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An Improved Method for Modeling Spatial Distribution of δD in Surface Snow over Antarctic Ice Sheet

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Abstract: Using the recent compilation of the isotopic composition data of surface snow of Antarctic ice sheet, we proposed an improved interpolation method of δD, which utilizes geographical factors (i.e., latitude and altitude) as the primary predictors and incorporates inverse distance weighting (IDW) technique. The method was applied to a high-resolution digital elevation model (DEM) to produce a grid map of multi-year mean δD values with 1km spatial resolution for Antarctica. The mean absolute deviation between observed and estimated data in the map is about 5.4‰, and the standard deviation is 9‰. The resulting δD pattern resembles well known characteristics such as the depletion of the heavy isotopes with increasing latitude and distance from coast line, but also reveals the complex topographic effects.
Keywords: δD; surface snow; ice sheet; Antarctica

1 Introduction

Polar ice sheets are archives of a wealth of valuable paleoclimatic information. During the recent decades, abundant studies on different deep ice cores from the Greenland and Antarctic ice sheets have led to substantial progress in palaeoclimatology (GRIP Members, 1993; NGICP Members, 2004; EPICA Community Members, 2004; Jouzel et al., 2007). Stable hydrogen isotope ratios (δD) from ice cores are crucial in reconstructing climate because they are regarded as a proxy for temperature (Dansgaard, 1964; Jouzel et al., 1997). The basis of the use of δD as a palaeothermometer is the strong empirical relationship between mean annual temperature (T) and the isotopic composition (δ) of snow (δ-T relationship) (Dansgaard, 1964; Yurtsever and Gat, 1981; Rozanski et al., 1993). Despite the widespread use of the indicator (Jouzel et al., 1997; 2003), there is some controversy to the extent δD can be used to estimate past temperature since the δ-T relationship appears to vary on different spatial and temporal scales (Robin, 1983; Cuffey et al., 1995; Johnsen et al., 1995; Jouzel et al., 1997; 2003; Masson-Delmotte et al., 2003). In addition to T (Dansgaard, 1964; Yurtsever and Gat, 1981; Rozanski et al., 1993), many other factors may affect δ-T relationship, such as changes in seasonality of precipitation (Noone et al., 1999; Schlosser and Oerter, 2002; Masson-Delmotte et al., 2005), microphysical processes in clouds during snow formation (Fisher, 1991; Ciais and Jouzel, 1994), variations in the inversion strength (Van Lipzig et al., 2002), shifts in large-scale circulation patterns (Noone and Simmonds, 2002), and source region distribution (Jouzel et al., 1997). Information of δD in Antarctic surface snow mainly recording the present climate change from many locations is required to address these issues. Unfortunately, it is difficult to determine the exact δD of an "average" year (the long-term mean annual δD) at one or more locations due to the logistical problems associated with harsh environmental conditions in Antarctica. Spatial interpolation provides a method for estimating δD in Antarctic surface snow where data are not available by generating a smoothed surface trend that captures the geographic variability of data.

Some simple spatial interpolation techniques, such as

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contouring, triangulation, and inverse distance methods, have been attempted to estimate the spatial distribution of stable water isotope. However, for limited δD observation sites, these interpolation methods are usually not available for accurate result. Recently, the more complex BW model which combines an empirical model for isotopic trends related to latitude and altitude with spatial interpolation (Bowen and Wilkinson, 2002) has been applied to deriving spatial distribution of the isotopic composition of precipitation all over the world (Bowen and Revenaugh, 2003). However, the confidence of δD estimates is low in Antarctica, possibly due to sparse data coverage or the poor fit of the empirical relationship between latitude and δD (Bowen and Revenaugh, 2003). In this study, firstly, the dependence of δD on latitude and altitude was analyzed. Secondly, we developed an interpolation method, based on a multiple linear regression model incorporating the inverse distance weighting (IDW) technique. At last, we drew a high-resolution spatial distribution map for δD in Antarctic snow using the interpolation method on a digital elevation model (DEM) of Antarctica.

2 Data and Methods

2.1 Data

Hydrogen isotope data discussed herein are expressed in per mille (‰) as the deviation of a sample from the Vienna Standard Mean Ocean Water (V-SMOW) standard. Multi-year mean δD data came from Antarctic surface snow isotopic composition database by Masson-Delmotte et al. (2008), which is available at http://www.lsce.cea.fr/Pisp/24/valerie.masson-delmotte.html. The database includes δD observations from 938 sampling sites. Among them, 567 observations were used for this study. The remaining ones were not used as a result of limited geographic information (latitude, longitude or elevation). As evident in Fig. 1, the sampling sites are not evenly distributed within Antarctica. More than 50% of the sites are located in the sector from 90°E to 180°E. δD data were measured from archival direct precipitation sampling at a few sites (Global Network for Isotopes in Precipitation stations from the International Atomic Energy Agency stations, Neumayer, Dumont d'Urville, Vostok, Dome Fuji) over varying durations, snow-pit samples typically 1m shallow snow-cores, as well as shallow ice cores with a sub-annual resolution. The samples were collected from the 1960s to present, but mostly between the 1980s and the 1990s.

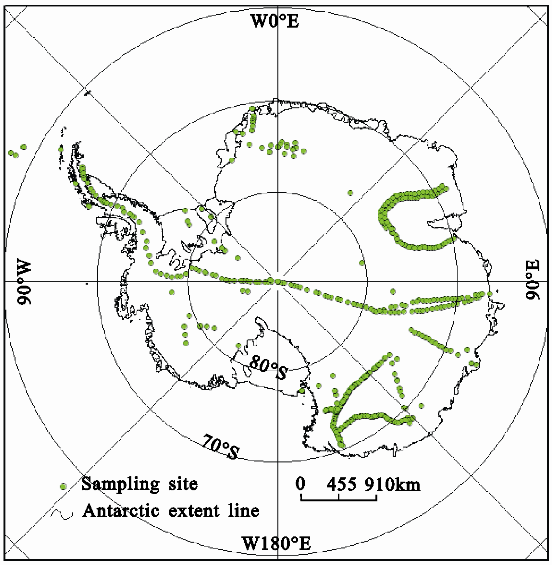

Fig. 1 Spatial distribution of sampling sites for δD in Antarctic surface snow

Continuous grid map of multi-year mean δD was generated by using the Radarsat Antarctic Mapping Project digital elevation model version 2 (RAMP/DEM) provided by National Snow and Ice Data Center (NSIDC), USA. RAMP/DEM incorporates topographic data from European Remote Sensing Satellite-1 radar altimetry, airborne radar echo-sounding 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 (http://nsidc.org/data/docs/daac/nsidc0082_ramp_dem_v2.gd.html). In comparison to the original version, version 2 was improved by incorporating new topographic data, error corrections, extended coverage, and other modifications. Vertical accuracy of the DEM is ±100m over rugged mountainous areas, ±15m for steeply sloped coastal regions, ±1m on the ice shelves, ±7.5m for the gently sloping interior ice sheet, and ±17.5m for the relatively rough and steeply sloped portions of the ice sheet perimeter. For areas south of 81.5ºS, within the interior East Antarctic ice sheet and away from the mountain ranges, vertical accuracy is ±50m (Liu et al., 2001).

2.2 Uncertainty of isotopic composition data

The δD data used for this study consist of records that are obtained 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 of less than 50 years. The standard deviation of local δD measurements varies from 3‰ to 53‰. This might induce misinterpretations when modeling spatial variations statistically in order to define optimal interpolation criteria. However, average isotopic value over the last 200 or the last 40 years are very similar for Dronning Maud land (Graf et al., 2002). The local isotopic values remain stable over the last 30 years, at least in central Antarctica (Masson-Delmotte et al., 2008). Stable isotopes do not indicate a drastic change during the last 200 years in the East Antarctica (Schneider et al., 2006). For example, δD measurements from the snow-pit samples and an ice core at Vostok cover a period of about 60 and 170 years, respectively. Despite the different average time intervals, they represent very similar mean δD values of –440.05‰ (Ekaykin et al., 2002) and –441.9‰ (Ekaykin et al., 2002), respectively. The differences in δD values, which might originate partly from the result of the uneven distribution of isotope data over time and seasonal/inter-annual precipitation isotopic composition variability, are small compared to the range of the spatial distribution of annual mean δD data (Masson-Delmotte et al., 2008). Therefore, we think this kind of error could not significantly corrupt the quality of a spatially modeled picture of δD.

2.3 Methods

As expected, there is a strong correlation between δD and latitude and altitude, respectively. Therefore, we used a linear regression technique to deconvolve the effects of latitude and altitude on δD in Antarctic surface snow.

$$P_i = a * L_i + b * A_i + c \quad (1)$$

where P_i is the initial estimate of δD of the sampling site i (‰), L_i is latitude (°) of the sampling site i, A_i is altitude (m) of the sampling site i, and a, b and c are the empirical parameters. The best-fit parameters for all the temperature data are described by the following polynomial, which accounts for 85% of the δD variance.

$$P_i = (5.198 \pm 0.25) * L_i - (0.066 \pm 0.001) * A_i + (222.754 \pm 18.115) \quad (R^2 = 0.85) \quad (2)$$

Figure 2 shows the anomalies between the observed δD and mean δD estimated by Equation (2). The standard deviation of the anomalies for δD (27‰) remains limited. Positive anomalies (measured values are greater than estimated) occur in the central Antarctic Peninsula, Marie Byrd land and the flanks of the ice sheet, while negative anomalies concentrate in the central East Antarctic Plateau, especially around Dome C and Vostok regions and west Antarctic Peninsula. These regional anomalies may result from the different histories of distillations and the different moisture origin and trajectories. To represent the effects, we interpolated spatially δD variability that is not accounted for by Equation (2), based on the IDW interpolation technique. Combining this interpolation with equations (1) and (2) gives the following composite model equation:

$$\delta_\chi = \frac{\sum_{i=1}^{n} \frac{\delta_i - P_i}{d_i^{\beta}}}{\sum_{i=1}^{n} \frac{1}{d_i^{\beta}}} + P_\chi \quad (3)$$

where P_x and δ_x are the initial and final estimates of δD of grid x respectively, δ_i and P_i are the observed and the estimated δD at the sampling site i, respectively, d_i is the distance between a grid point and sampling site i, and β is a distance weighting parameter. Equation (3) allows mean annual δD to be estimated at any location where the two independent variables are available. Thus, regular gridded δD was derived from the DEM as the Equation (3) input.

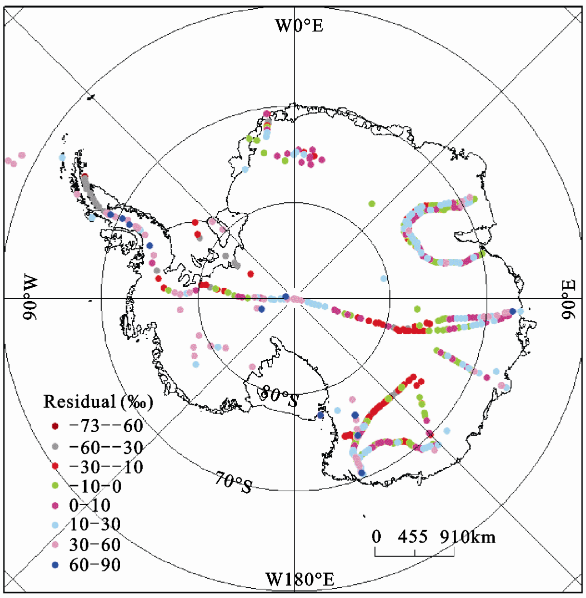

Fig. 2 Deviations between observed mean annual δD values and estimated by Equation (2)

3 Results and Discussion

3.1 Spatial distribution of δD

The multi-year mean δD map (Fig. 3) depicts the relationships between δD and a number of explicit (latitude, altitude) and more obscure (vapor sources, storm tracks) geographic variables, which may be useful for the forcing of Antarctic ice sheet models using isotopic tracers (Lhomme et al., 2005). The predominant features of the mean annual δD include the lowest value over the central Antarctic Plateau, where the lowest value of temperature may occur, and the strongest isotopic gradients can be observed over the steep slopes of East Antarctica, corresponding to both the strong temperature gradients and the continentality. The spatial distribution of δD displays the decrease trend from the middle to high latitudes (latitude effect), low δD at high altitudes (altitude effect) (Dansgaard, 1964), depletion of the heavy isotopes with increasing distance from the coast line (continental effect) (Rozanski et al., 1993). The depiction of a continental effect depends on the presence of data stations that document regional heavy isotope depletion in the continental interiors.

Because Fig. 3 takes the effect of local topography on δD at a single location into account, estimates of mean annual δD may be better than output from general circulation models (GCMs) equipped with isotope tracers (AGCMs) and Mixed Cloud Isotopic Model (MCIM). The isotope values of snow are overestimated in the east Antarctic Plateau for the GCMs and MCIM (Werner and Heimann, 2002; Noone and Simmonds 2002; Schmidt et al., 2005; Helsen et al., 2007, Masson-Delmotte et al., 2008). These biases may be due to an underestimation of kinetic effects and inadequate representation of large scale advection of water vapor in MCIM (Salamatin et al., 2004; Masson-Delmotte et al., 2008), and in part due to a warm bias found or be linked to their representation of the transport of moisture towards central Antarctica in the GCMs (Schmidt et al., 2005; Masson-Delmotte et al., 2008). Also, GCMs and MCIM do not necessarily include the correct topography of Antarctica in their boundary conditions, especially for the steep mountainous area of the eastern Antarctic Plateau.

3.2 Estimate of uncertainties

Uncertainties in the multi-year mean δD map for Antarctica (Fig. 3) may be associated with interpolation algorithm and DEM errors. The accuracy of the δD map was evaluated based on cross validation techniques. The relationship between estimated δD values and 567 in-situ measurements is linear with a slope of 0.99 and R^2=0.98 (Fig. 4). We calculated the deviation between the measured and the estimated δD values based on cross validation techniques. The mean absolute error is 5.4‰, and the standard deviation is 9‰. δD data from station lacking elevation data were not used to fit the Equation (3). These data make it possible to further compare multi-year mean δD estimated in Fig. 3 and field measurements (Fig. 5). A direct linear regression with the 44 measurements yields a correlation coefficient of 0.97 and a regression slope of 1.14. Therefore, we think the estimate in Fig. 3 is of high accuracy given that measurements mostly cover different periods and that DEM bias exists.

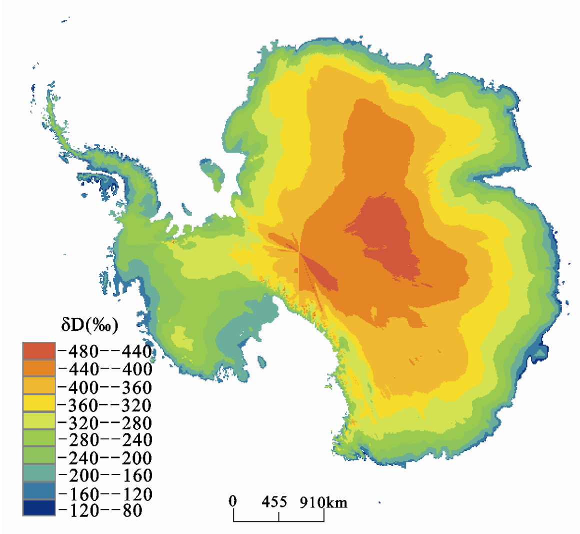

Fig. 3 Mean annual δD in Antarctic surface snow

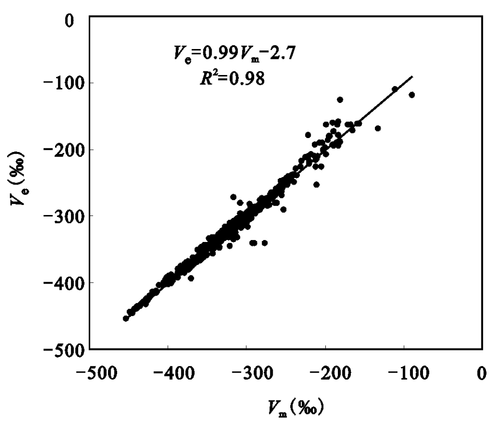

Fig. 4 Scatter plot of measured δD values (V_m) versus estimated δD values (V_e)

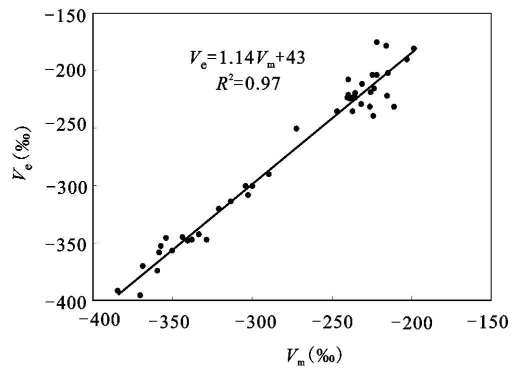

Fig. 5 Scatter plot of extra measured δD values (V_m) versus estimated δD values (V_e)

4 Conclusions

This paper presented an improved interpolation method, based on the DEM to depict the spatial distribution of δD in Antarctic surface snow. The approach captures the relationship between δD and some explicit (latitude and altitude) and implicit (vapor sources, storm tracks) geographic variables. The mean magnitude of predictor error of δD is about 5.4‰, and the standard deviation is 9‰. The high-resolution (1km) δD map reflects effects estimated based on theory of Rayleigh type distillation or previously observation, including latitudinal, altitudinal, and continental effects. Furthermore, it can be used as a benchmark for comparison with the output of GCMs and MCIM.

It is needed to point out that the δD map is still influenced by the density of sampling localities. To further improve the accuracy of the map, new observations from many places of Antarctica are urgently needed. This is a focus of traverses to be conducted as part of the 2007–2009 International Polar Year.

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