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Validity of the isotopic thermometer in central Antarctica: limited impact of glacial precipitation seasonality and moisture origin.

Gilles Delaygue^{1,3}, Jean Jouzel¹, Valérie Masson¹, Randal D. Koster², Edouard Bard³

Abstract. The classical interpretation of water stable isotopes (deuterium or oxygen 18) retrieved from ice cores into past local temperature relies on the use of the spatial isotope/temperature slope as a surrogate of the temporal slope. Whereas this assumption has been challenged by independent methods in central Greenland, it is still considered as valid in central Antarctica. We use an atmospheric General Circulation Model (GCM) to study two parameters highlighted by previous studies as being among the most important with respect to this assumption. We show that in the GCM, between present-day and Last Glacial Maximum, the change in precipitation seasonality and the cooling of the moisture sources have limited and opposite effects on the isotopic record of the Antarctic local temperature. This conclusion strengthens the validity of the classical interpretation of isotope records in central Antarctica.

1. Introduction

The oxygen 18 (H₂¹⁸O) and deuterium (HDO) composition of ice cores recovered in Greenland and Antarctica give access to continuous records of past temperature changes over these ice caps. However, the classical interpretation based on the assumption that the present-day spatial isotope/surface temperature slope (hereafter the spatial slope) holds true in a temporal sense and can be used for interpreting paleodata, the isotopic thermometer, is now being challenged, at least for Greenland. Borehole paleothermometry shows that the cooling between present-day and the Last Glacial Maximum (LGM, about 21 000 years ago) was about twice larger in central Greenland than predicted using the spatial slope [Cuffey *et al.*, 1995; Johnsen *et al.*, 1995]. Nitrogen and argon isotopic anomalies recorded in the air bubbles indicate that the temporal slope is also weaker than the spatial slope for rapid changes (see Jouzel [1999], for a review).

Both simple Rayleigh-type isotopic models and complex atmospheric General Circulation Models (GCM) implemented with water isotopes are helpful to shed light on this difference between temporal and spatial slopes [Jouzel *et al.*, 1997]. They allow to examine separately the influence of the various processes that can affect the temporal slope, ie changes in the origin, seasonality and intermittency of the precipitation as

well as the microphysical processes that lead to their formation and the relationship between cloud and surface temperature. Previous process studies suggest that the low temporal slopes derived for central Greenland could result from a modification of the precipitation seasonality [Krinner *et al.*, 1997; Werner *et al.*, 2000], or alternatively from changes in its origin [Charles *et al.*, 1994; Boyle, 1997].

The situation appears different in central Antarctica. Borehole paleothermometry [Salamatin *et al.*, 1998] also suggest lower temporal than spatial slope but to a more limited extent and with large uncertainties due to the rapid signal diffusion compared to the low precipitation rates [Rommelaere, 1997]. Unlike Greenland, Antarctic temporal slopes calculated from glacial GCM experiments are, although quite noisy, slightly higher on the average than present-day spatial slopes [Hoffmann *et al.*, 2000]. Limited changes in precipitation seasonality are likely to have little influence on the Antarctic temporal slope [Krinner *et al.*, 1997]. However, the isotopic thermometer needs obviously to be further examined either in developing alternative empirical ways of estimating the temporal slope and/or in extending the isotope modeling approach. Here we use new simulations and diagnosis to understand how changes in precipitation seasonality (a local parameter) and cooling of the moisture sources (a remote parameter) affect the isotopic thermometer in the GISS GCM.

2. Methodology

We use the GISS 8°x10° tracer atmospheric GCM and build on the experiment of Koster *et al.* [1992] who analysed the origin of Antarctic precipitation and its influence on deuterium content for a present-day July. We conduct multiannual experiments for three different climates (present-day, LGM and LGM with cooler tropical oceans). We define 19 evaporative sources in each hemisphere based on their modern annual mean temperature and oceanic basin [Delaygue *et al.*, 2000]. For the LGM, two different sea surface temperature (SST) reconstructions are used: the CLIMAP [1981] one, and CLIMAP with a 2-to-3° cooler intertropical zone, which seems to be more realistic (eg, Mix *et al.* [1999]; Bard [1999]).

Simple Rayleigh-type isotopic models show that the isotopic content of precipitation δp (δ , which stands for either $\delta^{18}\text{O}$ or δD , is the deviation in permil of this isotopic content compared to the V-SMOW standard) relates to the vapor mass exhaustion due to the condensation process from low to high latitudes. This exhaustion depends itself, at first order, on the difference between the evaporative ocean temperature, T_e , and the final condensation temperature T_c (itself related to the surface temperature): $\delta p = \alpha T_c - \beta T_e$ (Equation 1).

Figure 1 illustrates the simulated influence of source temperature T_e on the precipitation $\delta^{18}\text{O}$ in central East Antarctica (top) and central Greenland (middle). As expected from the

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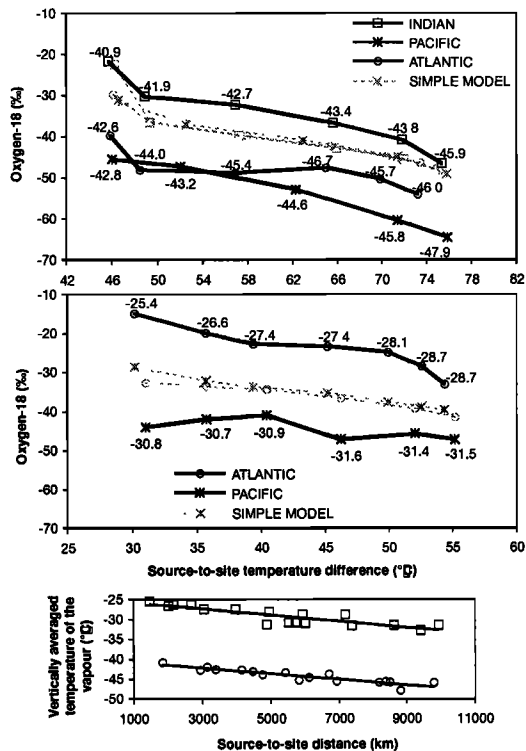


Figure 1. Simulated $\delta^{18}\text{O}$ of precipitation for central East Antarctica (top) and central Greenland (middle), originating from different oceanic sources characterized by their annual temperature (T_e , in abscissa) and the oceanic basin. Full lines: simulation with the GISS AGCM for the present-day (PD) climate (10-year average). Stippled lines: simulation with a simple isotopic model, initialized with the GISS GCM conditions. Both models show the same first-order dependence to the source temperature T_e (about $-0.6\text{‰}/^\circ\text{C}$). The GCM also depicts a second-order dependence to the distance (between the closest basin and the furthest ones), which relates to the temperature of the vapor at the site of precipitation, expressed by the annotations (vertically averaged vapor temperature in $^\circ\text{C}$). This relationship is shown at bottom for central East Antarctica (circles) and central Greenland (squares). For the same source temperature T_e , the more distant the source, the more elevated and cooler is the moisture, and the more isotopically depleted it is.

simple Rayleigh-type model (stippled lines), the relationship between source temperature and isotopic content is nearly the same for the different oceans, with a rough dependency of the isotopic content to the source temperature ($-\beta$) of $-0.6/-0.7\text{‰}/^\circ\text{C}$. This confirms for a full annual cycle the results obtained by *Koster et al.* [1992] for a single month ($-4.8\text{‰}/^\circ\text{C}$ in δD , equivalent to a $-0.6\text{‰}/^\circ\text{C}$ dependency in $\delta^{18}\text{O}$). However, unlike predicted by simple models, δp also depends on the distance between the source and the precipitation site: for the same source temperature T_e , the $\delta^{18}\text{O}$ value is shifted by about 20‰ between the nearest ocean and the furthest one. This shift is comparable to the isotopic difference between the warmest and coolest sources of each ocean. This apparently large effect is partly counterbalanced by the lowest contribution of remote sources: in our simulation, central East Antarctica receives precipitation mainly from the closest Indian Ocean (about 50%, *Delaygue et al.* [2000]) and central Greenland from the nearby Atlantic (33%, as in *Charles et al.* [1994]). These shifts

between oceanic basins are not due to the compositions of the first vapor but mainly result from moisture transport at different vertical levels. For the same evaporative temperature, the further the source, the higher the vapor is transported in the GCM and the cooler it condenses (Fig. 1, bottom). By comparison (Fig. 1, stippled lines), the Rayleigh-type isotopic model does not distinguish these different condensation temperatures and predicts an intermediate relationship, still with the same slope.

To address the role of precipitation origin on δp in the GCM, we write δp as the sum $\sum \delta_i P_i$ (Equation 2) over the i oceanic sources, with δ_i the isotopic composition of the precipitation originating from source i , and P_i its relative contribution. This allows to write the climatic change (Δ) of δp as: $\Delta \delta p \approx \sum \delta_i \Delta P_i + \sum P_i \Delta \delta_i$ (Equation 3). The first term approximately represents the effect of changing the relative contributions P_i , the second one of changing each individual composition δ_i through the variations of T_c and T_e (Eq. 1). We thus estimate the ratio $R_{\text{orig}} = (\sum \delta_i \Delta P_i) / \Delta \delta p$ which gives the proportion of the total isotopic change (Eq. 3) bound to the sole change in precipitation origin. For the change $\Delta \delta_i$, we try to separate the local T_c change, which is precisely the classical interpretation of $\Delta \delta p$, from the change in T_e by rewriting Eq. 1 as: $\Delta \delta p = \alpha \Delta T_c - \beta \Delta (\sum T_e P_i)$ (Equation 4). We thus estimate the source temperature change $\Delta T_e = \Delta (\sum T_e P_i)$ which indeed biases the imprint of ΔT_c on the isotopic change $\Delta \delta p$, given that $\alpha \approx -\beta$ ($\approx 0.6\text{‰}/^\circ\text{C}$, Fig. 1).

To assess the role of precipitation seasonality on δp , we follow *Krinner et al.* [1997] in defining in the GCM the (precipitation-weighted) condensation temperature T_c , which physically controls the isotopic fractionation. T_c is strongly correlated with the surface temperature, both in the real world (with a slope of 0.67 in Adélie Land, *Lorius and Merlivat* [1977]) and in our simulations (with a 0.75 slope). We calculate the contribution of the difference:

$$\frac{\sum T_c^{\text{PD}}(m) \cdot P^{\text{PD}}(m)}{\sum P^{\text{PD}}(m)} - \frac{\sum T_c^{\text{LGM}}(m) \cdot P^{\text{LGM}}(m)}{\sum P^{\text{LGM}}(m)} \quad \text{Eq. (5)}$$

with Σ the sum of the 12 months m , to the simulated annual $T_c^{\text{PD}} - T_c^{\text{LGM}}$ change, the difference between present-day (PD) and LGM temperatures. The first term is the annual T_c^{PD} , and in the second one we keep $T_c^{\text{PD}}(m)$ to estimate the effect of the only precipitation (and not T_c) seasonality change.

3. Results

Despite its low horizontal resolution, the GISS model reasonably simulates the main features of the vapor transport and is thus appropriate for our first-order present study of the isotope/temperature temporal slope [*Jouzel et al.*, 1997; *Delaygue et al.*, 2000].

3.1 Precipitation Seasonality

A weak seasonal cycle of Antarctic precipitation, quite variable in space and time, arises from the change in meridional temperature gradient, with the most frequent maxima in fall and spring [*Genthon et al.*, 1998]. The GISS model simulates a reasonable seasonality of modern Antarctic precipitation (Fig. 2), accounting for the interplay between vapor transport, sublimation and precipitation [*Genthon*, 1994].

Figure 2 shows that glacial conditions decrease the winter contribution to annual precipitation, in agreement with the

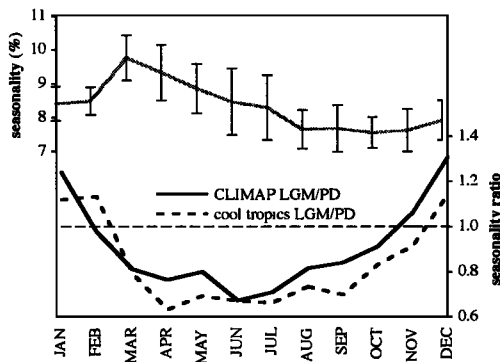


Figure 2. (top) Antarctic precipitation seasonality simulated by the GISS model for present-day (PD) conditions (10-year average, 2σ shown by the error bars), expressed as the contribution (in percent) of the monthly precipitation $P(m)$ to the annual average: $P(m)/\sum P(m)$, with \sum the sum over the 12 months. (bottom) Climatic change of this seasonality expressed as the ratio of LGM to PD monthly contributions to the annual precipitation. Full line: CLIMAP LGM vs PD. Dashed line: cool tropics LGM vs PD. In both LGM simulations, the summer contribution increases (seasonality ratio >1) and the winter one decreases (ratio <1), in relation with the temperature and vapor pressure.

predictions of other, better designed models [Krinner and Genthon, 1998]. The resulting higher summer contribution favours warmer precipitation-weighted annual temperatures (positive ratio in Figure 3). This means that, in our simulations, the annual condensation temperature recorded by the isotopes is slightly biased towards warmer values compared to present-day climate, typically less than 1°C in the central Plateau, ie 15% of the temperature change. Accounting for a glacial cooling stronger in winter than in summer may offset partially this bias. These results confirm the study of Krinner *et al.* [1997] showing limited impacts of local parameters in central Antarctica.

3.2 Change in the Origin of Precipitation

With the stronger meridional temperature gradient due to the prescribed glacial conditions of CLIMAP, Antarctica is found

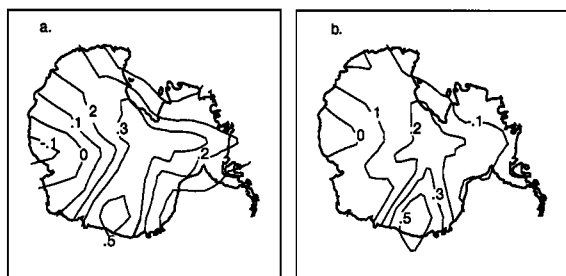


Figure 3. Effect of precipitation seasonality change (Fig. 2) on the (precipitation-weighted) condensation temperature T_c , between LGM and PD climates in Antarctica (Eq. 5). We show here the contribution of this effect to the total temperature change ΔT_c . (a) CLIMAP LGM vs PD, (b) cool tropics LGM vs PD. Using the accumulation instead of the precipitation for weighting T_c leads to a weaker seasonality effect. Calculating this ratio with alternatively T_c^{PD} or T_c^{LGM} in Eq. 5 gives the same result. Strong values in East Antarctica by 30°E are due to a 500m elevation decrease prescribed from CLIMAP.

to receive more isotopically depleted moisture from lower latitude sources. This effect is attenuated by cooling intertropical SSTs [Delaygue *et al.*, 2000].

We now use the decomposition introduced by Equation 3 to estimate the relative roles of the moisture origin (P_i) and the source-to-site temperature difference (δ_i) in the total isotopic change $\Delta\delta_p$. This decomposition is not rigorous since both terms are not independent. Still, they display quite different geographical patterns, which are the same when applying CLIMAP or cool tropics SSTs. The GISS GCM simulates a dominant role of the moisture origin term ($R_{orig} > 50\%$) only along the Antarctic coast where, (i) the PD local sources are replaced by remote (more depleted) sources with glacial conditions, and (ii) the local cooling (ΔT_c) is offset by the source cooling (ΔT_e , Eq. 1). However, in central Antarctica, the total isotopic variation is mostly influenced by $\Delta\delta_i$ (second term of Eq. 3), with the change in moisture origin explaining less than 30% of this variation. We now focus on the temperature effect on $\Delta\delta_i$, to understand why it is not muted by the glacial source cooling, as it appends along the Antarctic coast.

Boyle [1997]'s sketch popularized the idea that glacial source cooling (ΔT_e) could explain the lower temporal slope in central Greenland, by offsetting the site cooling (ΔT_c), hence reducing $\Delta\delta_p$ in Equation 1. This idea considered a unique source, given that all moisture sources cooled down at the LGM. In our simulations, polar δ_p results from the combination of several sources, which contribute differently under modern and glacial climates. Thus the global source temperature change (ΔT_e , the second term of Eq. 4) also depends on this contribution change. In fact, our simulations show that

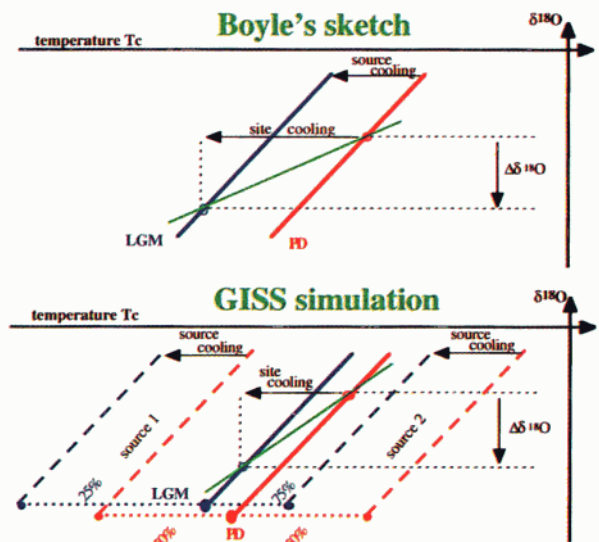


Figure 4. Diagrams relating the spatial $\delta^{18}\text{O}$ - T_c relationships (red lines) to the LGM-to-PD temporal one (green line, defined by the observed $\delta^{18}\text{O}$ change) for polar precipitation. In the Boyle [1997]'s sketch (top), the glacial cooling of the vapor source shifts the spatial relationship and defines a lower temporal slope. Our simulation (bottom) considers several vapor sources for the Antarctic precipitation, here two for clarity. The global $\delta^{18}\text{O}$ - T_c relationship (full red line) arises from the mixing of both source relationships (stippled red lines), assumed here to contribute equally for PD climate. The glacial cooling of each source is compensated for by a stronger contribution of the warmer source, which defines a temporal slope similar to the spatial slope, although slightly lower.

the Antarctic mean source temperature slightly warms ($\Delta T_c \approx 2^\circ\text{C}$) when using CLIMAP reconstruction, and remains close to its PD value (within 0.5°C) when cooling the 'tropics', which represents a 10-to-30% bias compared to the local temperature change ΔT_c . This stability is due to the compensation of the source cooling by changes in their contribution (Fig. 4). Therefore, in our simulations, T_e (second term of Eq. 4) does not display a strong cooling in central Antarctica comparable to the -5°C put forward by Boyle, and thus does not bias the isotopic record of ΔT_c (first term of Eq. 4) towards a limited temperature change (lower temporal slope).

4. Discussion and Conclusion

With the GISS atmospheric GCM, we show here that the change between LGM and PD of local and remote parameters have limited and opposite impacts on the central Antarctic isotope-temperature relationships. Indeed, the temperature change inferred from the isotopic change is weakened in the simulation by 15% due to the precipitation seasonality change, but increased by 10-to-30% (depending on the tropical SST reconstruction) due to the source temperature effect. Given this situation, it still appears justified to use the present-day spatial slope as a surrogate of the temporal slope to interpret central Antarctic isotopic profiles [Petit et al., 1999].

This second-order uncertainty appears quite limited compared to the 100% underestimation of the isotopic thermometer in Greenland. The complexity of the moisture transport to central Greenland from adjacent oceanic and continental sources allows us to expect a large sensitivity of the isotopes to local parameters. Indeed, high resolution GCMs are able to explain this bias by a drastic change in precipitation seasonality [Krinner et al., 1997; Werner et al., 2000]. We have not quantified here this seasonality effect given that, due to its poor resolution, the GISS model does not capture the present-day isotopic seasonality in central Greenland. For the moisture source effect, we find a warming of the average oceanic source temperature by 3 to 4°C with glacial conditions, as for Antarctica. However, the design of our moisture sources, with one single continental source, is not well adapted for Greenland where a significant proportion of glacial moisture comes from Northern America [Charles et al., 1994]. Still, this preliminary result reinforces the role of local parameters (ie seasonal cycle) in lowering the temporal isotope-temperature slope in Greenland, at the expense of the tropical cooling proposed by Boyle [1997].

We strongly underline that these results are bound to the accuracy of the GISS GCM, especially to what concerns the source temperature change. Therefore, this work deserves being repeated with other GCMs, especially high resolution models specifically designed for high latitudes, and with alternative reconstructions of the glacial ocean.

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