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A new spatial distribution map of $\delta^{18}\text{O}$ in Antarctic surface snow

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[1] We developed a gridded map of surface Antarctic snow isotopic composition using a recently compiled database and the modified Bowen and Wilkinson (2002) model using latitude and elevation as the primary predictors while also incorporating regional and local deviations based on available isotopic data. The map was generated using a 1-km digital elevation model grid data as the model input. The average of the absolute deviations between observations and predictions was about 0.8‰, and the standard deviation is 0.9‰. The resulting $\delta^{18}\text{O}$ patterns reproduced correctly spatial isotopic gradients with respect to geographical characteristics, as well as climatic features.

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1. Introduction

[2] Oxygen isotope values from the polar snow exhibit a robust linear correlation with annual mean air temperature at the deposition site [e.g., Dansgaard, 1964; Lorius and Merlivat, 1977]. Assuming that this relationship remains valid over time, $\delta^{18}\text{O}$ in polar ice has long been regarded as a valuable proxy for temperature reconstruction [e.g., GRIP Members, 1993; EPICA Community Members, 2004]. Moreover, the spatial relation between $\delta^{18}\text{O}$ in the Antarctic surface snow ($\delta^{18}\text{O}_{\text{AS}}$) and temperature (the so-called spatial slope) can be used as a surrogate for the temporal slope on a glacial-interglacial time scale [Jouzel et al., 2003].

[3] Many geographic and climatic factors, including latitude, elevation, distance from coast and humidity that control surface air temperature are correlated with $\delta^{18}\text{O}_{\text{AS}}$ values [Dansgaard, 1964; Rozanski et al., 1993]. However, there are also other factors that might affect the $\delta^{18}\text{O}$ values, such as change in seasonality of precipitation [e.g., Masson-Delmotte et al., 2005], change in magnitude of the ratio between advective and turbulent transport [Kavanaugh and Cuffey, 2003], change in the inversion strength [Van Lipzig et al., 2002], storm track trajectories, and moisture origin [Jouzel et al., 1997]. There is evidence for seasonal or interannual variation that differs from the spatial differences [Jouzel et al., 1983]. Furthermore, in the low accumulation areas, the short-term spatial slope (i.e., over several years) is not strong enough to infer the climate changes from isotope records with confidence [e.g., Helsen et al., 2005]. To

address these issues, it is beneficial to generate a spatial reference framework of $\delta^{18}\text{O}_{\text{AS}}$.

[4] Bowen and Wilkinson [2002] proposed an interpolation method (BW model) that treats the isotopic composition of precipitation as the sum of temperature driven rainout effects and regional patterns of vapor sourcing and delivery. A global $\delta^{18}\text{O}$ map was generated, based on the model [Bowen and Wilkinson, 2002; Bowen and Revenaugh, 2003]. However, the accuracy of $\delta^{18}\text{O}$ estimates is low in Antarctica [Bowen and Revenaugh, 2003]. This may result from sparse data coverage or the poor fit of the relation between latitude and $\delta^{18}\text{O}$. Stable isotope measurements on Antarctic surface snow are expected to provide valuable data improving $\delta^{18}\text{O}$ estimates of the model for this area [Bowen and Revenaugh, 2003]. Hereafter, the BW model is extended to refine spatial $\delta^{18}\text{O}_{\text{AS}}$ patterns. We modified the partial model parameters with an attempt to improve the $\delta^{18}\text{O}$ estimates for Antarctica. A high resolution map of $\delta^{18}\text{O}_{\text{AS}}$ was then generated by coupling the modified model with a digital elevation model (DEM).

2. Data

[5] Mean $\delta^{18}\text{O}_{\text{AS}}$ data come from the most recently compiled Antarctic surface snow isotopic composition database by Masson-Delmotte et al. [2008]. The database includes $\delta^{18}\text{O}_{\text{AS}}$ observations at 1125 locations. Among them, 757 $\delta^{18}\text{O}_{\text{AS}}$ data were used for this study due to the availability of geographic data from these stations (Figure 1). The dataset consists of records that are sampled irregularly in space and time, covering a wide variety of time periods. Average time intervals range from several years to several hundreds of years, with the majority <50 years. The standard deviation of local $\delta^{18}\text{O}_{\text{AS}}$ measurement varies from 0.28‰ to 6.6‰. While the differences in $\delta^{18}\text{O}_{\text{AS}}$ values might arise partly as the result of the uneven distribution of isotope data over time and seasonal/inter-annual precipitation isotopic composition variability, the temporal variations are small when compared to the range of the spatial distribution of mean $\delta^{18}\text{O}_{\text{AS}}$ data [Masson-Delmotte et al., 2008] (see the auxiliary material¹). Continuous grid maps of $\delta^{18}\text{O}_{\text{AS}}$ were generated using the Radarsat Antarctic Mapping Project digital elevation model (RAMP/DEM) version 2 (see the auxiliary material).

3. Methods

[6] Despite of the many factors that control the oxygen isotope compositions of Antarctic surface snow, there is a negative relationship between $\delta^{18}\text{O}_{\text{AS}}$ and latitude (Figure 2a). This may result from the condensation and distillation of water vapor during transport from low or mid-

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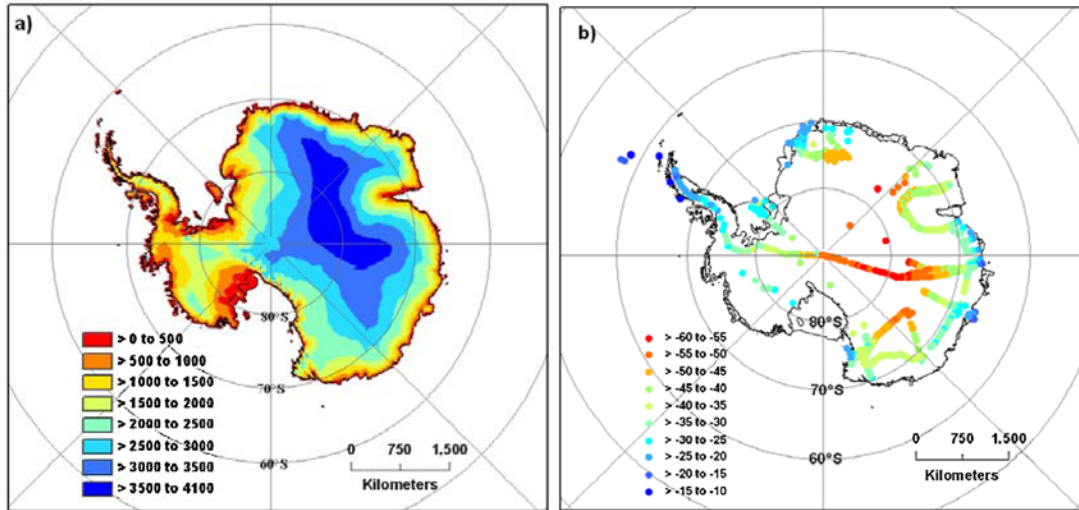


Figure 1. Map of Antarctica showing (a) Radarsat Antarctic Mapping Project (RAMP) DEM (in meters) and (b) $\delta^{18}\text{O}$ (‰) information available for 757 surface oxygen isotope data points in a polar stereographic projection with reference to the WGS84 ellipsoid.

latitude oceanic regions toward Antarctica. Following *Bowen and Wilkinson* [2002], a second-order polynomial best describes the relationship between mean annual $\delta^{18}\text{O}_{\text{AS}}$ and absolute latitude value for all the sampling stations below 200 m asl, where LAT is the latitude in decimal degree. This elevation limit was chosen because there is no significant relation between $\delta^{18}\text{O}_{\text{AS}}$ and elevation below 200 m asl.

$$\delta^{18}\text{O}_{\text{AS}<200} = -0.0211|\text{LAT}|^2 + 2.3345|\text{LAT}| - 81.295 \quad (1)$$

Where LAT is the latitude in decimal degree, $r^2 = 0.72$, $n = 52$, and $p < 0.01$.

[7] Deviations of $\delta^{18}\text{O}_{\text{AS}}$ measurements from equation (1) systematically increase with increasing elevation (see auxiliary material). This primarily reflects the influence of Rayleigh distillation of water vapour as air masses orographically rise and cool. To further explore quantitatively the relationship between $\delta^{18}\text{O}_{\text{AS}}$ and elevation, equation (1)

was used to estimate $\delta^{18}\text{O}_{\text{AS}}$ values for all stations based on their latitudes. The least-squares regression between residuals from equation (1) (RES_{AS}) and station elevations quantified the effect of elevation on $\delta^{18}\text{O}_{\text{AS}}$ where the Y-intercept was fixed at 0. The best-fit equation ($r^2 = 0.78$, $n = 757$, $p < 0.01$) is:

$$\text{RES}_{\text{AS}} = -0.0068\text{ELEV} \quad (2)$$

Where ELEV is the elevation in meter. This yields the $\delta^{18}\text{O}_{\text{AS}}$ lapse rate of 6.8‰/km.

[8] Isotopic composition dependence on latitude and elevation is described by combining equations (1) and (2).

$$\delta^{18}\text{O}_{\text{AS}} = -0.0211|\text{LAT}|^2 + 2.3345|\text{LAT}| - 0.0068\text{ELEV} - 81.295 \quad (3)$$

[9] Differences between estimated and measured $\delta^{18}\text{O}_{\text{AS}}$ values range from -8.3 to $+17.7$ ‰, with a standard

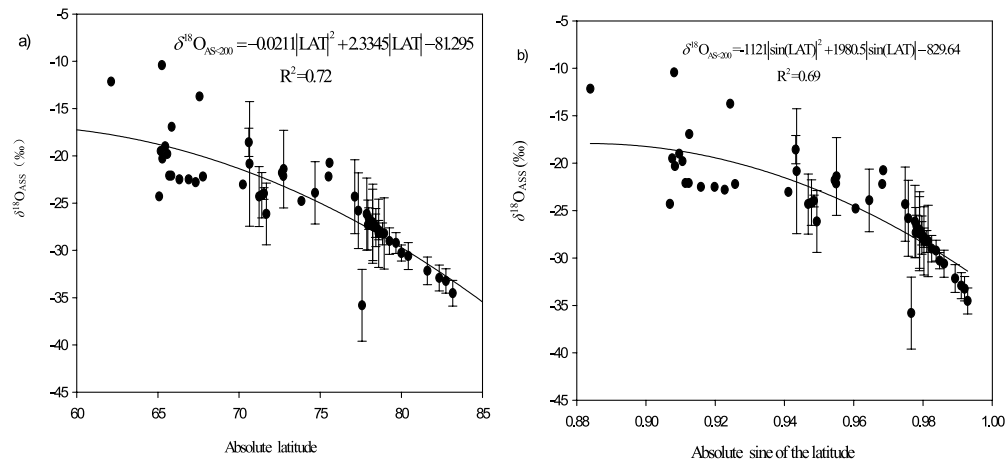


Figure 2. The $\delta^{18}\text{O}_{\text{AS}}$ for all the stations with elevation below 200 m across Antarctica versus (a) latitude and (b) the sin of latitude, respectively.

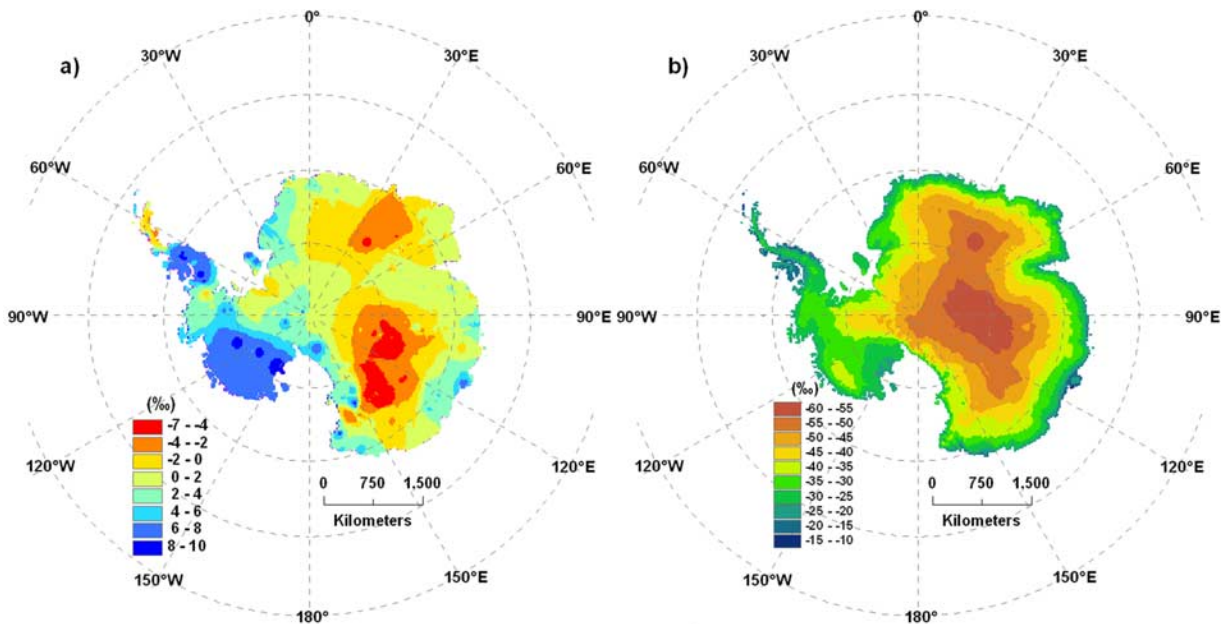


Figure 3. (a) Residuals from equation (4) contoured using a kriging method; (b) map of $\delta^{18}\text{O}_{\text{AS}}$ calculated for continents at 1km resolution in a polar stereographic projection with reference to the WGS84 ellipsoid. Map values are sum of model-derived $\delta^{18}\text{O}_{\text{AS}}$ estimates from latitude and elevation data and spatially interpolated model residuals.

deviation of 3.8‰ and mean absolute error of 2.9‰. The relationship between estimated and measured values is linear with a slope of 1.1 and $r^2 = 0.84$.

[10] Additionally, we estimated $\delta^{18}\text{O}_{\text{AS}}$ as a function of the sine of the latitude (Figure 2b) and elevation, respectively, with the following equation:

$$\delta^{18}\text{O}_{\text{AS}} = -1121|\sin(\text{LAT})|^2 + 1980.5|\sin(\text{LAT})| - 0.0067\text{ELEV} - 892.64 \quad (4)$$

[11] Residuals between measured and estimated by equation (4) have a smaller range (−7.8 to 13.8‰), and exhibit smaller standard deviation of 3.5‰ and mean absolute error of 2.7‰ than those estimated by equation (3). The 89% explained variance of $\delta^{18}\text{O}_{\text{AS}}$ is higher than the variance (84%) explained by equation (3). Therefore, equation (4) is superior to equation (3) for the $\delta^{18}\text{O}_{\text{AS}}$ estimation. These residuals may result from other factors affecting $\delta^{18}\text{O}_{\text{AS}}$, such as distance from the coast line, water vapor transport patterns, intermittency of precipitation, orographic uplift, and kinetic effects that are not accounted for by only considering latitude and elevation. In order to improve the accuracy of $\delta^{18}\text{O}_{\text{AS}}$ estimates, there is a need to generate a map of spatial variation of the residuals.

4. Spatial Distribution of Latitude-Elevation Model Residuals (a Part of BW Model)

[12] To investigate the spatial distribution of the model residuals, we interpolated the residuals using an ordinary kriging routine on a spherical surface (Figure 3a). The observations show more enriched in ^{18}O than the prediction (positive anomalies) in the Antarctic Peninsula, Marie Byrd Land and on the flanks of Law Dome, while negative

anomalies centre in the central East Antarctic Plateau, especially around Dome F, C and Vostok regions. These regional anomalies may be attributed to the temperature, different histories of water vapor distillation and the different moisture origin and trajectories. Not all locations with similar latitude and elevation have similar (precipitation weighted) temperature. There is a positive correlation ($r^2 = 0.24$, $n = 637$) between the residual of latitude-elevation model and temperature. Moisture deposited in the central plateau undergoes very high elevation and long distance transport, while coastal areas receive storm track type heavy snowfall events, with local sources. Backward air parcel trajectories reveal that the air masses to Vostok and Dome C come mainly from the Southern Indian Ocean side, while the Pacific Ocean is the main moisture source for Byrd [Reijmer *et al.*, 2002]. Similarly, the moisture trajectory affects the spatial distribution of $\delta^{18}\text{O}_{\text{AS}}$. On the flanks of Law Dome, for instance, the distribution along an east-west transect is a main driver of isotopic depletion because moisture is advected from south-east cyclonic activity. In this case, the east-west gradient of isotopic depletion links to a gradient of accumulation, due to an orographic shadow effect on air masses that cross the ice divide [Morgan *et al.*, 1997]. However, large positive anomalies in Marie Byrd may also result from the limited set of $\delta^{18}\text{O}_{\text{AS}}$ observations and their uncertainties. Negative anomalies occurring in the East Antarctic Plateau may be, at least in part, due to the great transport distance of air masses from the coast. In addition, post-depositional processes may lead possibly to systematic disturbance on $\delta^{18}\text{O}_{\text{AS}}$ due to wind-driven ablation effects on the flanks of the ice sheet where local topography can be complex [Ekaykin *et al.*, 2002; Frezzotti *et al.*, 2004] or sublimation effects in the dry plateau [Neumann and Waddington, 2004]. Despite the relatively

large residuals in a certain regions, most of the Antarctica exhibits residuals with an absolute value less than 2‰.

5. Spatial Distribution of $\delta^{18}\text{O}_{\text{AS}}$

[13] A grid with 1km resolution was generated from application of equation (4) to the RAMP/DEM grid points. This grid was added to the interpolated residual grid (Figure 3a) to produce a map grid representing the $\delta^{18}\text{O}_{\text{AS}}$ estimation, which may be useful for the forcing of Antarctic ice sheet models using isotopic tracers [Lhomme et al., 2005] (Figure 3b). The predominant features of the map include the most depleted values over the central Antarctic Plateau, where the lowest values of temperature are expected to be found due to the continentality and elevation effects. The strongest isotopic gradients can be observed over the steep slopes of East Antarctica, corresponding both to the strong temperature gradients and the continentality. A significant ($p < 0.01$) linear regression between $\delta^{18}\text{O}$ and temperature obtained from the whole database with a slope of $0.80 \pm 0.01\text{‰ per }^\circ\text{C}$ ($n = 745$) [Masson-Delmotte et al., 2008]. However, observed spatial slopes vary depending on the location of the sampling sites (a detailed discussion can be found in the auxiliary material). The spatial distribution of $\delta^{18}\text{O}_{\text{AS}}$ displays the depletion of the heavy isotopes from the middle to high latitudes [Dansgaard, 1964], depletion of the heavy isotope with increasing distance from the coast line [Dansgaard, 1964], and low $\delta^{18}\text{O}_{\text{AS}}$ at high elevations [Dansgaard, 1964]. Of all the geographical factors, the surface elevation appears as the first driver for $\delta^{18}\text{O}_{\text{AS}}$ spatial variations [Masson-Delmotte et al., 2008]. The elevation effect is particularly striking for mountain ranges. The $\delta^{18}\text{O}_{\text{AS}}$ lapse rate (6.8‰/km) is also of interest because it can be adopted in reconstructions of Antarctic growth history or paleotopography from the ^{18}O content of ice core. In addition to these previously documented effects, one of the most dramatic patterns depicted in the map is the enhanced meridional heterogeneity of $\delta^{18}\text{O}_{\text{AS}}$, which is not only caused by temperature gradients but also likely due to the heterogeneity of vapor transport and moisture origins. The coastal site receives moisture provided by cold high latitude ocean sources, and is transported towards the coastal locations where it precipitates. In contrast, the moisture that precipitates in central Antarctica has been travelling at higher elevations, which reduces the high latitude ocean moisture contribution and undergoes a different distillation path and kinetic effects [Noone and Simmonds, 2002; Masson-Delmotte et al., 2008].

[14] $\delta^{18}\text{O}$ data of stations for which elevation information was missing in the initial dataset enables a comparison between the gridded isotopic composition estimate and the field data. The mean absolute error is 1.7‰ , with a standard deviation of 2.1‰ ($n = 90$). In addition, the map reproduces well the $\delta^{18}\text{O}_{\text{AS}}$ of sampling stations with a mean absolute error of 0.8‰ , and a standard deviation of 0.9‰ ($n = 733$). The relationship between $\delta^{18}\text{O}_{\text{AS}}$ estimations and measurements is linear with a slope of 1.0 and $r^2 = 0.98$.

[15] The $\delta^{18}\text{O}_{\text{AS}}$ map presented here improves upon that of Giovinetto and Zwally [1997], and Zwally et al. [1998] primarily as a result of increased spatial density of stations, especially in the flanks of the East Antarctica, which improves the definition of the interpolation criteria and

the significance level of the statistics. The $\delta^{18}\text{O}_{\text{AS}}$ map in this study shows lower $\delta^{18}\text{O}_{\text{AS}}$ values along the segment of the Transantarctic Mountains than the map published by Giovinetto and Zwally [1997] and Zwally et al. [1998]. This may result from the poor representation of the topography or the implicit surface slope gradient in the areas by the 100km resolution DEM used by Giovinetto and Zwally [1997] and Zwally et al. [1998]. In comparison with the previously simulated $\delta^{18}\text{O}_{\text{AS}}$ spatial distributions using general circulation models (GCMs) equipped with isotope tracers [Schmidt et al., 2005; Masson-Delmotte et al., 2008], and Mixed Cloud Isotopic Model (MCIM) [Helsen et al., 2007], differences do exist especially in the east Antarctic Plateau where the isotopic depletion of snow is underestimated by about 10‰ for the GCMs and MCIM [Schmidt et al., 2005; Helsen et al., 2007; Masson-Delmotte et al., 2008]. These biases may be due to an underestimation of kinetic effects from tracers of different moisture transport paths at different atmospheric heights and inadequate representation of large scale advection of water vapor in MCIM [Salamatin et al., 2004; Masson-Delmotte et al., 2008]. They may also result from a warm bias found or be linked to the GCM representation of the transport of moisture towards central Antarctica [Schmidt et al., 2005; Masson-Delmotte et al., 2008]. In addition, GCMs do not necessarily include the correct topography of Antarctica in their boundary conditions. This may result in large errors in the simulated temperature. Because the BW model is primarily driven by the high-resolution DEM, it does capture the striking effect of elevation on isotopic values. Furthermore, the other factors affecting the $\delta^{18}\text{O}_{\text{AS}}$ such as kinetic effects, moisture resource effects are represented by the spatial interpolation of the model residuals. Therefore, our map has better agreement with $\delta^{18}\text{O}_{\text{AS}}$ measurements over much of the east Antarctic Plateau.

6. Conclusions

[16] The BW model, modified here, improves its precision of $\delta^{18}\text{O}_{\text{AS}}$ estimates in comparison with the original BW model and represents the observed $\delta^{18}\text{O}_{\text{AS}}$ gradients. The high-resolution $\delta^{18}\text{O}_{\text{AS}}$ map reflects the enhanced meridional heterogeneity of $\delta^{18}\text{O}_{\text{AS}}$. Furthermore, it can provide a particularly useful benchmark for comparison with GCMs and MCIM.

[17] Significant deviation from the mean geographic and physiographic trends in the Antarctic Peninsula, Dome F, C and Vostok regions may provide a meaning of detecting changes in the atmospheric moisture supply to Antarctica, including changes in moisture origin. The observed spatial $\delta^{18}\text{O}$ -temperature slopes in Antarctica vary regionally, indicating that this widely used relation is not applicable to all sites.

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