, it is applied to the RAMP/DEM to produce a regular grid map of the surface temperature.

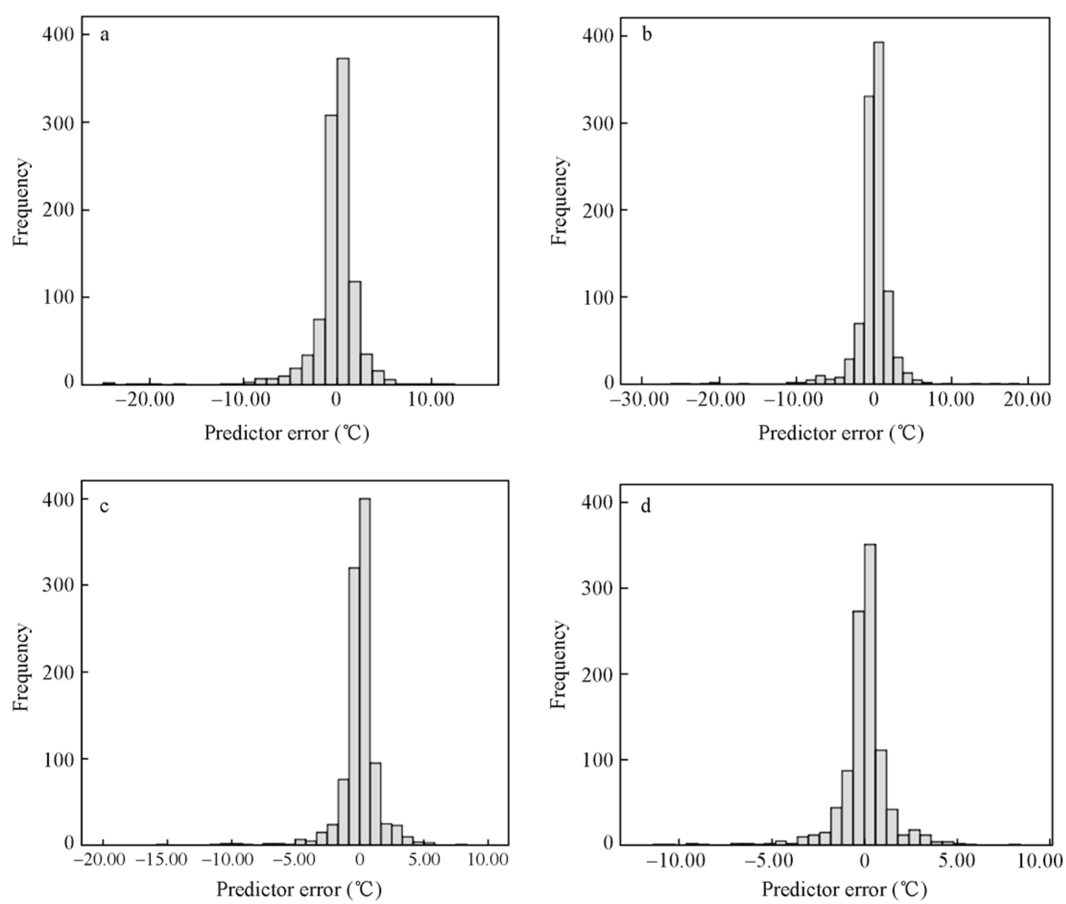

Fig. 3. Frequency distributions of the estimation error at the 1024 sampling sites in the cross-validation for (a) spline, (b) inverse distance weight, (c) universal kriging, and (d) the new interpolation method. Prediction error equals the difference between the measured temperature at a site and what is predicted by interpolation from all the other sites.

4. Results and discussion

4.1. Comparison of interpolation schemes

All the frequency distributions of the estimation error for the cross-validation of the four interpolation methods (Fig. 3) are roughly symmetric and leptokurtic. Therefore, we choose to use mean bias error (MBE), mean absolute error (MAE), and the root mean square errors (RMSE) to highlight the difference between the interpolation methods.

$$MBE = \frac{1}{n}\sum_{i=1}^{n}(Z*(\chi_i) - Z(\chi_i))$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}(|Z*(\chi_i) - Z(\chi_i)|)$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(Z*(\chi_i) - Z(\chi_i))^2}$$

where n stands for the number of observations, $Z(\chi_i)$ for the estimated value at site i, and $Z*(\chi_i)$ for the measured value at site i. Prediction error equals the difference between the measured temperature value measured at a site and what is predicted at this site by interpolation from all the other sites. As shown in Table 2, our new interpolation method provides relatively more accurate estimates than the other methods. The *MBE* of this new method is approximately zero, indicating absence of skew in the distribution of residuals. Additionally, residuals are not correlated with the prediction variables, suggesting that error is randomly distributed.

Table 2
Cross-validation errors (°C) of the four interpolation methods.

Model	MBE	MAE	RMSE
IDW	−0.085	1.24	2.61
Spline	−0.145	1.4	2.63
Universal kriging	0.035	1.54	2.6
The new method	−0.012	0.79	1.33

4.2. Estimate of uncertainties

The annual mean temperature grid map for Antarctica is shown in Fig. 4. Its uncertainties may be associated with the interpolation algorithm, seasonal/inter-annual change in temperature, and DEM errors. Linear regression between the measured temperature values and their corresponding estimated values yields a correlation coefficient of 0.99 and a regression slope of 0.99 (Fig. 5). This result is quite remarkable, given the facts that measurements cover different time scales and that DEM bias exists. Additionally, there are measured sites where elevation is unavailable that makes it possible to make the comparison between the measured and estimated temperature values of these sites (Table 3). The average of absolute residuals is 1.54 °C, with a standard deviation of 1.8 °C ($n = 17$).

4.3. Spatial distribution of surface temperature

Annual mean surface temperature varies strongly with topography, having a minimum of below −55 °C over central East Antarctica, where ice domes rise to over 3500 m. The strongest temperature gradients can also be observed

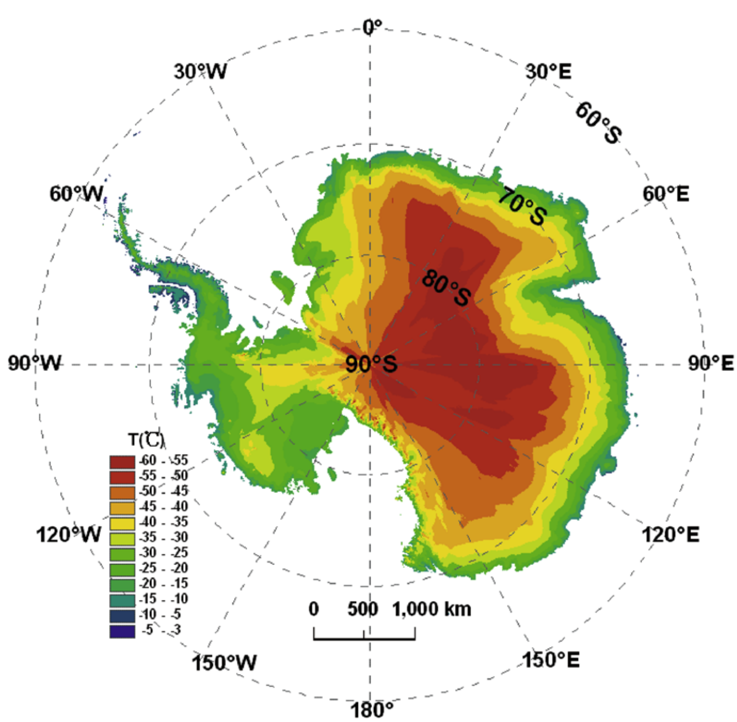

Fig. 4. A map of annual mean surface temperature for Antarctica.

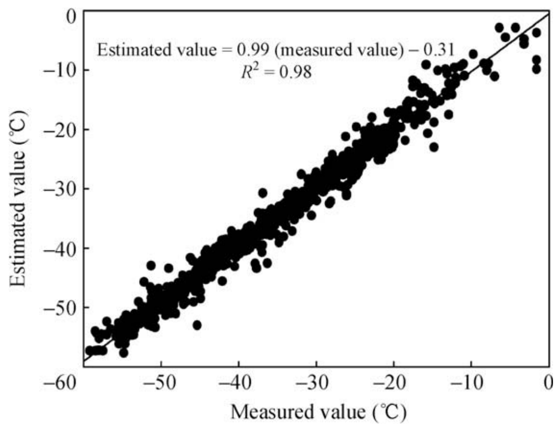

Fig. 5. Regression between the measured and the estimated annual mean surface temperature values.

over the steep slopes of East Antarctica. In the coastal regions around Antarctica, the annual mean surface temperature varies from −20 to −10 °C.

In comparison with the previously published map generated by the linear interpolation of the nearest observation sites [24], the new annual mean temperature map (Fig. 4) improves primarily as a result of the greatly increased spatial density of sites, especially across East Antarctica, which improves the definition of the interpolation criteria. Although the 40-year re-analyses of the European Centre for Medium-Range Weather Forecasts (ERA-40) represents the annual cycle of surface temperature reasonably well, the annual mean surface temperature is overestimated by typically 3 K over Antarctica, probably due to errors in the surface energy budget [25]. The general circulation models (GCMs) and the Hadley Centre coupled model (HadCM3) perform reasonably well for the broad-scale structure of the annual mean temperature over Antarctica [26–28]. Furthermore, the modeled and observed temperatures generally agree well for the east Antarctica plateau. However, annual mean temperatures are overestimated for the Antarctic peninsula and some large ice shelves, and underestimated in the coastal regions of east Antarctica for the output of the GCMs. The model's resolution which is insufficient to resolve the steep orography may result in large errors in the modeled temperature [29]. Model errors in the large ice shelves may result from the treatment of ice shelves as sea ice rather than land ice in the GCMs [27]. As for the output of HadCM3, the modeled temperatures are up to 10 °C, too cold over Dronning Maud Land and too warm around 70°E [28]. The areas with large temperature errors correspond to the locations of large orography biases in the model [28]. However, the new interpolation method is primarily driven by high resolution DEM. It can represent the striking effect of orography on temperature values. Furthermore, the other factors affecting the temperature such as regional atmosphere circulation is implicitly represented in the new interpolation method. Therefore, the new surface temperature map indicates more approximate annual mean temperature measurements.

Table 3
Validation statistics for the 17 annual mean temperature measurements.

Latitude (°)	Longitude (°)	Measured value (°C)	Estimated value (°C)	Error
−69.61	96.74	−38.1	−36.6	−1.5
−67.23	94.03	−24.5	−22.1	−2.4
−79.04	149.68	−44	−44.9	0.9
−77.78	152.37	−44.4	−42.9	−1.5
−77.88	158.46	−41	−40.2	−0.8
−79.16	−104.97	−27.6	−30.8	3.2
−77.84	−102.91	−25	−26.6	1.6
−78.12	−95.65	−25.9	−28.3	2.4
−77.06	−89.14	−26.4	−27.8	1.4
−82.86	−150.89	−27.7	−25	−2.7
−82.08	−153.67	−27	−24	−3
−80.36	−117.47	−26.7	−27.5	0.8
−80	−120	−26.5	−27.6	1.1
−83.52	−156.03	−26.4	−26	−0.4
−84.25	−151.91	−25.8	−25.4	−0.4
−83.41	−151.22	−25.1	−25.1	0
−81.58	−151.73	−24.5	−26.7	2.2

The highly accurate evaluation of the amount and pattern of Antarctic surface temperature will confer benefit on many active areas of research including the validation of weather and climate models, and the selection of ice-coring sites before drilling. Interpolation of the site data by the new method produces an Antarctic surface temperature distribution which could be expected in nature. In comparison to field data based on a small number of transects [24], the presented result is an improvement in resolution and accuracy and can be used for the validation of numerical climate models at regional or continental scales. The high resolution map (Fig. 4) reflects the continuously and gradually changed climate pattern and accounts for climatic dependence on topography. Additionally, it highlights the extremely low annual mean temperature (<−55 °C) regions in central Antarctica. Knowledge of these characteristics is important for future deep ice core drilling, especially for selecting the most appropriate site of a deep ice core that extends through the mid-Pleistocene transition (MPT), roughly 700–1250 kyr [30], a time period when the Earth's climate shifted from a 41,000 year to a 100,000 year glacial-interglacial cycle, because the extremely low temperature is one of the preconditions for retrieving the oldest ice core from the Antarctic ice sheet [31,32].

5. Conclusion

A new interpolation method has been developed to depict the distribution of Antarctic surface temperature. The annual mean surface temperature map, generated using this method, presents a quantitative, statistically robust depiction of the spatial distribution of Antarctic surface temperature. With this information, suitable sites for the recovery of ice cores can be chosen for further climatic research as part of the International Partnerships in Ice Core Sciences (IPICS) plans. Furthermore, the Antarctic surface temperature map can provide a particularly useful benchmark for comparison with the output of GCMs and HadCM3.

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