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Geostatistical analysis and isoscape of ice core derived water stable isotope records in an Antarctic macro region

István Gábor Hatvani [a,*], Markus Leuenberger [b,c], Balázs Kohán [d], Zoltán Kern [a]

[a] Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, MTA, Budaörsi út 45., H-1112 Budapest, Hungary
[b] Division of Climate and Environmental Physics, Physics Institute, University of Bern, Sidlerstrasse 5, CH-3012, Bern, Switzerland
[c] Oeschger Centre for Climate Change Research, Falkenplatz 16, CH-3012, Bern, Switzerland
[d] Department of Environmental and Landscape Geography, Eötvös Loránd University, Budapest, Hungary

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ABSTRACT

Water stable isotopes preserved in ice cores provide essential information about polar precipitation. In the present study, multivariate regression and variogram analyses were conducted on 22 δ^2H and 53 $\delta^{18}O$ records from 60 ice cores covering the second half of the 20th century. Taking the multicollinearity of the explanatory variables into account, as also the model's adjusted R^2 and its mean absolute error, longitude, elevation and distance from the coast were found to be the main independent geographical driving factors governing the spatial $\delta^{18}O$ variability of firn/ice in the chosen Antarctic macro region. After diminishing the effects of these factors, using variography, the weights for interpolation with kriging were obtained and the spatial autocorrelation structure of the dataset was revealed. This indicates an average area of influence with a radius of 350 km. This allows the determination of the areas which are as yet not covered by the spatial variability of the existing network of ice cores. Finally, the regional isoscape was obtained for the study area, and this may be considered the first step towards a geostatistically improved isoscape for Antarctica.

1. Introduction

Due to the increasing interest in the understanding of past global changes, additional and complementary information about past climates is needed. Ice cores play an important role in relation to this issue (EPICA, 2006; NGRIP, 2004; Wolff et al., 2010). For instance, the water stable isotope characteristics stored in them hold crucial information concerning the precipitation they were formed from. The isotopic composition of precipitation, in turn, gives insights into (i) the origin of the water vapor, (ii) the conditions during condensation, and (iii) those during precipitation (Araguás-Araguás et al., 2000; Dansgaard, 1964; Merlivat and Jouzel, 1979). Ice cores can yield information about past climates ranging in time-scale from the seasonal (Hammer, 1989; Kuramoto et al., 2011) up to several hundred millennia (EPICA, 2004), and provide relevant indications about the large-scale dynamics of the Earth's climatic system (Jouzel, 2013). By integrating the knowledge gained from studying stable isotopes in ice cores into global circulation models, a more detailed picture can be obtained of the climatic factors driving temporal water isotope variability (Werner and Heimann, 2002).

However, dealing with stable isotope data from ice cores in Antarctica is a challenging task, since the spatial availability of cores is sparse and highly variable over the continent (IPICS, 2006; Masson-Delmotte et al., 2008; Steig et al., 2005). Apart from process-based modeling, interpolation is therefore one of the only means available to make estimations between locations for which data are available (Rotschky et al., 2007; Wang et al., 2010).

Interpolated maps representing the global distribution of water stable isotopes in precipitation have been developed (Terzer et al., 2013; van der Veer et al., 2009). These, however, do not cover Antarctica. The only product that maps the spatial distribution of stable isotopic composition in Antarctic surface snow (Wang et al., 2010) neglects the shelf areas. Of these regions, the Filchner-Ronne-, Riiser-Larsen and Fimbul ice shelves cover a fair portion of the area investigated in the present study.

* Corresponding author. Institute for Geological and Geochemical Research, Research Centre for Astronomy and Earth Sciences, Hungarian Academy of Sciences, H-1112 Budapest, Budaörsi út 45 Hungary.
E-mail addresses: hatvaniig@gmail.com (I.G. Hatvani), leuenberger@climate.unibe.ch (M. Leuenberger), balazs.kohan@gmail.com (B. Kohán), zoltan.kern@gmail.com (Z. Kern).
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Isoscapes are predictive models that estimate the local isotopic composition of environmental materials as a function of observed local and/or extralocal environmental variables (Bowen, 2010). The horizontal and vertical resolution of isotope enabled global circulation models (GCMs) are steadily improving (e.g. Werner and Heimann, 2002; Xi, 2014), such that isotope enabled GCMs using resolutions previously only attainable in regional models are now available (Sjolte et al., 2011; Werner et al., 2011). In the settings where station based precipitation stable isotope records are available, these are naturally the primary inputs to evaluate the performance of isotope enabled circulation models (Lachniet et al., 2016; Sturm et al., 2005). However, gridded products of precipitation stable isotopes (e.g. isoscapes) can be used as additional benchmarks when observations are missing to assess the global/regional circulation models' effectiveness in replicating observed/interpolated data representing the hydrological cycle and its isotopic counterparts.

The aims of this study were (i) to determine the geographic factors driving the stable isotope variability in a chosen Antarctic macro region; (ii) to assess the spatial continuity properties (variograms) of the stable isotope records, an absolute necessity for geostatistical mapping (Herzfeld, 2004), and (iii) to determine the regional isoscape for ice core derived stable isotope records.

Variogram analysis was used in the hope that it would reveal those areas insufficiently represented by the current set of ice cores, giving an indication of where their spatial coverage might be increased and reveal the spatial dependence structure of the stable isotope records. In addition, variography is vital for kriging (Cressie, 1990; Oliver and Webster, 2014; van der Veer et al., 2009), an "optimal" interpolation which is then employed in the study to estimate the covariances to the highest degree of accuracy possible before mapping. Consequently, the derived isoscape (Bowen, 2010) will be able to describe the spatial distribution of isotopes in the region in a representative way.

Worthy of mention is the fact that the aims of this study are in close agreement with the goals of the International Partnerships in Ice Coring Sciences initiative, since the regional nature of climate and climate forcing requires data from a geographically extensive area. In addition, in order to be able to interpret the water stable isotope records from the past 2 ky of ice cores precisely, these have to be supplemented by additional shorter cores for validation (IPICS, 2006).

2. Materials and methods

2.1. Description of the study area and the used dataset

The Antarctic study area (Latitude: 71°S, 83°S; Longitude: 61°W, 12°E; Fig. 1) covering about 2.6×10^6 km^2 in the Atlantic sector, was chosen on account of the relatively high abundance of available ice core derived water stable isotope records, and the fact that it disposes of numerous deep ice cores, which have played and continue to play an important role in paleoclimatology. The region is considered to be diverse from both the topographic and glacio-climatologic perspectives, as well (Graf et al., 1994; Oerter et al., 2000; Rotschky et al., 2007), with areas of low elevation (e.g. the Coastal Dronning Maud Land, Ronne Ice Shelf etc.) at sea level, and significantly higher ones (e.g. the Central Dronning Maud Land > ~2500 m a.s.l.). Field observations have shed light on an atypical continental precipitation distribution obtaining in the region, in which the accumulation and mean air temperature decrease with distance from the shoreline and with the increase in elevation (Vaughan et al., 1999). The difference in accumulation between the highly elevated inland regions and the coast may be as great as a factor of six (Graf et al., 1994; Oerter et al., 2000), and vary by up to e.g. 500 kg m^{-2} a^{-1} over a distance of <3 km in certain areas of the Western Dronning Maud Land (Rotschky et al., 2007); for details see Table S1.

2.2. Dataset used

The data used were acquired from open access data repositories (NOAA (2014); PANGAEA (2014)) and the corresponding research groups (Divine et al., 2009; Naik et al., 2010). Altogether, an array of 22 δ^2H (Figs. S1a and b) and 53 δ^{18}O (Figs. S1c and d) records was assembled from 60 ice cores spanning various time intervals. In the compiled ice core derived water isotope database, isotope abundances are expressed as per mil (‰), differences from the V-SMOW standard (Coplen, 1994) using the δ notation, $\delta X = [(R_{sample}/R_{standard}) - 1] \times 1000$, where X is ^{2}H or ^{18}O, R_{sample} is the sample ^{2}H/^{1}H or ^{18}O/^{16}O ratio, and $R_{standard}$ is the ^{2}H/^{1}H or ^{18}O/^{16}O ratio of the standard. The longest time interval spanned was almost a millennium (Fig. S1d), while the shortest covered only a couple of years (Fig. S1c).

The study was restricted to the period 1970–1988, corresponding to 44 δ^{18}O, and from 1970 to 1989 with 22 δ^2H records before pre-processing and filtering. In this way, both the time span and the available number of records were maximized. By choosing the higher number of cores against the longer timescale, the possibility of better signal replication arose, as emphasized e.g by Jones et al. (2009). In addition, there were five ice cores (c5, c7, c9, c11 and c13) which only had δ^2H records; these were converted to δ^{18}O using the regional δ^2H - δ^{18}O relation established (Fig. S2) based on five neighboring cores with both δ^2H and δ^{18}O records, (for details see SOM). Note that in one special case, the δ^{18}O and δ^2H records of two cores spaced only 6 km apart, namely, c48 & c49 NM01C82 _04 (B04) and NM02C02_02 (FB0202) in Schlosser and Oerter (2002) and Fernandoy et al. (2010) respectively were merged together. These are referenced in the present study under code c62 (Fig. S3). In this way, the total numbers of δ^{18}O and δ^2H records studied using their 1970–1988 averages were 48 and 21 respectively. Reported dating uncertainty of the set of ice cores was ±1yr in both the Dronning Maud Land (Oerter et al., 2000) and the Ronne Ice Shelf (Graf et al., 1999) for the periods closest to the ones assessed in the present study. Therefore, in the case of the ~20yr averages used in the study, dating uncertainty documented above is expected to be negligible.

It is generally acknowledged that the isotopic composition of meteoric precipitation is related to geographical position (Dansgaard, 1964), and can be statistically modeled employing geographical parameters (Bowen and Revenaugh, 2003). These global trends can indeed be generalized to the Antarctic continent (e.g. Wang et al., 2009). On a regional scale, however, the set of independent variables to describe isotope variations may change. In order to be able to analyze the spatial autocorrelation and derive an isoscape of the stable isotope records, their dependence on geographical factors has to be determined, as in Lorius and Merlivat (1977) or Smith et al. (2002). For the reasons for this and further details, see Section 2.3.

Therefore, in order to determine the geographical factors controlling the ice core water isotopes' variability, latitude (LAT), longitude (LON), elevation (ELE), and distance from the coast (D) were considered in this study. LAT & LON were obtained from the original repository files and converted into meters on a polar stereographic projection with reference to the World Geodetic System 1984 ellipsoid. ELE was extracted from the high-resolution Antarctic digital elevation model of Liu et al. (1999), while D was calculated using the shortest perpendicular distances between the sample points representing the ice cores and the coast line.