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Climate of the Past Discussions

Interactive comment on "Spatial gradients of temperature, accumulation and δ^{18}O-ice in Greenland over a series of Dansgaard-Oeschger events" *by* M. Guillevic et al.

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1 Reply to comments by Anonymous Referee 1

Guillevic et al. reconstructed magnitudes of temperature changes (including d18Oice) as well as accumulation rate change for the D/O events (8-10) using nitrogen isotopes occluded air in NEEM ice cores from Greenland. Then, the results were compared with other temperature and accumulation rate reconstructions from different sites (NGRIP and GISP2). Results are important for ice-sheet modeling and more importantly for climate modeling community providing temperature constrains for abrupt climate changes on Greenland. Therefore, I recommend publishing this paper in CP with minor revision. Especially, it will be beneficial if it includes more discussion on the causes of differences in magnitude of temperature changes during abrupt climate change in different sites in Greenland, which should be useful for wider audiences. You can probably look more into climate modeling studies and modern climate condition of NEEM, GISP2, and NGRIP (different altitudes and latitudes) to investigate the causes. Here, I describe some specific comments on the papers.

p5211. Abstract. It would be useful to provide values of temperature changes including uncertainties for each D/O events in different sites. Also, it would be good to describe your hypothesis for causes of the difference of temperature changes.

We have added the uncertainties in temperature increase reconstructions for each site in the abstract.

We do not have a definite explanation for the spatial gradient of temperature increase at the different sites. We still note that our results are consistent with the modelling output of Li et al. (2010). In this study, they model the response of Greenland temperature to different sea-ice extent in the North Atlantic region. They note a particular influence of sea-ice retreat in the Nordic seas on the gradient of temperature increase at the GS-GI transition: the temperature increase is higher going South. We refer to this paper in the new version of the abstract and manuscript.

p. 5219. Line 10. You may want to cite (Craig et al., 1988) and (Schwander, 1989) for gravitational fractionation and (Severinghaus et al., 1998) for thermal fractionation.

The references have been added to the revised manuscript.

p. 5221. Line 8. Have you considered changes in depth of convective zone?

NEEM site may have experienced stronger katabatic winds during the deep glacial period.

A deeper convective zone during the glacial period at NEEM is indeed possible, created by strong katabatic winds due to a steep ice sheet flank (like the 14 m convective zone at YM85 site in Antarctica (Fig. 2 and Kawamura et al., 2006). However, during the glacial period, the Greenland ice sheet may have been connected to Ellesmere Island and the lateral margins were extended compared to present. This would create a more flat surface at the NEEM site, possibly also NGRIP, and would not favor the existence of strong katabatic winds. Moreover, Marshall and Koutnik (2006) modeled the icebergs delivery from the Northern Hemisphere ice sheets over DO events and showed that the ice sheets margins from Greenland and the Canadian Arctic do not particulartly respond to DO events, because these regions remains too cold even during GI. This is not in favor of abrupt change in convective zone due to ice sheet shape changes at the GS-GI transition.

A convective zone may also be created by a low accumulation rate (like Vostok or Dome F, Fig. 2). The 23 m convective zone at the zero-accumulation site Megadunes in Antarctica is remarkable (Severinghaus et al., 2010). However, note that there is no convective zone at Dome C (Landais et al., 2006) where the present-day annual mean accumulation rate is 2.5 cm.w.e.a^{-1}, slightly higher than Vostok and Dome F. Note also that for NEEM and NGRIP during MIS3, our best guess accumulation rate, using a 2 m convective zone, is always higher than at Dome C (Fig. 2). This is also true for the GISP2 site (Orsi et al., in prep.). These observations are in favor of no deep convective zone at NEEM, NGRIP and GISP2 during MIS3.

In our particular study, the existence of a convective zone would affect the average level of δ^{15}N, through the reduction of the diffusive zone, but not the modeled delta-depth which is a function of the total firn thickness (LID), itself dependant of surface temperature and accumulation. To reproduce both the measured delta-depth and δ^{15}N values, using the original DJ accumulation rate, we need to reduce the temperature

scenario d3 by 9 degrees everywhere and use a 50 m convective zone. The obtained system of temperature-accumulation-convective zone is inconsistent with present-day observations in Greenland and Antarctica (accumulation rate much too large compared to the temperature and convective zone).

We have made new simulations with the Goujon model using a constant convective zone of 12 m during MIS3 for NGRIP and NEEM and added the results to the manuscript. We explain in the Appendix the way we model this convective zone in the Goujon model.

Manuscript:

Several explanations can be proposed to explain the underestimation of the Δdepth by the model:

- (other items, not modified in manuscript)
- a convective zone could affect the glacial NEEM firn. Considering the present-day Antarctic sites as an analogue for the past NEEM firn, a convective zone of 0 m (like Dome C, Landais et al., 2005) to 12 m (like Vostok, Bender et al., 1994) can be considered (Fig. 2 and Appendix). A convective zone has no direct impact on the Δdepth but it lowers the δ^{15}N level. To still match it, lowering the temperature is necessary and this increases the Δdepth.

With a constant 2 m convective zone, by adjusting changes in accumulation rate and the δ^{18}O-temperature relationship (Fig. 1c and b), we manage to reproduce the NEEM δ^{15}N profile as presented in Fig. 1, scenario d3. This best δ^{15}N fit corresponds to a mean DJ accumulation reduction of 34 % (30 to 40 %, depending on the DO event). Because the depth-age correspondence is imposed by the layer counting, this accumulation rate reduction by 34 % directly implies the same 34 % decrease in the ice thinning. If we use this accumulation scenario as input for the DJ model, with keeping the original DJ accumulation scenario in the remaining ice core sections, the output time scale is just at the limit of the age uncertainty estimated by annual layer counting. With a 12 m convective zone (Fig. 1, d4), the δ^{15}N profile can be reproduced using the temperature scenario d3 systematically lowered by 2 C and the DJ accumulation rate reduced by 28 %.

For NGRIP, the Goujon model can reproduce the measured δ^{15}N profile with the correct Δdepth when using a convective zone of 2 m and the DJ accumulation rate reduced by 26 % over the all section (Manuscript, Fig. 7). Alternatively, we can use a 12 m convective zone with a 19 % reduction in accumulation. This impacts the mean temperature level which has to be lowered by 2 C. We further discuss past changes in accumulation rate in Sect. 3.4.

Based on these calculations, we conclude that reducing the DJ accumulation scenario is necessary to match both δ^{15}N data and Δdepth with a firnification model over the sequence of DO 8-10, even when accounting for uncertainties linked with the presence of a convective zone. This reduction has no impact on the reconstructed rapid temperature variations but requires a lower mean temperature level (Fig. 1, d3 and d4). Our 19 to 26 % accumulation reduction for NGRIP supports the findings by Huber et al. (2006) where the original accumulation scenario was reduced by 20 %, without convective zone.

P. 5225. Line 8. "(within uncertainties)" means not significant? Please provide confidence interval. For temperature estimates, you have to provide uncertainties in main text as you already calculated in Appendix, and also specify 1 sigma or 2 sigma somewhere in main text.

We have specified *1 sigma* in Sect. 3.2. We agree that calculating confidence intervals is necessary as pointed out by both Referees. When comparing 2 temperature increases to conclude if they are significantly different or not, we cannot apply the usual Student test because each temperature increase was determined using a different number of data points and has a different value for σ. We therefore use a different approach: we take a couple of temperatures increases ΔT_1 and ΔT_2, assume both to have gaussian distribution, and calculate the probability of the difference ΔT_1-ΔT_2 to have a value X:

$$\Delta T_1 - \Delta T_2 = X \tag{1}$$

$$p(X = x) = \int d\tilde{x}\; p(\Delta T_1 = \tilde{x})\; p(\Delta T_2 = \tilde{x} - x) \tag{2}$$

$$p(X = x) = \frac{1}{\sqrt{2\pi}\sqrt{\sigma_1^2 + \sigma_2^2}} \int exp\left(-\frac{1}{2(\sigma_1^2 + \sigma_2^2)}(x - (\Delta T_1 - \Delta T_2))^2\right) dx \tag{3}$$

To account for the uncertainties calculated for ΔT_1 and ΔT_2, we wider our calculation to p(ΔT_1-ΔT_2)=0±($\sigma_1 + \sigma_2$):

$$p(-\sigma_1 - \sigma_2 < x < \sigma_1 + \sigma_2) \;=\; \int_{-\sigma_1 - \sigma_2}^{\sigma_1 + \sigma_2} p(X = x)\, dx \tag{4}$$

$$= \frac{1}{\sqrt{2\pi}\sqrt{\sigma_1^2 + \sigma_2^2}} \int_{-\sigma_1 - \sigma_2}^{\sigma_1 + \sigma_2} exp\left(-\frac{1}{2(\sigma_1^2 + \sigma_2^2)}(x - (\Delta T_1 - \Delta T_2))^2\right) dx \tag{5}$$

Finally, we consider ΔT_1 and ΔT_2 to be significantely different when $p(-\sigma_1 - \sigma_2 < x < \sigma_1 + \sigma_2)$ is less than 0.05. For example, we calculate p=0.81 when comparing the temperature increases from NEEM and NGRIP for DO 8: they are not significantely different.

p. 5229. Line 27. Please provide uncertainties. These estimates are important but needs uncertainty estimates to be useful.

We have added the corresponding uncertainties.

2 Reply to comments by Anonymous Referee 2

This is a very well written and organized paper addressing an important topic with relevant existing and new data. I have comments, below, that I think need to be addressed, but are hopefully relatively easy to deal with. A main concern is whether the temperature changes at the different sites are truly statistically different, something I think could be addressed with some additional statistical analysis.

Page 5212, Lines 5 and 6. I don't think that Blunier and Brook claimed that all DO events are associated with AMOC changes. In any event I do not think there is strong oceanic evidence for such a statement. It might be true, but I do not think there is ironclad evidence that it is so.

Page 52,12, Lines 7 and 8. Similarly, I don't think that the ID of counterpart Antarctic warmings necessarily proves AMOC involvement, and I think our community should be a little skeptical that there are actually counterpart warmings for each DO cooling – is this really robustly demonstrated?

Indeed, Blunier and Brook (2001) proposed that onsets of the largest DO events (D-O events 21, 20, 19, 17, 15, 12, and 8) where associated with a cooling in Antarctica (Antarctic events A7 to A1), as seen in the Byrd Antarctic ice core. Blunier and Brook (2001) wrote: *This pattern provides further evidence for the operation of a bipolar seesaw in air temperatures and an oceanic teleconnection between the hemispheres on millennial time scales.* Indeed they didn't claimed this for all DO events but for the most prominent ones and suggested that higher resolution data may show the same patterns for the minor DO events.

The one-to one coupling (Antartic cooling at the onset of DO events) was then evidenced when comparing the high resolution EDML Antarctic core and the NGRIP ice core on a common time scale (EPICA community members, 2006; Capron et al., 2010;

Veres et al., 2012), as clearly depicted in Fig. 4, 5 and 6 below. The smooth temperature increases/decreases in Antarctica and the delay between Greenland cooling and Antarctic warming are consistent with the theoretical impact of AMOC changes and can be captured by models of different complexity (Stocker and Johnsen, 2003; Roche et al., 2010; Buiron et al., 2012). We still agree that other processes, like atmospheric teleconnections involving westerlies (Buiron et al., 2012), cannot be ruled out and we try to be more cautious in the new version of the paper.

We have added new references to this paragraph:

The identification of ice rafted debris horizons during stadials in North Atlantic sediments (Heinrich, 1988; Bond et al., 1993; Elliot et al., 2001), together with proxy records pointing to changes in salinity (Elliot et al., 2001, 2002), reduced North Atlantic Deep Water formation (Rasmussen and Thomsen, 2004; Kissel et al., 2008) and Atlantic Meridional Overturning Circulation (AMOC) (McManus et al., 1994), had led to the theory that DO events are associated with large scale reorganizations in AMOC and interhemispheric heat transport (Blunier and Brook, 2001). The identification of a systematic Antarctic counterpart to each Greenland DO event (EPICA community members, 2006; Capron et al., 2010; Veres et al., 2012) supports this theory. This observation can be reproduced with a conceptual see-saw model using the Antarctic ocean as a heat reservoir and the AMOC as the way to exchange heat between Antarctica and Greenland (Stocker and Johnsen, 2003), and also with intermediate complexity Earth system models (e.g. Roche et al., 2010). Other mechanisms can also be at play: it has been proposed that the timing of local Antarctic warming with respect to Greenland cooling can be influenced by atmospheric teleconnections originating from the tropics (Buiron et al., 2012).

Page 5212, Lines 20-23. We may be surprised by higher resolution CO2 data. I suggest saying that CO2 appears not to be in play based on existing data.

Indermühle et al. (2000) showed about 20 ppm CO_2 oscillations during MIS3 apparently related to the major Antarctic warming and Ahn et al. (2012) showed more abrupt variations (with a similar magnitude, 20 ppm) associated with Heinrich Stadial 4, with a 5 to 10 ppm increase at the onset of DO 8, while CO_2 was stable over DO9-11. Bereiter et al. (2012) showed that during MIS3, the pacing of CO_2 oscillations was not following the pattern of DO events. We have modified the manuscript according to these recent datasets and following the reviewer's suggestion: *The correct amplitude of temperature change over the Bølling-Allerød is only reproduced in a fully coupled and high resolution atmosphere-ocean global circulation model (Liu et al., 2009). However, a large part of the simulated warming is due to the simultaneous large changes in insolation (not at play for most DO events) and atmospheric* CO_2 *concentration (mostly stable or not in phase with DO events, based on existing data (Indermühle et al., 2000; Ahn et al., 2012; Bereiter et al., 2012)).*

Page 5213, Lines 12-14. Are there any data to support this: "Unlike Central Greenland where snow falls year round, NW Greenland precipitation is simulated to occur predominantly in summer (Steen-Larsen et al., 2011; Sjolte et al., 2011; Persson et al., 2011)."

Yes there are seasonal reconstructions of accumulation rate based on snow pit studies at Summit (Shuman et al., 1995) and in the north-west area (Shuman et al., 2001) which support this statement. We have added these 2 references in the manuscript.

Page 5213, Lines 23 and 24. Can you be more specific about what "conditions" means?

The isotopic composition of the vapor formed by evaporation of the ocean is influenced by the isotopic composition of the ocean, the temperature, the relative humidity and the wind regime at the surface of the ocean (e.g., Merlivat and Jouzel, 1979; Petit et al., 1991). To take these conditions into account is important for modelling the isotopic composition of Greenland and Antarctic snow (e.g., Johnsen et al., 1989; Ciais and Jouzel, 1994). We have added these explanations in the manuscript.

Page 5216, line 7. Is accuracy the term desired here? We have remplaced "‘accuracy"’ by "‘precision"’.

Page 5216, line 7. Small point, but saying that the uncertainty is 1439 a seems to imply a 1 a precision, which is probably not appropriate.

For the GICC05modelext time scale, based on annual layer counting, a specific parameter has been defined to give the uncertainty of the dating, called Maximum Counting Error (MCE, Rasmussen et al., 2006; Andersen et al., 2006). Each uncertain annual layer is counted as 0.5 a ±0.5 a. The MCE at a given depth/age in the ice core is the sum of all the uncertain layers from the begining of the core. It is therefore normal to get for example a 1439 a MCE at 38 ka b2k. But I agree that using the word *uncertainty* could lead to misunderstanding and MCE exclusively should be used. We have modified the text into: *The Maximum Counting Error (MCE), that can be regarded as a 2* σ *error estimate (Rasmussen et al., 2006) is 1439 a at 38 ka b2k.*

Page 5216, line 7. Lines 20-25. Will all of these match points be published in this paper and made available?

No, these match points will not be published in this paper. They will be published in a specific paper from I. Seierstad. These match-points have been obtained following the same method as in Rasmussen et al. (2008) and we have therefore added this reference: *The GISP2 core is matched to NGRIP using the same method as Rasmussen et al. (2008), with match points from I. Seierstad (personal communication, 2012).*

Page 5217, line 7. Another small thing, layer counting in GISP2 only goes to 40 ka if I recall correctly (I think it was actually blended with an d18Oatm based time scale between 40 and 50 ka.

Meese et al. (1997) actually publised an annual layer counted time scale for the entire GISP2 core but this data were not taken into account in the time scale used by Cuffey and Clow (1997). Orsi et al. (in prep.) actually scaled the Meese et al. (1997)

annual layer counted time scale to GICC05 using the match points from I. Seierstad (pers. com., 2012). The accumulation rate from Cuffey and Clow (1997) was then re-calculated according to this new time scale. This way, a maximum of information from the GISP2 annual layer counting is kept. We have done the same and modifed accordingly the text (below) and Fig. 4 in the manuscript.

The GISP2 core is matched to NGRIP using the same method as Rasmussen et al. (2008), with match points from I. Seierstad (personal communication, 2012). Using these match points, we scale the Meese et al. (1997) GISP2 time scale, based on annual layer counting, to the GICC05 time scale, in order to keep the informations from the annual layer count while producing an age scale consistent with GICC05.

Page 5221, Line 22. I think you should explain a bit more about Ca being a dust proxy. As written only ice core scientists "in the know" will know what you mean.

Indeed, calcium and dust in Greenland ice cores are both originating from low-latitudes Asian deserts and their content is influenced by source strengh and transport conditions (Svensson et al., 2000; Ruth et al., 2007). They co-vary in Greenland ice cores from seasonal to millenial time scales (Hörhold et al., 2012; Thomas et al., 2008; Steffensen et al., 2008) and that's why one can be used as a proxy for the other one. Hörhold et al. (2012) showed evidence of a relationship between a positive density anomaly and calcium (Ca^{2+}) concentration in the firn. They chose calcium because high resolution data concerning this impurity were available. It is actually not well known if soluble impurities (like calcium) have the same effect on firn densification as unsoluble impurities (like dust) (Cuffey and Paterson, 2010). We have chosen to follow Hörhold et al. (2012) and use the more general term "'impurities"'. We corrected this paragraph into: *A recent study has shown that the firn density profile could be strongly influenced by impurities, the density increasing with calcium and dust content in the ice (Hörhold et al., 2012). During cold periods (glacials, stadials), calcium and dust content in Greenland ice cores are strongly enhanced compared to warm periods (interglacials, interstadials).*

Section 3.1. If we accept that the right way to fit the data is to reduce accumulation rate, then what about the dust issue, do you think it is not important?

The impurities issue is important in general but it does not seem to be the main explanation for the observed mismatch between measured δ^{15}N and Δ-depth and modeled ones (scenario d1 and d2).

The addition of impurities effect, using the same temperature and accumulation forcings as in our study, would produce a shallower firn. This would even enhance the mismatch between model and data in scenarios d1 and d2.

Moreover, any impurities change happening at a time t=0 at the surface (for example, at the onset of a DO event) would affect the firn density profile only when reaching a certain depth, likely hundred of years later. Therefore, the inpurities effect would likely affect the absolute values of temperature and accumulation reconstructed by firn models, but not the reconstructed increases in temperature and accumulation at the onset of DO events.

Page 5225, Lines 6-10. Given the larger uncertainties in NGRIP temperature reconstruction, what is the probability that all of the DO8 results actually show the same temperature change? I think that a more rigorous statistical analysis should be possible.

We have calculated the probability for 2 temperature increases to be significantly different (see answer to Referee 1) and reported the results in a new table in the revised manuscript. Significantly different temperature increases are : NEEM-GISP2 for DO 8 and NEEM-NGRIP for DO 10.

Page 5225, Lines 1-5 I think a bit more explanation of how the offset of dust and ions tells you about snowfall seasonality is needed.

Andersen et al. (2006) observed synchronous peaks maxima of the different species (calcium, sodium, ammoniac, nitrate, sulfate) in GS and asynchronous peaks maxima in GI, as present-day, with the transition occuring in a few years. A first possibility is that during GS, the snow income bringing these impurities to Greenland only occurs in a very narrow time window, from late spring to late summer. This would be in agreement with our suggestion of reduced winter accumulation rate during GS. Alternatively, they proposed a GS-GI change in long-range transport towards Greenland. Especially, following the suggestion of a split jet-stream across the Laurentide ice-sheet by Bromwich et al. (2004), they suggested that a favored path north of the Laurentide during GS and south during GI might be a explanation. The GS-GI impurities patterns are therefore in favor of different atmopheric circulation patterns between GS and GI, eventhough these patterns are not well defined yet. We have reported these hypotheses in the revised manuscript.

Page 5220, line 10-15. Based on the discussion in prior paragraphs it seems necessary to conclude that both kink height and some thickness change could be involved, not just kink height. Also, what is the justification for saying that the needed thickness changes are unrealistic? It seems a bit circular to trust ice sheet models for that. And what about margin location changes, don't they enter into this?

On thickness change: Concerning the DJ model applied to the NGRIP site, runs with constant ice sheet thickness history or the one from Vinther et al. (2009) were compared (Buchardt, 2009, Chap. 5, Fig. 5.22) and agree well for MIS3. We thus believe that to not consider thickness change in the DJ model shouldn't affect much the reconstructed accumulation rate for NGRIP. The effect may be a bit more significant for the NEEM site which experienced larger thickness variations.

On margin location change: The expansion of the ice sheet margins allow the ice sheet thickness to grow. To take this effect into account indeed influences the modeled past vertical velocity profile and the reconstructed accumulation rate. No test has been made on the effect of ice sheet margin location changes on the DJ model.

On the contrary, Cuffey and Clow (1997) reconstructed the accumulation rate for the GISP2 site using a combined heat and ice flow model, with different ice sheet margin scenarios. During the last deglaciation, they consider a 50 km, 100 km and 200 km margin retreat, the last scenario producing the highest glacial accumulation rate, the thicker glacial ice sheet (which was then as thick as present day) and the maximum thickness growth and regression during the Deglaciation - Early Holocene (150 m). We trust these reconstructions because they agree with geological evidence of margin location changes (Funder, 1989; Funder and Larsen, 1989) and elevation reconstruction based on ice core total air content (Raynaud et al., 1997). Cuffey and Clow (1997) concluded that the most likely accumulation was in the enveloppe corresponding to 100 to 200 km ice sheet margin retreat during the deglaciation.

It is actually very interesting to see how much the possible accumulation rates reconstructed by different ice flow modelling may be different from each other. Below we compare accumulation rate reconstructed for the Greenland Summit (GISP2, GRIP) based on different ice flow models.

Using a one-dimension ice flow model, Cutler et al. (1995) tried to reconstruct the past GISP2 accumulation rate. They tested the sensitivity of their model to different changes: thickness, margin location, description of the ice flow (basal sliding or not), vertical velocity profile (influenced by past temperature and impurities in the ice). The maximum glacial accumulation rate is produced using a constant ice-sheet thickness and fixed ice-sheet margin, the minimum accumulation (25 % less) with variable thickness (450 m less than present) and fixed ice-sheet margin. In between are the accumulations reconstructed using margin expansion up to 100 km, fixed glacial or interglacial vertical velocity profiles. Their output accumulation rate using variable ice sheet thickness and margin location is actually very close to the one with these two parameters fixed.

The GISP2 glacial accumulation reconstructed by Cuffey and Clow (1997) lies in the enveloppe proposed by Cutler et al. (1995), on the low hand. On the contrary, the GRIP accumulation reconstructed using a DJ model is systematically higher during the glacial period, from 30 to 60 %, compared to the high boundary proposed by Cutler et al. (1995). Part of this discrepancy may be due to a climatic signal. At present, the air masses reaching Summit are mostly comming from the Est and a possible Foehn effect, due to the presence of the ice divide, would result in a lower accumulation rate at GISP2 (28 km west of the divide) compared to GRIP (on the ice divide). On the contrary, the present-day accumulation at GISP2 is 8 % higher than at GRIP (Meese et al., 1994; Johnsen et al., 1992). Buchardt et al. (2012) noticed an insignificant Foehn effect in Central Greenland for the last 200 years. During the glacial period, the expansion of the ice sheet margins may create a more flat surface in Central Greenland and reduce an eventual Foehn effect. Therefore, we believe that the discrepancy is model-induced.

To conclude, we suggest that the accumulation rate reconstructed by the DJ model for Greenland Summit has to be taken as a high boundary, with the low boundary being at least 50% lower. This may apply to NGRIP and NEEM. Our firn-model-based accumulation rates lie in this enveloppe. We agree that both thickness and margin location changes should be taken into account in the DJ model, as suggested by Referee 2, and this suggestion will be included in the manuscript. We also believe that a better agreement between the Cutler et al. (1995) model, the Cuffey and Clow (1997) model and the DJ model may be found by letting the DJ vertical velocity profile to be influenced by the ice sheet temperature profile and the fabric of the ice. In other words, we suggest to use a variable kink height or even to use a different parametrization to describe the ice flow.

Legends of the Figures

Fig. 1, Manuscript, Fig.3: Measured and modeled δ^{15}N for NEEM on DO 8 to 10, plotted on a depth scale. **(a)** δ^{18}O ice ‰, this study. **(b)** and **(c)** “Best guess” temperature (black) and accumulation (magenta) scenarios, used for reconstruction **(d3)**. **(d0)** Measured δ^{15}N data. **(d1)** to **(d3)** Modeled δ^{15}N with the following scenarios: **(d1)**, DJ accumulation 100 %, temperature scenario **(b)** systematically increased by 3.5 C; **(d2)** DJ accumulation 100 % and temperature scenario **(b)**; **(d3)** “best guess” scenario, DJ accumulation reduced by 34 % and temperature scenario **(b)**.

Fig. 2: Bottom: Accumulation rate (m.w.e.a^{-1}) vs temperature (C). NEEM (red) and NGRIP (blue), modeled during MIS3. Green dots: measured for different present-day sites. Top: convective zone (m) vs temperature.

Fig. 3: Manuscript, Fig.4: NEEM (red), NGRIP (blue) and GISP2 (green) comparison. **(a)** Water isotopes, ‰ vs VSMOW. NEEM: this study. NGRIP: NGRIP members (2004). GISP2: Grootes et al. (1993). **(b)** Temperature reconstruction, C. **(c)** Accumulation rate reconstruction, m.i.e.a^{-1}.

Fig. 4: Fig. 2 from EPICA community members (2006). Methane synchronization of the EDML and the NGRIP records reveals a one-to one assignment of each Antarctic warming with a corresponding stadial in Greenland.

Fig. 5: Fig 1. from Capron et al. (2010).

Fig. 6: Fig 4. and corresponding legend from Veres et al. (2012). Water isotopic records of NGRIP (top), EDML (middle), and EDC (bottom), respectively, over GI-5 to 12 on the LD2010 time scale in pink, versus the new AICC2012 chronology using additional constraints (this study) in blue. For comparison on the timing of events, the black vertical lines mark the major GS/GI transitions in the NGRIP record.

References

Ahn, J., Brook, E., Schmittner, A., and Kreutz, K.: Abrupt change in atmospheric CO_2 during the last ice age, Geophys. Res. Lett., 39, L18 711, 2012.

Andersen, K. K., Svensson, A., Johnsen, S. J., Rasmussen, S. O., Bigler, M., Röthlisberger, R., Ruth, U., Siggaard-Andersen, M.-L., Steffensen, J. P., Dahl-Jensen, D., Vinther, B. M., and Clausen, H. B.: The Greenland Ice Core Chronology 2005, 15–42 ka. Part 1: constructing the time scale, Quaternary Sci. Rev., 25, 3246–3257, doi:10.1016/j.quascirev.2006.08.002, 2006.

Bender, M., Sowers, T., Barnola, J.-M., and Chappellaz, J.: Changes in the O_2/N_2 ratio of the atmosphere during recent decades reflected in the composition of air in the firn at Vostok Station, Antarctica, Geophys. Res. Lett., 21, 189 – 192, 1994.

Bereiter, B., Lüthi, D., Siegrist, M., Schüpbach, S., Stocker, T. F., and Fischer, H.: Mode change of millennial CO2 variability during the last glacial cycle associated with a bipolar marine carbon seesaw, Proceedings of the National Academy of Sciences of the United States of America, 109, 9755 – 9760, 2012.

Blunier, T. and Brook, E. J.: Timing of Millennial-Scale Climate Change in Antarctica and Greenland During the Last Glacial Period, Science, 291, 109–112, doi:10.1126/science.291.5501.109, 2001.

Bond, G., Broecher, W., Johnsen, S. J., MacManus, J., Laberie, L., Jouzel, J., and Bonani, G.: Correlations between climate records from North Atlantic sediments and Greenland ice, Nature, 365, 143–147, 1993.

Bromwich, D., Toracinta, E. R., Wei, H., Oglesby, R. J., Fastook, J., and Hughes, T.: Polar MM5 simulations of the winter climate of the Laurentide ice sheet at the LGM, J. Climate, 17, 3415 – 3433, 2004.

Buchardt, S., Clausen, H. B., Vinther, B. M., and Dahl-Jensen, D.: Investigating the past and recent δ^{18}O-accumulation relationship seen in Greenland ice cores, Clim. Past, 8, 2053 – 2059, 2012.

Buchardt, S. L.: Basal melting and Eemian ice along the main ice ridge in northern Greenland, Ph.D. thesis, Niels Bohr Institute, Faculty of Science, University of Copenhagen, 2009.

Buiron, D., Stenni, B., Chappellaz, J., Landais, A., Baumgartner, M., Bonazza, M., Capron, E., Frezzotti, M., Kageyama, M., Lemieux-Dudon, B., Masson-Delmotte, V., Parrenin, F., Schilt, A., Selmo, E., Severi, M., Swingedouw, D., and Udisti, R.: Regional imprints of millennial variability during the MIS 3 period around Antarctica, Quaternary Science Reviews, 48, 99 – 112, 2012.

Capron, E., Landais, A., Chappellaz, J., Schilt, A., Buiron, D., Dahl-Jensen, D., Johnsen, S. J., Jouzel, J., Lemieux-Dudon, B., Loulergue, L., Leuenberger, M., Masson-Delmotte, V., Meyer, H., Oerter, H., and Stenni, B.: Millennial and sub-millennial scale climatic variations recorded in polar ice cores over the last glacial period, Clim. Past, 6, 345–365, doi: 10.5194/cp-6-345-2010, 2010.

Ciais, P. and Jouzel, J.: Deuterium and oxygen 18 in precipitation: isotopic model, including mixed cloud processes, J. Geophys. Res., 99, 16 793 – 16 803, 1994.

Cuffey, K. M. and Clow, G. D.: Temperature, accumulation, and ice sheet elevation in central Greenland through the last deglacial transition, J. Geophys. Res., 102, 26 383–26 396, 1997.

Cuffey, K. M. and Paterson, W. S. B.: The physics of glaciers, Elsevier, forth edn., 2010.

Cutler, N., Raymond, C., Waddington, E., Meese, D., and Alley, R.: The effect of ice-sheet thickness change on the accumulation history inferred from GISP2 layer thickness, Annals of Glaciology, 21, 26 – 32, 1995.

Elliot, M., Labeyrie, L., Dokken, T., and Manthé, S.: Coherent patterns of ice rafted debris deposits in the Nordic regions during the last glacial, Earth Planet. Sc. Lett., 194, 151–163, 2001.

Elliot, M., Labeyrie, L., and Duplessy, J.-C.: Changes in North Atlantic deep-water formation associated with the Dansgaard–Oeschger temperature oscillations (60–10 ka), Quaternary Sci. Rev., 21, 1153–1165, 2002.

EPICA community members: One-to-one coupling of glacial climate variability in Greenland and Antarctica, Nature, 444, 195–198, doi:10.1038/nature05301, 2006.

Funder, S.: Quaternary geology of ice-free areas and adjacent shelves of Greenland, vol. 1, Geologycal survey of Canada, Ottawa, Ontario, 1989.

Funder, S. and Larsen, H.: Quaternary geology of the shelves adjacent to Greenland, vol. 1, 1989.

Grootes, P. M., Stuiver, M., White, J. W. C., Johnsen, S. J., and Jouzel, J.: Comparison of oxygen isotope records from the GISP2 and GRIP Greenland ice cores, Nature, 366, 552–554, doi:10.1038/366552a0, 1993.

Heinrich, H.: Origin and consequences of cyclic ice rafting in the Northeast Atlantic Ocean during the past 130,000 years, Quaternary Res., 29, 142 – 152, doi:10.1016/0033-5894(88)90057-9, 1988.

Hörhold, M., Laepple, T., Freitag, J., Bigler, M., Fischer, H., and Kipfstuhl, S.: On the impact of impurities on the densification of polar firn, Earth Planet. Sc. Lett., 325–326, 93–99, doi: 10.1016/j.epsl.2011.12.022, 2012.

Huber, C., Leuenberger, M., Spahni, R., Flückiger, J., Schwander, J., Stocker, T. F., Johnsen, S. J., Landais, A., and Jouzel, J.: Isotope calibrated Greenland temperature record over Marine Isotope Stage 3 and its relation to CH_4, Earth Planet. Sc. Lett., 243, 504–519, 2006.

Indermühle, A., Monnin, E., Stauffer, B., Stocker, T., and Wahlen, M.: Atmospheric CO_2 concentration from 60 to 20 kyr BP from the Taylor Dome ice core, Antarctica, Geophys. Res. Lett., 27, 735–738, 2000.

Johnsen, S. J., Dansgaard, W., and White, J. W. C.: The origin of Arctic precipitation under present and glacial climate, Tellus, 41B, 452–468, 1989.

Johnsen, S. J., Clausen, H. B., Dansgaard, W., Fuhrer, K., Gundestrup, N., Hammer, C. U., Iversen, P., Jouzel, J., Stauffer, B., and Steffensen, J. P.: Irregular glacial interstadials recorded in a new Greenland ice core, Nature, 359, 311–313, doi:doi:10.1038/359311a0, 1992.

Kawamura, K., Severinghaus, J. P., Ishidoya, S., Sugawara, S., Hashida, G., Motoyama, H., Fujii, Y., Aoki, S., and Nakazawa, T.: Convective mixing of air in firn at four polar sites, Earth Planet. Sci. Lett., 244, 672 – 682, 2006.

Kissel, C., Laj, C., Piotrowski, A., Goldstein, S., and Hemming, S.: Millennial-scale propagation of Atlantic deep waters to the glacial Southern Ocean, Paleoceanography, 23, PA2102, 2008.

Landais, A., Masson-Delmotte, V., Jouzel, J., Raynaud, D., Johnsen, S. J., Huber, C., Leuenberger, M., Schwander, J., and Minster, B.: The glacial inception as recorded in the NorthGRIP Greenland ice core: timing, structure and associated abrupt temperature changes, Clim. Dynam., 26, 273–284, doi:10.1007/s00382-005-0063-y, 2005.

Landais, A., Barnola, J., Kawamura, K., Caillon, N., Delmotte, M., Ommen, T. V., Dreyfus, G., Jouzel, J., Masson-Delmotte, V., Minster, B., Freitag, J., Leuenberger, M., Schwander, J., Huber, C., Etheridge, D., and Morgan, V.: Firn-air δ^{15}N in modern polar sites and glacial–interglacial ice: a model-data mismatch during glacial periods in Antarctica?, Quaternary Sci. Rev., 25, 49 – 62, doi:10.1016/j.quascirev.2005.06.007, 2006.

Li, C., Battisti, D., and Bitz, C.: Can North Atlantic sea ice anomalies account for Dansgaard–Oeschger climate signals?, J. Climate, 23, 5457 – 5475, 2010.

Liu, Z., Otto-Bliesner, B. L., He, F., Brady, E. C., Tomas, R., Clark, P. U., Carlson, A. E., Lynch-Stieglitz, J., Curry, W., Brook, E., Erickson, D., Jacob, R., Kutzbach, J., and Cheng, J.: Transient Simulation of Last Deglaciation with a New Mechanism for Bølling-Allerød Warming, Science, 235, 310–314, doi:10.1126/science.1171041, 2009.

Marshall, S. J. and Koutnik, M. R.: Ice sheet action versus reaction: distinguishing between Heinrich events and Dansgaard-Oeschger cycles in the North Atlantic, Paleoceanography, 21, PA2021, 2006.

McManus, J. F., Bond, G. C., Broecker, W. S., Johnsen, S., Labeyrie, L., and Higgins, S.: High resolution climate records from the North Atlantic during the last interglacial, Nature, 371, 326–329, 1994.

Meese, D. A., Gow, A. J., Grootes, P., Stuiver, M., Mayewski, P. A., Zielinski, G. A., Ram, M., Taylor, K. C., and Waddington, E. D.: The accumulation record from the GISP2 core as an indicator of climate change throughout the Holocene, Science, 266, 1680–1682, doi: 10.1126/science.266.5191.1680, 1994.

Meese, D. A., Gow, A. J., Alley, R. B., Zielinski, G. A., Grootes, P. M., Ram, M., Taylor, K. C., Mayewski, P. A., and Bolzan, J. F.: The Greenland Ice Sheet Project 2 depth-age scale: methods and results, J. Geophys. Res., 102, 26 411 – 26 423, 1997.

Merlivat, L. and Jouzel, J.: Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation, J. Geophys. Res., 84, 5029 – 5033, 1979.

NGRIP members: High-resolution record of Northern Hemisphere climate extending into the last interglacial period, Nature, 10.1038/nature02805, doi:10.1038/nature02805, 2004.

Orsi, A., Cornuelle, B., and Severinghaus, J.: Magnitude and temporal evolution of interstadial 8 abrupt temperature change inferred from nitrogen and argon isotopes in GISP2 ice using a new least-squares inversion, in prep.

Petit, J., White, J., Young, N., Jouzel, J., and Y.S.Korotkevich: Deuterium excess in recent Antarctic snow, J. Geophys. Res., 96, 5113 – 5122, 1991.

Rasmussen, S. O., Andersen, K. K., Svensson, A. M., Steffensen, J. P., Vinther, B. M., Clausen, H. B., Siggaard-Andersen, M.-L., Johnsen, S. J., Larsen, L. B., Dahl-Jensen, D., Bigler, M., Röthlisberger, R., Fischer, H., Goto-Azuma, K., Hansson, M. E., and Ruth, U.: A new Greenland ice core chronology for the last glacial termination, J. Geophys. Res., 111, doi: 10.1029/2005JD006079, 2006.

Rasmussen, S. O., Seierstad, I., Andersen, K., Bigler, M., Dahl-Jensen, D., and Johnsen, S.: Synchronization of the NGRIP, GRIP, and GISP2 ice cores across MIS 2 and palaeoclimatic implications, Quaternary Sci. Rev., 27, 18 – 28, 2008.

Rasmussen, T. L. and Thomsen, E.: The role of the North Atlantic Drift in the millennial timescale glacial climate fluctuations, Palaeogeogr. Palaeocl., 210, 101–116, 2004.

Raynaud, D., Chappellaz, J., Ritz, C., and Martinerie, P.: Air content along the Greenland Ice

Core Project core: A record of surface climatic parameters and elevation in central Greenland, J. Geophys. Res., 102, 26 607 – 26 613, 1997.

Roche, D., Wiersma, A., and Renssen, H.: A systematic study of the impact of freshwater pulses with respect to different geographical locations, Climate Dyn., 34, 997 – 1013, 2010.

Ruth, U., Bigler, M., Röthlisberger, R., Siggaard-Andersen, M.-L., Kipfstuhl, S., Goto-Azuma, K., Hansson, M. E., Johnsen, S. J., Lu, H., and Steffensen, J. P.: Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate, Geophys. Res. Lett., 34, L03 706, doi:10.1029/2006GL027876, 2007.

Severinghaus, J., Albert, M. R., Courville, Z. R., Fahnestock, M. A., Kawamura, K., Montzka, S. A., Mühle, J., Scambos, T. A., Shields, E., Shuman, C. A., Suwa, M., Tans, P., and Weiss, R. F.: Deep air convection in the firn at a zero-accumulation site, central Antarctica, Earth Planet. Sc. Lett., 293, 359 – 357, 2010.

Shuman, C., Alley, R., Anandakrishnan, S., White, J., Grootes, P., and Stearns, C.: Temperature and accumulation at the Greenland Summit: comparison of high-resolution isotope profiles and satellite passive microwave brightness temperature trends, J. Geophys. Res., 100, 9165 – 9177, 1995.

Shuman, C., Bromwich, D., Kipfstuhl, J., and Schwager, M.: Multiyear accumulation and temperature history near the North Greenland Ice Core Project site, north central Greenland, J. Geophys. Res., 106, 33 853 – 33 856, 2001.

Steffensen, J. P., Andersen, K. K., Bigler, M., Clausen, H. B., Dahl-Jensen, D., Fischer, H., Goto-Azuma, K., Hansson, M., Johnsen, S. J., Jouzel, J., Masson-Delmotte, V., Popp, T., Rasmussen, S. O., Röthlisberger, R., Ruth, U., Stauffer, B., Siggaard-Andersen, M.-L., Sveinbjörnsdóttir, A. E., Svensson, A., and White, J. W. C.: High-Resolution Greenland Ice Core Data Show Abrupt Climate Change Happens in Few Years, Science, 321, 680–684, 2008.

Stocker, T. F. and Johnsen, S. J.: A minimum thermodynamic model for the bipolar seesaw, Paleoceanography, 18, 1087, doi:10.1029/2003PA000920, 2003.

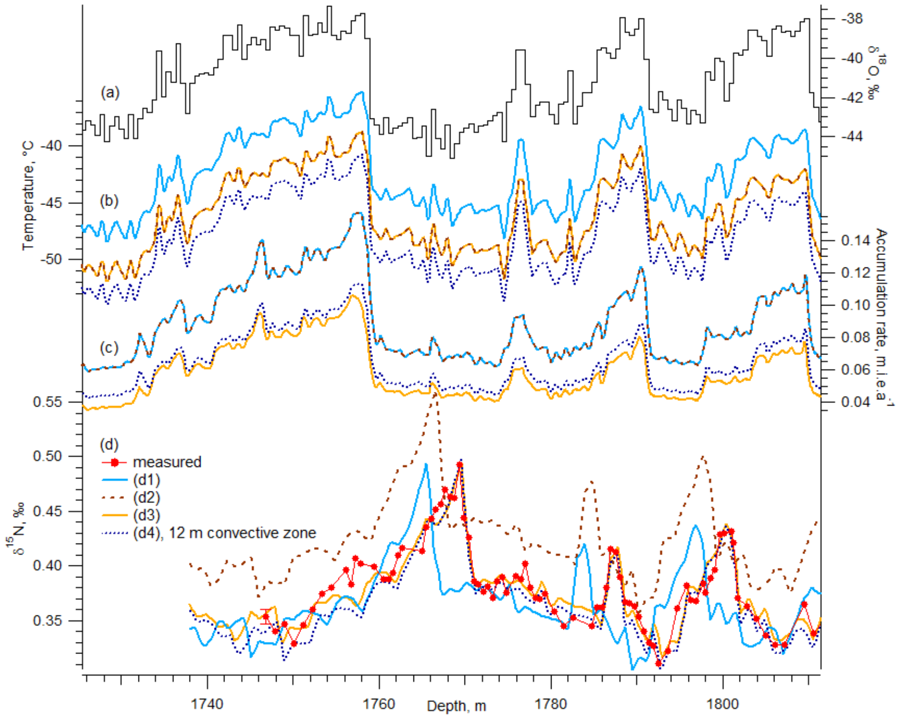
Svensson, A., Biscaye, P. E., and Grousset, F. E.: Characterization of late glacial continental dust in the Greenland Ice Core Project ice core, J. Geophys. Res., 105, 4637 – 4656, 2000.

Thomas, E. R., Wolff, E. W., Mulvaney, R., Johnsen, S. J., Steffensen, J. P., and Arrowsmith, C.: Anatomy of a Dansgaard-Oeschger warming transition: High-resolution analysis of the North Greenland Ice Core Project ice core, J. Geophys. Res., 114, doi:10.1029/2008JD011215, 2008.

Veres, D., Bazin, L., Landais, A., Kele, H. T. M., Lemieux-Dudon, B., Parrenin, F., Martinerie, P., Blayo, E., Blunier, T., Capron, E., Chappellaz, J., Rasmussen, S. O., Severi, M., Svensson, A., Vinther, B., , and Wolff, E. W.: The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years, Clim. Past Discuss., 8, 6011 – 6049, 2012.

Vinther, B. M., Buchardt, S. L., Clausen, H. B., Dahl-Jensen, D., Johnsen, S. J., Fisher, D. A., Koerner, R. M., Raynaud, D., Lipenkov, V., Andersen, K. K., Blunier, T., Rasmussen, S. O., Steffensen, J. P., and Svensson, A. M.: Holocene thinning of the Greenland ice sheet, Nature, 461, 385–388, doi:10.1038/nature08355, 2009.

Interactive comment on Clim. Past Discuss., 8, 5209, 2012.



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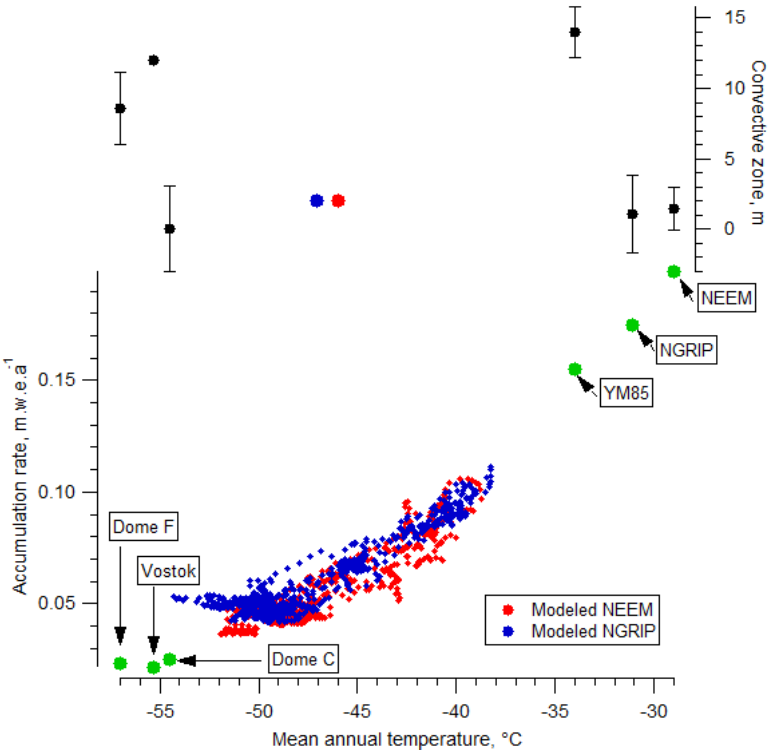

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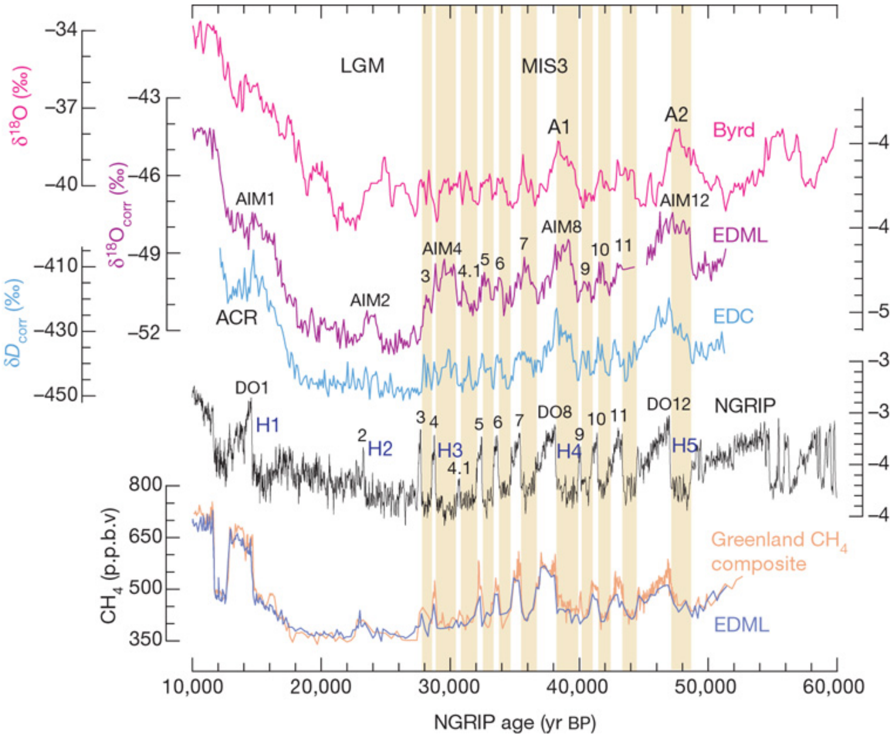

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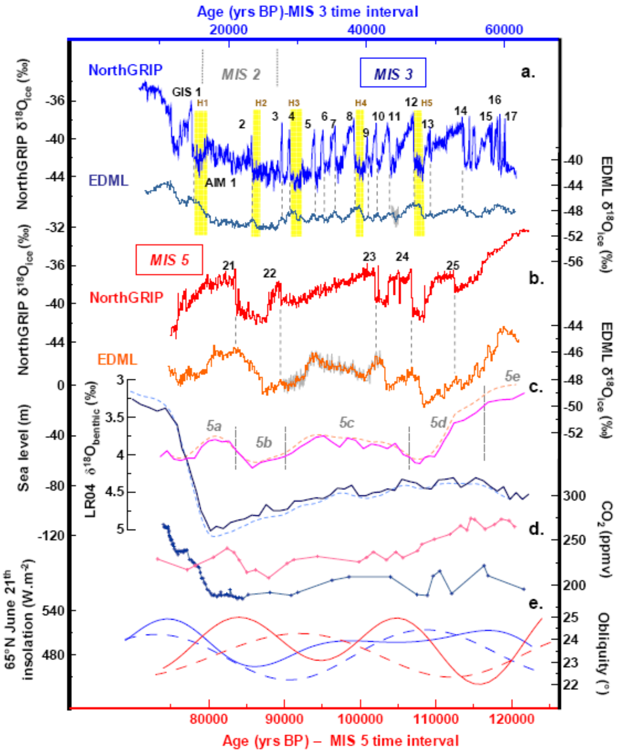

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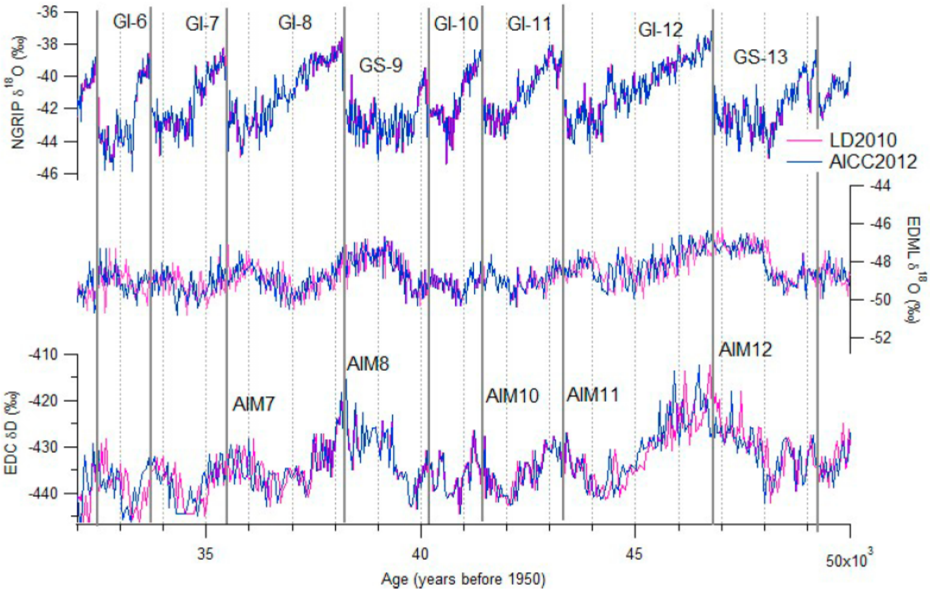

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