An investigation of rapid warm transitions during MIS2 and MIS3 using Greenland ice-core data and the CLIMBER-2 model

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Abstract

In the search for a better understanding of the dominant mechanisms of the Earth's climate system, we present a study of the rapid warm climate transitions into the Dansgaard-Oeschger events as seen in the ice-cores from the Greenland Ice Sheet. We present a continuous δ^{18}O-record from the GRIP core with a resolution of 5 yrs until 50 kyrs BP and 20 yrs until 100 kyrs BP. These data are compared with other high-resolution records, i.e. the GISP2 chemistry-record (25 yrs until 50 kyrs BP) and the GRIP Ca^{2+}-record (3 yrs until 100 kyrs BP). All records have been transformed to the GISP2 Meese/Sowers time scale.

The high-resolution records are separated into interstadials and stadials, defined by the GRIP and GISP2 δ^{18}O records. We examine in detail the transitions into the Dansgaard-Oeschger events, and propose a scenario for the changes taking place in the different ice core records during the approximately 50 yrs the transitions takes. The main difference from previous studies is in the much higher resolution data sets available until 50 kyrs BP; previous high-resolution studies by (Taylor and others, 1997) have focused on only the YD/PB transition.

The data are compared to model simulations of the Dansgaard-Oeschger events performed with the CLIMBER-2 model of intermediate complexity (Ganopolski and Rahmstorf, 2001; Petoukhov and others, 1998).

Introduction

Dansgaard-Oeschger events are still a much-discussed topic within the paleoclimate research community. More paleo-data are adding hints and pieces to the puzzle of the large and very rapid climate changes that took place some 24-30 times during the last glacial. Ocean sediment cores have helped in understanding the role of the oceans in these different climate changes. However, the dating is still inadequate for determining in what order the changes happened.

We present here isotopic data from the two Greenland Summit ice cores, GRIP, (Dansgaard and others, 1993), and GISP2 (Grootes and others, 1993).

We present a continuous (GRIP) δ^{18}O-record with a resolution of 5 yrs going back to 50 kyrs BP and 20 yrs until 100 kyrs BP. The GRIP δ^{18}O data will be compared with other high-resolution records, i.e. the GISP2 chemistry-record (25 yrs until 50 kyrs BP) and the GRIP Ca^{2+}-record (3 yrs until 100 kyrs BP). All records are converted to the GISP2 Meese/Sowers time scale for comparison purposes.

The high-resolution records are separated into interstadials and stadials, defined by the GRIP and GISP2 δ^{18}O-records. The signal analysis performed will be compared to previous studies of the high-resolution Ca-record from GRIP and the GISP2 ion records and the new high-resolution GISP2 δ^{18}O-record. The present study is generally based on much higher resolution data than was used in previous studies dating back to 50 kyrs BP (Fuhrer and others, 1999; Johnsen and others, 2001; Mayewski and others, 1994). Finally the data will be compared to the model simulations of the Dansgaard-Oeschger events performed by the CLIMBER-2 model, (Petoukhov and others, 1998).

Ice core data

The data used in this study originates from the two deep ice cores GRIP (Fuhrer, 1991; Greenland Ice-Core Project (GRIP) Members, 1993) and GISP2, (Grootes and others, 1993; Mayewski and others, 1997) and (Journal of Geophysical Research Vol. 102, No. C12, CDrom, 1997). The data have been sampled at very high resolution, which offers an opportunity to make a detailed study of the transitions from stadials to interstadials and vice versa. Here we will mainly focus on the stadial to interstadial transitions.

Fig. 1 shows the resolution of the raw data discussed in this paper. There are a few holes in the records that we have bridged by interpolation; for details see (Mogensen, 2001). The raw data series were resampled at the resolution shown in Table 1 by using occasional minor over-sampling (Mogensen, 2001).

In order to be able to work with data from the two ice cores, the GRIP data has been converted to the GISP2-time scale, (also named GISP2 *Meese/Sowers* time scale; Bender and others, 1994); for details on how this conversion was done see (Mogensen, 2001). This approach allows us to work with a greater number of continuous high-resolution datasets. The errors in the relative timing are dependent on the resolution and the noise of the data used to match the transitions in the two cores. The δ^{18}O-records used for matching the two records had a resolution of 20 yrs until 50 kyrs BP and 50 yrs until 110 kyrs BP for GISP2 and 20 yrs for the GRIP δ^{18}O-record. Hence we expect to “hit” the same event in the two records within 2-3 data points, thus ~50 yrs back to 50 kyrs BP and ~150 yrs for the rest of the record. Using higher resolution than 20-yr averages for tying the two time scales together gives too much noise for the method used, and would therefore not increase the "hit-rate" substantially.

We will first present how the trend of the GRIP δ^{18}O-record and the trend of the GRIP Ca-record correlate with the duration of the stadials and interstadials respectively.We will then present the transitions at the onsets of the Dansgaard-Oeschger events. These very sharp transitions are easier to distinguish than the less-sharp transitions from interstadials to stadials.

Methods

The δ^{18}O-record in ice cores is the primary paleo-data proxy for the Dansgaard-Oeschger events, and therefore has been chosen to define the onset and termination of these events.

All the Dansgaard-Oeschger events (Dansgaard and others, 1993) were then located using the 20 yrs sampled δ^{18}O data sets. The transition marks were placed at the steepest gradient for the onset and termination of each event.
As tiepoints for transferring the GISP2 chronology to the GRIP records we used a total of 68 rapid transitions including all of the 48 Dansgaard-Oeschger transitions.

To classify the Dansgaard-Oeschger events we determined the linear trends or slopes of the GRIP δ^{18}O-record and GRIP Ca-record for each stadial and interstadial. Fig. 2 shows the GRIP δ^{18}O-record and the GRIP Ca-record and the linear segments found. We see that for most interstadials, the trend for the δ^{18}O-record is decreasing as time proceeds, (negative trends). For each sub-period of the entire Wisconsin glacial the linear-trend was plotted against the duration of the event (see Fig. 3). Fig. 3a shows the relationship for the interstadials, and Fig. 3b for the stadials. We find that the shorter an interstadial is, the steeper is its trend in both δ^{18}O and Ca. The longest interstadials are found in the beginning of the last glacial, i.e. Marine Isotope stages 4, 5a and 5b. The shorter events are found in Marine Isotope stage 3, which is dominated by Bond cycles, (Broecker, 1994), which consist of one long (over one thousand years) and 3-4 shorter Dansgaard-Oeschger events (few hundred years). Lastly, Marine Isotope Stage 2 is dominated by the very long LGM (Last Glacial Maximum), perturbed by only two events, only one of which is classified as a Dansgaard-Oeschger event)GI-2, which is only about 300 yrs in duration).

In Fig. 3a the trends for the calcium record almost mirror the δ^{18}O trends. This agrees well with previous results, which detect a high anti-correlation between δ^{18}O and Ca (Greenland Ice-Core Project (GRIP) Members, 1993; Mayewski and others, 1994; Fuhrer and others, 1999). For stadials the picture is somewhat more blurred; however, the averaged trend for both δ^{18}O and calcium is more or less zero.

Results

We present here a close-up of the 13 warm transitions from 10-50 kyrs BP, Fig. 4, and discuss the averaged transition. This is compared to CLIMBER-2 model results of changes in Greenland temperature, deep Antarctic water in the Atlantic, North Atlantic Deep Water formation (NADW), and the Nordic Seas Salinity.

The CLIMBER-2 model produces annual means for a variety of variables, and we have chosen those that are of most interest with respect to the ice core data.

Fig. 4c+d+e+f shows the 13 warm transitions that occurred from 10 kyrs BP to 50 kyrs BP, leaving out transition 1 (Wisconsin to Holocene). They show that the switch from stadial to interstadial takes about 50-70 yrs from the last cold value to the maximum. One large step seems to be taken during each transition, with a single jump in the δ^{18}O values of 2.3°/∞. Since the most rapid shifts in δ^{18}O are used to define the transitions, we can expect to find this single jump in the averaged record as well. If one examines the δ^{18}O values separately (not shown here,) during a transition there is a pronounced jump in the δ^{18}O value in most transitions. Sometimes this jump is succeeded by a temporary drop in the δ^{18}O value superimposed on the general transition climb.

If we compare the CLIMBER-2 Dansgaard-Oeschger transitions and the ice core data, as done in (Ganopolski and Rahmstorf, 2001) (Fig. 4b), we see some striking similarities. The model variables are 5 year averages, and Fig. 4a+b show a Dansgaard-Oeschger transition spanning 200 yrs, as for the GRIP data. The variables shown were chosen because they all show clear changes through a transition. The model was forced with a sinusodial fresh water flux into the North Atlantic region in a similar way as was done in the (Ganopolski and Rahmstorf, 2001) study. Our forcing did not, however, include the strong fresh water pulse introduced by Ganopolski and Rahmstorf for simulating a Heinrich event. Fig. 4a shows the Greenland temperature shift and the amount of Antarctic deep water that enters the Atlantic. The CLIMBER-2 Greenland temperature bears a fair resemblance to the Greenland δ^{18}O profile (Ganopolski and Rahmstorf, 2001). The Antarctic deep water entering the Atlantic is also shown, since this variable precedes the temperature shift in Greenland. It is not possible to trace directly the Antarctic deep water inflow in the Greenland ice core data. We do see that the initial drop in calcium precedes both the jump in δ^{18}O and the onset of the influx of Antarctic water. This is most likely due to an artefact in the averaged Ca data as discussed below.

The early influx of Antarctic deep water in the CLIMBER-2 model is in agreement with data from ocean sediment cores off the coast of Portugal, which show that Antarctic bottom water flows into the Atlantic before the Dansgaard-Oeschger events (Shackleton, 2001). Fig. 4b shows the modelled NADW flux and the Nordic Seas salinity. On entering the interstadial the NADW formation is restored, and the salinity of the Nordic Seas increases, as convection shifts from taking place south of Iceland north of Iceland (Ganopolski and Rahmstorf, 2001). In the CLIMBER-2 output the transition into an interstadial is quicker than shown in the δ^{18}O data. This is probably due to the atmospheric model's very rapid reaction to changes in the ocean conditions.

The onset of the thermohaline circulation decreases the meridional temperature and pressure gradient, which again decreases the zonal winds in CLIMBER-2 (not shown). This should lead to a rapid fall in the calcium concentrations, which is not mirrored in the more slowly changing calcium data.

The Ca-record (Fig. 4d) does not show the same large jumps as the δ^{18}O, even though it is often suggested that dust/Ca^{2+} reacts faster to shifts in the climate system (e.g. transition 1, where the dust reaches Holocene values in only 20 yrs, whereas it takes the δ^{18}O-record about 50 yrs (Dansgaard and others, 1989)).

The Ca-record could be influenced by larger noise, which smoothes any sharp transition when making an averaged record. Indeed, in the individual transitions (shown in gray) we do see in some cases a pronounced step right around or before the in the δ^{18}O step (this can be seen for individual transitions, i.e. (Fuhrer and others, 1999) and figure 4b+c [Dansgaard, 1984]). Also the sodium and magnesium transitions are smoother than the δ^{18}O-record. Sodium is usually considered a proxy for the sea salts in the ice, and magnesium and calcium are considered *tracers* for land-dust blown onto the ice.

The smooth transitions in the sodium and magnesium records can originate from imprecise tie points between the two ice core records. Similar tie point errors can also help explain why the averaged GRIP calcium record is even smoother in the transition even though some transitions in the calcium record are quite sharp (Fuhrer and others, 1999).

Conclusion

We have here used high resolution ice core data and the CLIMBER-2 model to investigate in detail what happens during the rapid warming transitions into the Dansgaard-Oeschger events.

In Fig. 4 both GRIP calcium, GISP2 sodium and magnesium all show a decrease prior to the large δ^{18}O jump. We consider this early decrease to be an artefact in the averaged ionic data. We conclude that the weakening of the atmospheric circulation (zonal wind speed) (Mayewski and others, 1997) leading to the drop in the ionic concentrations is most likely taking place in phase with the isotopic shifts in Greenland. This conclusion is also supported by the CLIMBER-2 model runs presented here. The CLIMBER-2 model runs show even faster shifts into a Dansgaard-Oeschger event than is evidenced by the δ^{18}O data.

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Figure captions

Fig. 1 : The resolution of the raw data (sample size) used in this paper. (a) shows the sample size for the GRIP δ^{18}O record (Johnsen and others, 1997), (b) shows the sample size for the GRIP calcium record (Fuhrer, 1995), (c) shows the GISP2 sample size (Stuiver and Grootes, 2000) and (d) shows the sample size of the GISP2 ion records (Mayewski and others, 1997).

Fig. 2 : The GRIP δ^{18}O-record and calcium record for the last glacial. Warm periods are shaded and the linear segments for each interstadial and stadial have been plotted in light gray.

Fig. 3 : The trends/slope of the linear segments shown in Fig. 2 are plotted against the duration of the corresponding event. (a) shows the δ^{18}O and calcium trends for the interstadials, and (b) shows the δ^{18}O and calcium trends for the

stadials. It is clear that the strong anti-correlation between Ca and $\delta^{18}O$ is very pronounced during the interstadials.

Figure 4 : (a) shows the 5 year smoothed Greenland temperature and in gray the Antarctic water flow into the Atlantic.

(b) shows the 5 year smoothed North Atlantic Deep Water formation in Sv, and in gray the Nordic Seas salinity.

(c), (d), (e), and (f) show in light gray the 13 transitions into the Dansgaard-Oeschger events from 50 kyrs BP for respectively GRIP $\delta^{18}O$, GRIP Ca^{2+}, GISP2 Na', and GISP2 Mg^{2+}. The averages of these transitions are shown in black.

Data type	Resolution until 50 kyrs BP	Resolution 50-100 kyrs BP
GRIP $\delta^{18}O$	5 yrs	20 yrs
GRIP Ca^{2+}	3 yrs	3 yrs
GISP2 Cl^{-}	25 yrs	50 yrs
GISP2 Mg^{2+}, Na^{+},Ca^{2+}	25 yrs	50 yrs

Table 1: The table shows the resolution of the data series discussed in this article.

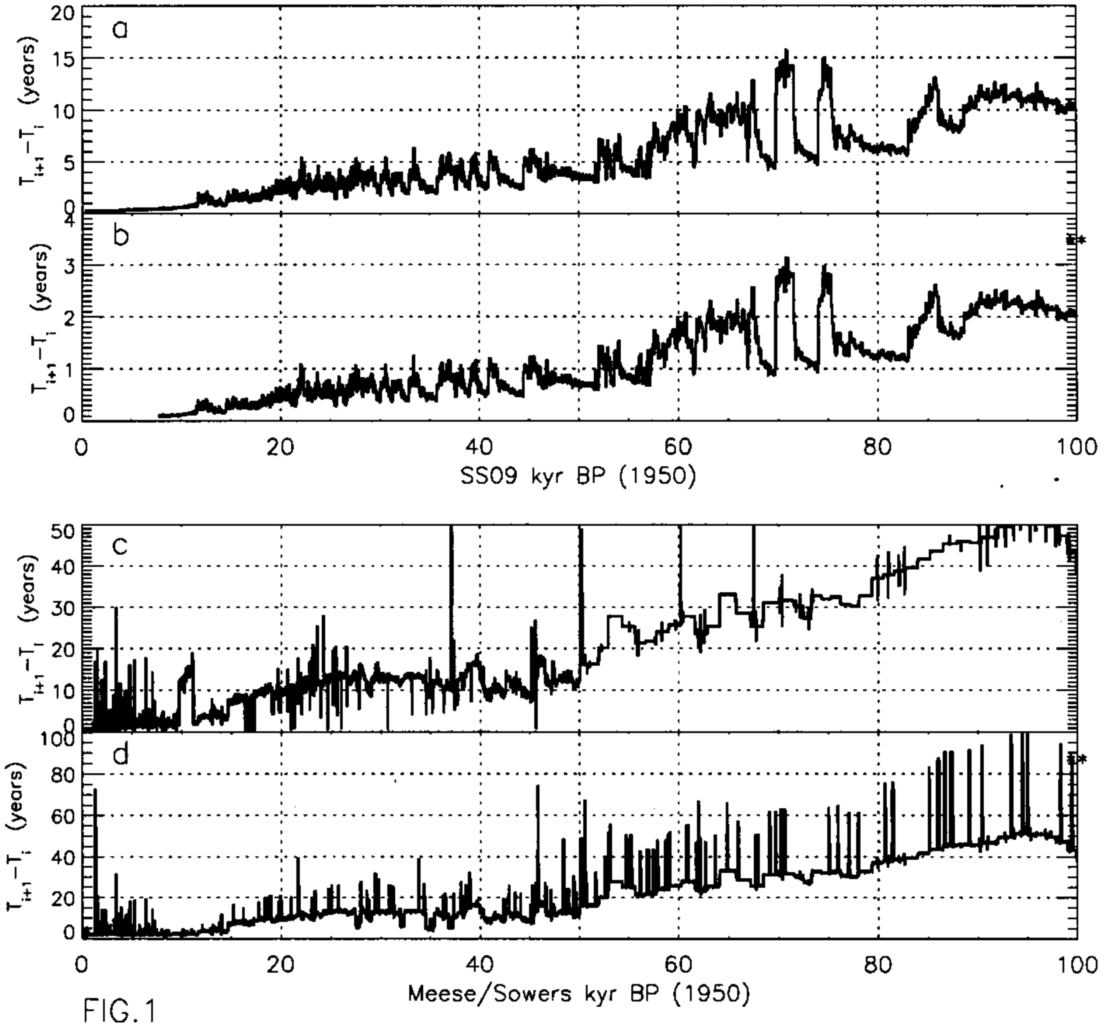
a
b
c
d
$T_{i+1}-T_i$ (years)
20
15
10
5
0
4
3
2
1
0
0
20
40
60
80
100
SS09 kyr BP (1950)
50
40
30
20
10
0
100
80
60
40
20
0
Meese/Sowers kyr BP (1950)

FIG. 1

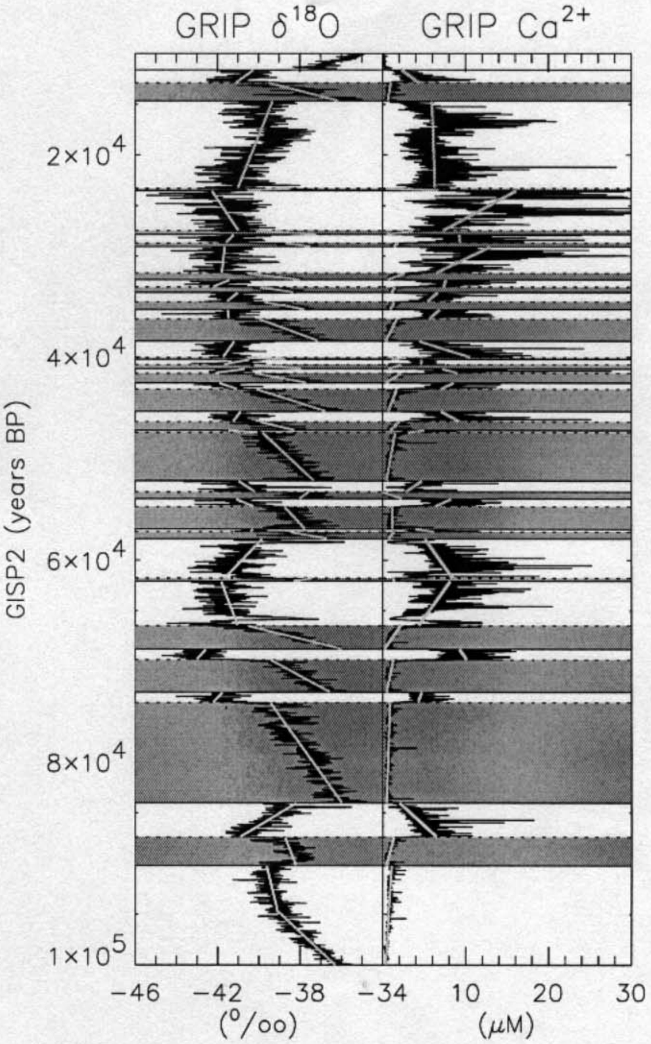
GRIP $\delta^{18}O$
GRIP Ca^{2+}
GISP2 (years BP)
2×10^4
4×10^4
6×10^4
8×10^4
1×10^5
−46
−42
−38
−34
10
20
30
(°/oo)
(μM)

FIG.2

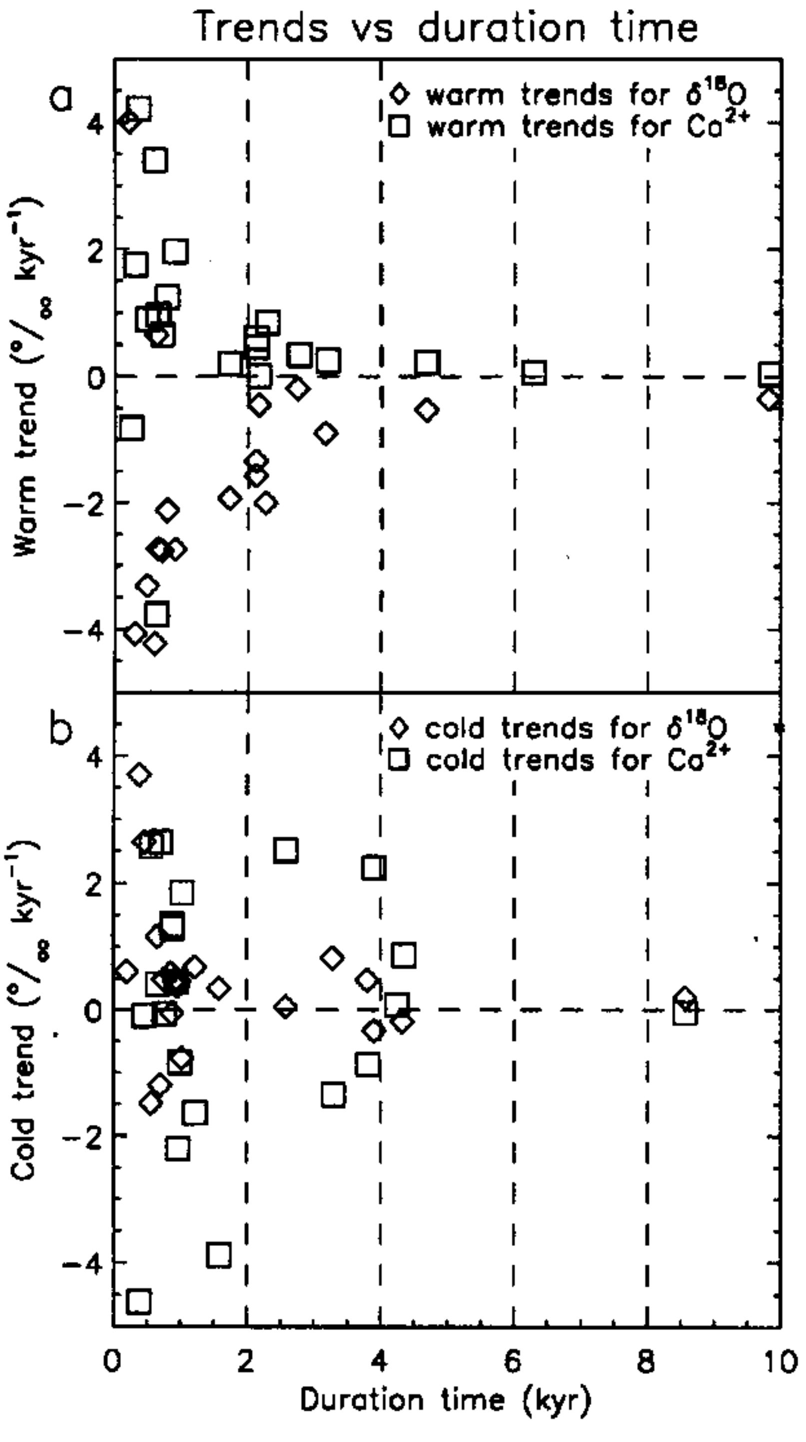
Trends vs duration time
a
◇ warm trends for $\delta^{18}O$
□ warm trends for Ca^{2+}
Warm trend (°/∞ kyr⁻¹)
4
2
0
−2
−4
b
◇ cold trends for $\delta^{18}O$
□ cold trends for Ca^{2+}
Cold trend (°/∞ kyr⁻¹)
4
2
0
−2
−4
0
2
4
6
8
10
Duration time (kyr)

FIG.3

FIG. 4