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## GCM analysis of local influences on ice core $\delta$ signals

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**Abstract.** A high resolution GCM is used to examine the effect of changes in local surface climate parameters on the ice sheets that can influence the interpretation of the isotopic signal of the ice from deep cores. The model suggests that the 10°C difference between the LGM surface temperature deduced from borehole thermometry and that deduced from the water isotope analysis to a great extent may be due to a modification of the precipitation seasonality in central Greenland. For central East Antarctica, the model tends to suggest a weak opposite bias.

### Introduction

The linear relationship between annual values of the deuterium or  $^{18}\text{O}$  concentrations in polar snow and annual mean temperature at the precipitation site, extremely well obeyed over Greenland [Johnsen *et al.*, 1989] and Antarctica [Lorius and Merlivat, 1977], has long been used to reconstruct paleotemperatures from polar ice cores. This approach, in which the present-day spatial isotope vs. surface temperature relationship  $\delta = aT_s + b$  defined over a certain region is assumed to hold in time throughout the region, is now being challenged, particularly for Greenland [e.g., Johnsen *et al.*, 1995]. As a result, it is now widely accepted that the Modern - Last Glacial Maximum (LGM, 21 kyr ago) cooling exceeded 20°C in central Greenland rather than  $\approx 10^\circ\text{C}$  as previously thought. Rommelaere [1997] has shown that similar borehole thermometry results for Vostok [Salamatin *et al.*, 1997] are subject to large uncertainties because of signal diffusion due to low precipitation rates. Consequently, it is unclear whether the isotopic record at Vostok gives correct information on LGM surface temperatures.

Following Jouzel *et al.* [1997], the various factors possibly influencing the temporal  $\delta$  vs.  $T_s$  relationship are, broadly speaking, the origin, seasonality and intermittency of precipitation as well as the microphysical mechanisms leading to their formation and the difference between cloud and surface temperatures. In this letter, we aim to extract information concerning local influences (e.g., seasonality and intermittency of precipitation) on the  $\delta$  vs.  $T_s$  temporal slope directly from AGCMs experiments.

### Methodology

We use the LMDz (where 'LMD' stands for Laboratoire de Météorologie Dynamique, Paris, and 'z' stands for zoom)

stretched-grid AGCM to study the precipitation temperature in Greenland and Antarctica for the present-day and LGM conditions at a spatial resolution of 100 km. The model has been specifically adapted for the polar regions by Krinner *et al.* [1997], who demonstrated that the model succeeds well in reproducing the present-day Antarctic climate and in particular the hydrological cycle [Krinner and Genthon, 1997]. Separate present-day simulations were carried out over 5 years for the two ice sheets. For the LGM simulations, CLIMAP [1981] boundary conditions (sea-surface conditions etc.) were prescribed except for the topography. For Antarctica, a 5-year LGM simulation was run using the Peltier [1994] paleo-topography, whereas a 3-year Greenland LGM simulation was run using the output of an ice sheet model [Ritz *et al.*, 1997] for the topography of Greenland. The rationale for using this alternative paleo-topography for Greenland is that the Peltier [1994] paleo-topography is much higher in central Greenland than the present-day one, and is thus in contradiction to the much lower central Greenland accumulation rates inferred for the LGM [e.g. Dahl-Jensen *et al.*, 1993]. The simulations, especially the Greenland LGM simulation, are quite short. However, this does not seem to be a problem in the present context, because the results discussed in this letter are also valid for each single year of the simulation. In other words, the model is in steady state.

Simulated present-day and LGM climate of the two ice sheets is quite realistic [Krinner, 1997]. Throughout this letter, the different simulations will be referred to as AA0, AA21, GL0, and GL21, where the first letters stand for the focused region (GreenLand or AntArctica), and the number indicates the period in kyr b.p.

For each grid point, the precipitation temperature

$$T_{pr} = \frac{\int \sum_k (T(k, t) pr(k, t)) dt}{\int \sum_k (pr(k, t)) dt} \quad (1)$$

is calculated, where  $T(k, t)$  is the instantaneous temperature at the model layer  $k$  and  $pr(k, t)$  is the instantaneous rate of precipitation (in mm/day) originating from that level. The temporal integration is carried out at each time step over the whole duration of the model run.  $T_{pr}$  is thus the precipitation-weighted temperature of the model layers where the precipitation forms. It represents the local component of the water isotope signal  $\delta$ .

Classically, the  $\delta$  thermometer is set up by regressing the present-day precipitation (oxygen or hydrogen) isotope ratio against the measured surface temperature  $T_s$ , both in time (seasonal cycle) and in space. This yields an affine global relationship  $\delta = aT_s + b$  both for  $\delta^{18}\text{O}$  and for  $\delta\text{D}$  with correlation coefficients close to 0.9 [Johnsen *et al.*, 1989; Lorius and Merlivat, 1977].

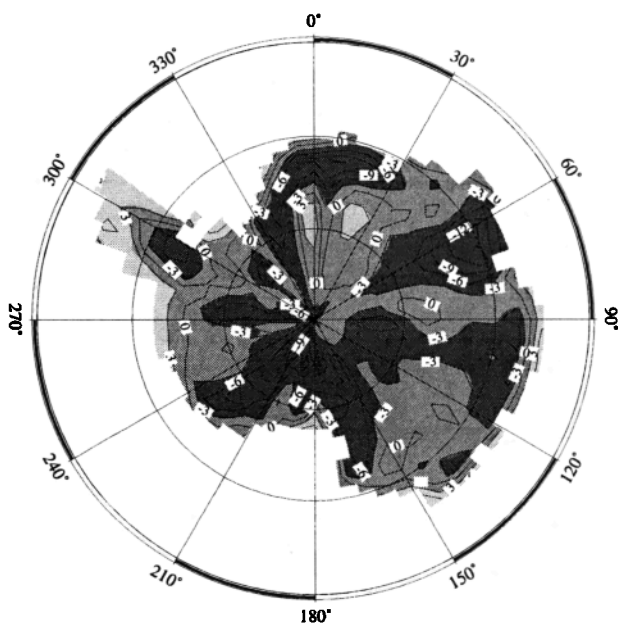
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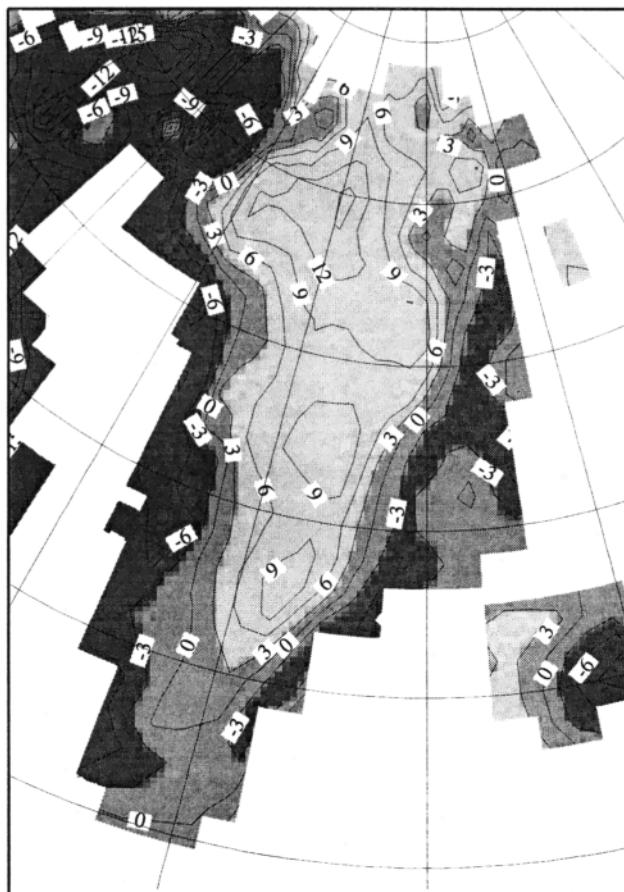
We can proceed in an analogous way by regressing  $T_{pr}$ , our proxy for  $\delta$ , against  $T_s$  for each ice sheet. The present-day  $T_s$  vs.  $T_{pr}$  regression can then be applied to the simulated LGM precipitation temperature  $T_{pr}$ , yielding a precipitation-temperature-deduced surface temperature  $\tilde{T}_s(T_{pr})$ , which has to be compared to the simulated surface paleo-temperature. If the regression between  $T_s$  and  $T_{pr}$ , calculated for the present-day model runs, still holds for the LGM model runs, then  $\tilde{T}_s(T_{pr})$  will be close to the simulated surface temperature  $T_s$ . Note that this is analogous to using the present-day  $\delta$  vs.  $T_s$  regression to deduce paleo-surface temperatures from the isotopic signal drawn from the ice cores. We can then address the following questions: 1) How does the climate change between the LGM and present-day influence the (local or global) relationship between  $\delta$  and the surface temperature? 2) Can the apparent discrepancy between the oxygen isotope temperature reconstructions and the borehole temperature measurements at Summit be explained by these changes? 3) If so, what is the relative importance of the changes in inversion strength, precipitation seasonality etc.? 4) Are the simulated changes in the relationship between  $T_{pr}$  and  $T_s$  similar for Antarctica and Greenland?

## Results

The present-day  $T_s$  vs.  $T_{pr}$  relationships over the two ice sheets exhibit quite high correlation coefficients ( $r^2 = 0.85$  and  $0.90$ ). As a consequence, the present-day error  $\Delta_{pr} = \tilde{T}_s(T_{pr}) - T_s$ , i.e., the difference between the surface temperature estimate  $\tilde{T}_s(T_{pr})$ , obtained from the present-day  $T_{pr}$  by using the present-day  $T_s$  vs.  $T_{pr}$  regression, and the simulated present-day surface temperature  $T_s$ , is generally very small over both ice sheets (not shown).



**Figure 1.** The LGM surface temperature estimation error  $\Delta_{pr}$  (in  $^{\circ}\text{C}$ ) over Antarctica. The contour interval is  $3^{\circ}\text{C}$ . Dark gray shading indicates values below  $-3^{\circ}\text{C}$ , medium gray from  $-3^{\circ}\text{C}$  to  $+3^{\circ}\text{C}$ , and light gray shading indicates values above  $+3^{\circ}\text{C}$ .



**Figure 2.** The LGM surface temperature estimation error  $\Delta_{pr}$  (in  $^{\circ}\text{C}$ ) over Greenland. The contour and shading intervals are the same as in figure 1.

Figure 1 displays the LGM error  $\Delta_{pr} = \tilde{T}_s(T_{pr}) - T_s$  over Antarctica, where  $\tilde{T}_s(T_{pr})$  was calculated using the present-day Antarctic regression applied to the LGM  $T_{pr}$ .  $\Delta_{pr}$  tends to be slightly negative in the largest part of East Antarctica. This means that  $\tilde{T}_s(T_{pr})$  tends to be somewhat lower than  $T_s$ . However, the signal is somewhat spatially inhomogeneous over the East Antarctic Plateau area.

Figure 2 displays  $\Delta_{pr}$  over Greenland for the *GL21* simulation. A clear significant signal is visible; its strength increases with altitude (i.e., decreases with temperature). The error attains its maximum in the northern part of Greenland and a secondary maximum of about  $10^{\circ}\text{C}$  in the Summit area. This means that at Summit,  $\tilde{T}_s(T_{pr})$  overestimates the simulated surface temperature by that amount.

## Discussion and Conclusion

Following *Jouzel et al.* [1997], one can imagine several causes for a change in the  $T_s$  vs.  $T_{pr}$  relationship:

- The precipitation primarily forms near the warmest tropospheric layer [*Bromwich*, 1988]. Both in reality [*Phillpot and Zillman*, 1970] and in the LMDz GCM, the inversion strength over the ice sheets is well linearly correlated to the surface temperature. If this relationship changes, then the  $T_s$  vs.  $T_{pr}$  relationship is also likely to change. We thus regress the present-day  $T_{pr}$  against the annual mean inversion tem-

perature  $T_{inv}$ , i.e. the temperature of the warmest tropospheric layer. In an approach similar to that used for  $T_{pr}$ , this regression may then be applied to the simulated LGM inversion temperature  $T_{inv}$ , yielding an estimation  $\hat{T}_s(T_{inv})$  of the simulated paleo-surface temperature. A comparison of the errors  $\Delta_{inv} = \hat{T}_s(T_{inv}) - T_s$  and  $\Delta_{pr}$  allows to determine how much of the  $\Delta_{pr}$  signal is induced by a possible change in the  $T_s$  vs.  $T_{inv}$  relationship.

- A second possibility is a change in the precipitation seasonality. If, for example, precipitation decreases relatively more strongly in winter than in summer in a colder climate, the isotopic signal is likely to carry a warm (summer) bias, leading to an overestimation of the paleo-surface temperatures. In order to estimate the effect of the change in the precipitation seasonality, one can proceed in the same way as above by using the precipitation-weighted inversion temperature

$$T_{inv,pr} = \frac{\sum \bar{T}_{inv} \bar{p}\bar{r}}{\sum \bar{p}\bar{r}} \quad (2)$$

instead of the annual mean inversion temperature.  $T_{inv,pr}$  is an intermediate diagnostic variable between  $T_{inv}$  and  $T_{pr}$ . For calculating  $T_{inv,pr}$ , the monthly precipitation quantities  $\bar{p}\bar{r}$  and inversion layer temperatures  $\bar{T}_{inv}$  are used, thus isolating the effect of the seasonality of the precipitation, but not taking into account short-term variability. As above, regressing  $T_s$  against  $T_{inv,pr}$  for the present and using this regression for calculating an estimated paleo-surface temperature  $\hat{T}_s(T_{inv,pr})$  and an estimation error  $\Delta_{inv,pr} = \hat{T}_s(T_{inv,pr}) - T_s$  allows to evaluate the importance of this effect.

- A third possibility is a change in the short-term correlation (on a time scale of the order of a few days) between temperature and precipitation. High precipitation events on the ice sheets are mostly due to intrusions of warm air which cools down during its ascent and thus loses its moisture-holding capacity. Strong precipitation events are thus generally characterized by a positive deviation of the atmospheric temperature compared to the longer-term (e.g., monthly) mean temperature. A change in this short-term precipitation - temperature covariance can cause the residual error which is not explained by the two effects discussed above.

Table 1 displays the simulated mean surface temperature  $T_s$  for the higher parts of both ice sheets (above 3000m a.s.l.) and for the present-day and the LGM. Additionally, it shows the errors  $\Delta_{pr}$ ,  $\Delta_{inv}$ , and  $\Delta_{inv,pr}$  discussed above. As the regressions were calculated from the present-day conditions, the errors for the present-day estimations are generally low (mostly below 1°C). Note that the correlation coefficients  $r^2$  of the regressions discussed in this section are all above 0.85, and mostly above 0.90.

The LGM error  $\Delta_{inv}$  is quite low because for the higher parts of the ice sheets, the linear  $T_s$  vs.  $T_{inv}$  relationship, when calculated for the whole ice sheet, does not change dramatically [Krinner, 1997].

Using the precipitation-weighted inversion temperature  $T_{inv,pr}$  yields an error  $\Delta_{inv,pr}$  of about 7°C in the estimation of the LGM surface temperature in the Summit area. Thus, the largest part (about 70%) of the total  $\Delta_{pr}$  of about 10°C seems to be caused by a change in the precipitation seasonality. Indeed, the LMDz GCM simulates an important change in the central Greenland precipitation seasonality. In accordance with observations reported by Shuman *et al.* [1995], the model does not simulate a clear seasonality of present-day precipitation in the higher regions of the Greenland ice

**Table 1.**  $T_s$  and the regression errors  $\Delta_{pr}$ ,  $\Delta_{inv,pr}$ , and  $\Delta_{inv}$  (in °C, explanations see text) on the higher parts of Greenland and Antarctica (mean values for all grid points above 3000m a.s.l.)

run	$T_s$	$\Delta_{pr}$	$\Delta_{inv,pr}$	$\Delta_{inv}$
AA0	-54.9	0.8	0.2	-0.2
AA21	-60.7	1.9	0.8	1.4
GL0	-35.8	1.3	0.9	0.4
GL21	-51.8	9.8	6.9	0.8

sheet. During the LGM, however, the model simulates a clear summer precipitation maximum on the Greenland plateau areas, with very low accumulation rates in winter. This is due to the fact that in the LGM simulation, the winter cyclones advect much less humidity to Greenland than today because of the southward shift of the sea ice margin which inhibits evaporation over the North Atlantic. Thus, according to the model, the annual-mean isotopic composition of precipitation, which has little seasonal bias at the present, would carry a strong warm (summer) signature during the LGM. On the East Antarctic Plateau, however, the annual cycle does not change that drastically; the model simulates the precipitation maximum in autumn and lower accumulation rates in summer for both climatic periods. The isotopic seasonal bias is thus essentially unaffected in that region.

Some experimental support for the simulated change in the annual precipitation cycle over central Greenland comes from work by Raynaud *et al.* [1997], who state that the magnitude of close-off porosity changes observed ice from the GRIP core could partially be explained by changes of the annual cycle of snow deposition.

Note that the role of seasonality for explaining GRIP and GISP2 isotopic data, pinpointed by Steig *et al.* [1995], may be model dependent. For example, it does not appear to be supported by the NASA/GISS model experiments [Charles *et al.*, 1994]. On the other hand, many of the models participating in the Paleoclimate Modeling Intercomparison Project (PMIP, Joussaume and Taylor [1995]) do show similar changes in the Greenland precipitation seasonality [Krinner, 1997]. Furthermore, the results depend on the imposed sea surface boundary conditions. Simulations with dramatically reduced LGM winter sea ice extents, as suggested by Weinelt *et al.* [1996], do not yield the same results.

As a whole, the LMDz model provides, principally through changes in precipitation seasonality, a plausible explanation for the  $\approx 10^\circ\text{C}$   $\delta^{18}\text{O}$  - borehole thermometry conflict.

We obviously keep in mind that our study deals with only part of the factors which influence the  $\delta$  vs.  $T_s$  relationship. In particular, we do not account for possible changes in the origin of the precipitation, the importance of which has been illustrated by Boyle [1997]. One way to separate the role of, for example, seasonality and source conditions would be to incorporate the precipitation temperature diagnostic in isotopic GCMs and to run them for different LGM oceanic temperatures. This can be done with existing isotopic GCMs and hopefully in the near future with an isotopic version of the LMDz model we have used in this study.

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