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Climate of the Past Discussions

Interactive comment on "Millennial and sub-millennial scale climatic variations recorded in polar ice cores over the last glacial period" *by* E. Capron et al.

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This paper presents some new data and insights into millennial and sub-millennial scale climate variations. The authors present an interesting analysis and discussion of the occurrence of precursor and rebound events associated with the well-known interstadial events of the last interglacial-glacial period (although I am not completely convinced by their discussion of an insolation control on the occurrence of these events given that the posited relationships do not seem consistent – see below). Their analysis of temperature change amplitudes between north and south in the context of the bipolar seesaw is very interesting and highlights extreme glacial conditions as distinct from intermediate states (this section needs more discussion in the text). The paper is well written and generally clearly presented. In general I would like to see more contextual discussion of climate records from other archives, particularly from the marine environment. There is also some ambiguity (understandably) as there is a mixture of discussion about sub-millennial variability (precursors and rebounds) and D-O type variability itself (assuming that the two variants are actually distinct, which I feel is unlikely).

I have outlined my comments in order of their relevance:

-Abstract line 9: The authors refer to the abrupt changes within MIS 5 as D-O events. It strikes me that the term D-O event might better be reserved for those quasi-periodic and more frequent oscillations observed during MIS 3. This does not mean that the terms stadial and interstadial should not be used for events within MIS 5 but then we should be clear that the occurrence of stadials and interstadials does not define the background state (glacial or interglacial). This comment should be discussed more generally by those with interests in this field.

»We referred as DO events as it is classically as those abrupt climatic variations are defined in the literature back to the beginning of the last glacial period (e.g. NorthGRIP c. m., 2004). But we agree with the reviewer that in term of structure, MIS5 DO events are very different from the classical idea of what is a DO event as depicted over MIS3. We replace in the text "DO events" by the use of "stadial" and "interstadial" and we also change the sentence in the abstract:

The results display a succession of abrupt events associated with long Greenland Inter-Stadial phases (GIS) enabling us to highlight a sub-millennial scale climatic variability depicted by (i) short-lived and abrupt warming events preceding some GIS (precursor-type events) and (ii) abrupt warming events at the end of some GIS (rebound-type events).

»We made clearer in the introduction the definition of Greenland Interstadial and

Greenland Stadials:

GISP2 and GRIP δ18Oice records highlight millennial scale variability related to the succession of interstadials (defined as the warm phases of the millennial scale variability; hereafter noted GIS for Greenland InterStadial) and stadials (defined as the cold phase of the millennial scale variability; hereafter noted GS for Greenland Stadial; Dansgaard et al., 1993).

-It is not clear what new measurements this paper represents. In table 2 it states that d15N measurements for DO 21 and 22 are new yet from the text and Fig 3 it suggests that that d15N for DO 21 was published by Capron et al., 2010.

» We agree that the description of the new measurements was not precise enough in our initial manuscript. To make it clearer: δ15N measurements over GIS21 were published in Capron et al. (2010) but no temperature variation calculations were made at that time since it was only used to help synchronizing NorthGRIP and EDML through tie points defined between d15N and CH4 at the onset of GIS 21. In the present paper, we publish new measurements of δ15N over GIS22. But for both GIS21 and GIS22, the temperature variation estimates are new and done for the purpose of the present paper.

We have changed the sentence in the text to try to make it clearer :

In the present paper, we complete the quantification of MIS 5 abrupt warming events based on published δ15N measurements (Capron et al., 2010) with new δ40Ar data for the onset of GIS 21 and new δ15N measurements over GIS 22 (Figure 3). Following the approach of Landais et al. (2004a), we obtain that the GIS 21 onset is marked by a warming of 11 $\pm$ 2.5 °C while new high resolution gas measurements over GIS 22 reveal a weak δ15N variation (0.063 ‰ corresponding to a maximum warming amplitude of 5 °C (Figure 3).

We have modified the legend of Table 2 as well as follow:

[c] Huber et al. (2006) and Landais et al. (2006) provide a quantification of abrupt temperature change through air isotopes measurements of most of the rapid events over the last glacial period and our study provides new results of temperature estimates at the onset of GIS 21 and GIS 22.

-P139 line 28: MIS 5 includes MIS 5e, which was of course an interglacial period, not part of the glacial inception. The authors should be careful with their use of these terms.

» Our sentence was indeed not correct so we rephrase it as the following:

MIS 5 (∼73.5-130 ka; Shackleton, 1987) includes the last glacial inception and the early glacial which are a time period of great interest since they represent an intermediate stage between full interglacial conditions (defined as MIS 5e, Shackleton et al., 2003b; Figure 1) and glacial conditions encountered during MIS 2-3.

- P140 para 2: It would be useful to be given some context as to how the timing of GIS within MIS 5 relate to the sub-stages MIS 5a-e (see also next point). For example an oxygen isotope stack could be added to Fig. 1 rather than just the isotope boundaries (this would require careful consideration of relative age scales – e.g. via Shackleton's MD95-2042 records?).

» We agree with the reviewers that a careful consideration of relative age scale has to be done and was missing in the previous version of the manuscript. So, we made some modifications on Figure 1: We have replaced the sea level curve from Waelbroeck et al. (2002) by the reconstructed one of Bintanja et al. (2005) and we have also added the benthic stack LR04 from Lisiecki and Raymo (2005). Note that both the sea level curve and the LR04 stack were transferred on EDC3 timescale by Parrenin et al. (2007) meaning that it is coherent with the EDML1 timescale (Ruth et al., 2007) on which are displayed the NorthGRIP and the EDML isotopic profiles. The timing of GIS within MIS5 relate to the sub-stages MIS5a-e is added and discussed now in the legend of Figure 1:

Figure 1. Comparison of some climatic parameters over MIS 3 and MIS 5. a. MIS 3 NorthGRIP δ18Oice (light blue curve, NorthGRIP c. m., 2004) and EDML δ18Oice (dark blue curve, EPICA c. m., 2006; grey curve, this study). b. MIS 5 NorthGRIP δ18Oice (red curve, NorthGRIP c.m., 2004) and EDML δ18Oice (orange curve, EPICA c. m., 2006; grey curve, this study). Note that new δ18Oice measurements on EDML ice core were performed over AIM events 11 and 23 (grey curve) at Alfred Wegener Institute (Germany) with a depth resolution of 0.05 m, using the CO2 (H2)/water equilibration technique (Meyer et al., 2000). c. MIS 3 (dotted light blue curve) and MIS 5 (dotted orange curve) sea level variations (Bintanja et al., 2005) reconstructed from the LR04 δ18Obenthic stack (Lisiecki and Raymo, 2005). Both the sea level curve and the LR04 δ18Obenthic stack are displayed on EDC3 timescale. The timescale synchronisation is done in Parrenin et al. (2007). d. MIS 3 (dark blue curve) and MIS 5 (pink curve) CO2 concentration. CO2 records are from EDC Monnin et al., 2001) and Vostok ice cores (Petit et al., 1999) and compiled by Luethi et al., 2008. e. MIS 3 and MIS 5 orbital contexts: 65°N summer insolation (full line) and obliquity (dotted line) (Laskar et al., 2004). Heinrich Events (H-events) and Greenland InterStadials (GIS) are indicated on the NorthGRIP record. Dotted grey lines show the one to one coupling observed between AIM and DO events. Marine Isotopic Sub-stages are indicated on the LR04 δ18Obenthic stack. This highlights the close link between the long-term variations of ice sheet volume and the millennial scale variability since the onsets of GIS 24, 22 and 21 correspond to the transition from Marine Isotopic Sub-stages 5d to 5c, 5c to 5b and 5b to 5a respectively.

-P142 line 21: The authors state that their timescale can be compared with independent chronologies from other paleoclimatic archives – I think it would be very useful for them to show such a comparison here. Furthermore it would be very useful if they would include more discussion on how these records compare in terms of their implications for climate reconstruction.

» Actually, such a comparison was already displayed in the old version of the manuscript in Table 1. This was perhaps not clear. We have thus rephrased this paragraph to make it more obvious and to highlight such a comparison. Table 1 provides a comparison of DO duration inferred from the EDML-NorthGRIP timescale with their duration on other timescales. From this comparison we were able to give an uncertainty on each event duration. We think that the Table is sufficient since a figure would highlight different details during GIS and GS between different archives (due to regional or proxy specificities) that we do not want to discuss here.

We compare this new timescale with independent chronologies from other paleoclimatic archives (Table 1) and this enables us to derive uncertainties associated with the duration of each GIS/GS succession over MIS 5. In the North Atlantic region, marine cores show rapid cooling events (C events) (McManus et al., 1994) that were associated with the GS (i.e. event C 24 is associated with GS 25, McManus et al., 1994; NorthGRIP c.m., 2004; Rousseau et al., 2006). Using such associations, NorthGRIP DO event duration is compared to the one deduced from two marine sediment cores: (i) MD95-2042, providing an age scale with two absolute age markers derived from the Hulu cave between 115 and 81 kyrs (Shackleton et al., 2003; Wang et al., 2001) and (ii) NEAP18K, whose age model was constructed by correlation of the benthic δ18O records with an orbitally tuned δ18O stratigraphy (Shackleton and Pisias, 1985). Then, the same exercise is carried out by comparing our age-scale with the chronology from a lacustrine sediment core from Lago grande di Monticchio (Brauer et al., 2007) whose chronology is based on lamination counting. Finally, assuming synchronous climatic shifts at low and high latitudes enables us to compare rapid event succession recorded in ice cores through independent dating from speleothem records (i.e. Wang et al., 2001, 2008). Such a comparison is difficult because few speleothem records display a clear sequence of rapid events over MIS 5 except the record from Sanbao cave on which we can identify the onset of each GIS event (Wang et al., 2008). Uncertainties on DO event durations (i.e. duration of GIS plus GS) obtained from the comparison of the five records are summarized in Table 1. In the following we limit our study to DO events 24, 23, 22, and 21 since the EDML-NorthGRIP synchronisation lacks of robust chronological constraints around DO event 25 (Capron et al., 2010). The uncertainties associated with the durations of DO events 24, 23, 22 and 21 represent less than 13 % of the duration of each DO event. This general agreement makes the possibility of a large (greater than 1.3 kyrs) error in interstadial duration unlikely and provides firm basis to confidently analyse the interstadial structure and pacing of these events over MIS 5.

-Section 3.1: Here the authors describe the 'singular case' of GIS 24 but it seems to me that GIS 24 is only unique if one considers it as a single event. For example, GIS 15-17 within MIS 3 include between 6 to 8 individual warming events depending on what one counts as a distinct warming event.

» We agree and that is why, taking into account also the comment done about the paragraph p152 and especially line 16, we reorganize the presentation of the sub-millennial scale climatic events as follows: 1) precursor-type peak event 2) rebound-type event 3) a focus on GIS 24 instead of what was done in the CPD submitted version where it was 1) The particular case of GIS24, 2) precursor-type peak event 3) rebound-type event. It enables us to discuss GIS24 not only as a single event but to link it with GIS23 and GIS22 to compare this sequence of event with the GIS15-17 sequence of event, and also to include GIS 24 in the discussion about the links between strong 65°N insolation and sub-millennial scale variability. However, we really think that GIS 24 is singular since the first cooling occurs after a relatively long warm phase which is different to what is observed in the structure of sequence 15-17 or precursor-events.

Here are the modifications done in the text:

3.3. Abrupt coolings during GIS 24 GIS 24 presents a square wave structure beginning with an abrupt temperature warming of 16 °C (Landais et al., 2006) and ending 3.2 kyrs later by a sudden return to stadial conditions (Figure 6). The warm phase is punctuated by rapid cold events i.e. the slow δ18Oice decrease is interrupted by a first drop of δ18Oice by 3 ‰ lasting 200 yrs before a return to interstadial δ18Oice level. A second cooling phase occurs 500 yrs later with a 2.5 ‰δ18Oice decrease. Finally, a stable phase is observed with a duration of 500 yrs followed by the final return to stadial conditions in less than 200 yrs. The abrupt changes in δ18Oice are due to changes in surface temperature as confirmed by the associated two 0.04 ‰ drops in δ15N coincident with δ18Oice abrupt variations (Figure 4). The first rapid cooling over GIS 24 appears to be accompanied by low latitudes counterparts as documented by a simultaneous drop in CH4 concentration over 150-200 yrs. In addition, sub-millennial scale variations in δ18O of O2 have been identified during GIS 24 (Capron et al., 2010) reflecting significant changes of biosphere and hydrological cycles at these short timescales (Landais et al., 2010). The very rapid climatic variability observed during the sequence GIS 23-24 with rapid events occurring in addition to the classical succession of GIS and GS, shares some similarities with the sequence of GIS/GS 15-17 that include 6 to 8 individual warming events depending on what one counts as a distinct warming event (Figure 2). The particularity of GIS 24 is that the first short cold spell occurs only $\sim$1380 years after the beginning of the GIS. The general picture of sub-millennial variability for this period is thus the one of a cold event is interrupting a long warm phase (GIS). By contrast, the later sub-millennial variability is better described in terms of brief warm events (GIS or precursor events) interrupting a long glacial phase (GS). With this view of a sharp cold spell interrupting a rather long warm phase, the sub-millennial variability of GIS 24 can only be compared with the 8.2 ka-event that occurred at the beginning of the Holocene (Alley et al., 1997; Leuenberger et al., 1999; Kobashi et al., 2007, Thomas et al., 2007). These two cold events occur during two different periods of transition (glacial inception for the cold events of GIS 24, end of deglaciation for the 8.2 ka-event), but both at a time when ice sheets are relatively small. The AMOC during transitional periods is expected to be subject to rapid instabilities leading to sub-millennial variability because of strong modifications of the freshwater input linked to (i) freshwater discharge (von Grafenstein et al., 1998; Clarke et al., 2004) and/or (ii) enhanced precipitation (Khodri et al., 2001) and favoured by small ice sheets (Eisenman et al., 2009).

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»Consequently, we change the order of previously Figure 5 and Figure 6 and made modifications on the figure noted figure 5 now: we add GIS24 to the sequence of events 22-23.

-Section 4.1: The authors need to make clear what they are discussing here i.e. an explanation for the transitions between stadial and interstadial state per se or 'just' the occurrence of precursor (and rebound) events).

» Our purpose is mainly to discuss what could promote the additional variability (leading to sub-millennial scale variability) highlighted in the NorthGRIP isotopic profile in addition to the classical succession of GIS and GS phase. We thus clarified this point in the new version at the beginning of the discussion:

Inspired by the factors previously proposed for explaining the classical DO variability, we present here some of the possible mechanisms for favouring these additional sub-millennial scale features: (i) ice sheet size controlling iceberg discharges (MacAyeal, 1993) and the North Atlantic hydrological cycle (Eisenman et al, 2009), (ii) 65°N insolation affecting temperature, seasonality, hydrological cycle and ice sheet growth in the high latitudes (e.g. Gallée et al., 1992; Crucifix and Loutre, 2002; Khodri et al., 2003; Flückiger et al., 2004). Note that these influences may also be enhanced through feedbacks. In particular, sea ice extent variations are often given as trigger (Wang and Mysak, 2006) or amplifiers (Li et al., 2005) of abrupt warming events.

-P151 line 6: Can a 'rapid' event have a warm 'phase'? Use of the term rapid here implies that the event is short-lived.

»We have modified the sentence in the text

The detailed analysis of the long GIS of MIS 5 provides evidence for sub-millennial scale variations during these phases.

-P152 line 1: Do the authors mean 'more probable' or 'easier to test' (they do not reject the CO_2 control hypothesis based on mechanism but rather lack of data)?

» A lack of data unable us to discuss in detail the role of the CO2 on millennial and sub millennial scale variability observed. To make the discussion clearer, as also asked by the second reviewer, we have decided to remove the discussion on the CO2 control hypothesis.

P152 line 10: The authors have mentioned the occurrence of similar events during MIS 3 when ice sheets were larger than MIS 5. Can they define what that mean by large and small ice sheets?

»This hypothesis is mainly based on the observation that a main difference between MIS 5 and MIS 3 is the average size of the ice-sheets. It is however clear that some parts of MIS 5 (e.g. 5d) may be associated with ice sheet size similar to the one observed in some part of MIS 3. We can not really be more precise since the possible influence of ice sheets size on the sub-millennial scale variability is not necessary a linear one; it can also be associated with threshold effects or a combination of ice-sheet size with other effect (e.g. orbital configuration).

We made the following modifications in the new version:

We first discuss the link between the occurrence of the sub-millennial variability and the ice sheet volume. The length of the GIS displayed on Figure 6 appears to be related to the mean sea level with the long GIS 23 and 21 being associated with the highest sea level while GIS 11, 12, 14 and 16 are associated with lower sea level during MIS 3 (Figure 1). Such a link between the GIS length and sea level is expected from a simple Binge-Purge mechanism (MacAyeal 1993): largest ice-sheets are expected to be easier to destabilize. However, such a Binge-Purge mechanism is unlikely to explain the existence of sub-millennial scale climatic events during sequences of events 21-24 and 15-17 since they occurs during relative ice sheet volume minima (Bintanja et al., 2005). A more plausible mechanism for these precursor events would be that the smaller ice sheets as observed during MIS 5 (equivalent to sea level of about 20 to 60 m above present sea level; Bintanja et al., 2005) are more vulnerable than large ice sheets observed during MIS 2-3-4 (sea level between 60 and 120 m above present sea level; Bintanja et al., 2005) to local radiative perturbations. If so, a strong 65°N summer insolation would lead to intermittent freshwater outputs and trigger fast changes in the AMOC intensity.

-P152 lines 14-23 and Fig 6: This section is a little confusing as the authors discuss possible controls on the occurrence of precursor events but only concentrate on those events which have a rebound event. So they discuss e.g. GIS 11 and 12 (which don't have precursor events) but many other events also don't have precursors. My query could be rephrased; why should the occurrence or lack of a precursor event only be of interest if the GIS has a rebound event?

» We agree that in the previous version the main focus of the discussion was not really clear so we try to present it in another way in the new version. To summarize, the section aims at finding what could favour the occurrence of sub-millennial scale climatic variability in addition to the classical GS-GIS phase succession. The idea is not to concentrate only on the GIS that have a rebound but to benefit of long enough interstadials to discuss the intra-interstadial variability without the doubt that variations in the δ18Oice are part of the analytical noise as for some short GIS/GS sequence over MIS 3. For this reason, the discussion is mainly based on GIS with rebound-type events.

We propose now a new organisation of the discussion and decide to discuss in a more general view the occurrence of the sub-millennial scale variability instead:

The detailed analysis of the long GIS of MIS 5 provides evidence for sub-millennial scale variations during these phases. During GIS 21 and GIS 23, we depict a specific structure composed of a precursor-type warming event leading the GIS and a "rebound-type" abrupt event before the GIS abruptly ends. Such a structure is recurrent during MIS 3 at shorter timescales and Figure 6 displays a linear relationship between the durations of the "rebound-type event" and of the preceding GIS regular

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cooling. Inspired by the factors previously proposed for explaining the classical DO variability, we present here some of the possible mechanisms for favouring these additional sub-millennial scale features: (i) ice sheet size controlling iceberg discharges (MacAyeal, 1993) and the North Atlantic hydrological cycle (Eisenman et al, 2009), (ii) 65°N insolation affecting temperature, seasonality, hydrological cycle and ice sheet growth in the high latitudes (e.g. Gallée et al., 1992; Crucifix and Loutre, 2002; Khodri et al., 2003; Flückiger et al., 2004). Note that these influences may also be enhanced through feedbacks. In particular, sea ice extent variations are often given as trigger (Wang and Mysak, 2006) or amplifiers (Li et al., 2005) of abrupt warming events. We first discuss the link between the occurrence of the sub-millennial variability and the ice sheet volume. The length of the GIS displayed on Figure 6 appears to be related to the mean sea level with the long GIS 23 and 21 being associated with the highest sea level while GIS 11, 12, 14 and 16 are associated with lower sea level during MIS 3 (Figure 1). Such a link between the GIS length and sea level is expected from a simple Binge-Purge mechanism (MacAyeal 1993): largest ice-sheets are expected to be easier to destabilize. However, such a Binge-Purge mechanism is unlikely to explain the existence of sub-millennial scale climatic events during sequences of events 21-24 and 15-17 since they occurs during relative ice sheet volume minima (Bintanja et al., 2005). A more plausible mechanism for these precursor events would be that the smaller ice sheets as observed during MIS 5 (equivalent to sea level of about 20 to 60 m above present sea level; Bintanja et al., 2005) are more vulnerable than large ice sheets observed during MIS 2-3-4 (sea level between -60 and -120 m; Bintanja et al., 2005) to local radiative perturbations. If so, a strong 65°N summer insolation would lead to intermittent freshwater outputs and trigger fast changes in the AMOC intensity. The influence of the Milankovitch insolation forcing on the sub-millennial variability can also be explored (Figure 5). During MIS 5, the GIS 21 precursor-type event and GIS 24 are both in phase with two relative maxima in summertime insolation at 65°N while the GIS 23 precursor-type event occurs during a relative strong 65°N insolation and lags the preceding insolation maximum only delays by ∼2.5 kyrs (Figure 5). During MIS

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3, we again observe that precursor-type events GIS 14 and 16 are associated with secondary insolation maxima. On the contrary, GIS 11 and 12 are not preceded by a precursor and occur at a time without a marked anomaly in 65°N summer insolation. Our data therefore suggest a link between high 65°N insolation and the presence of a sub-millennial scale climatic variability in addition to the GS-GIS succession. This hypothesis also applies to the last deglaciation. Indeed, centennial-scale variations in the NorthGRIP δ18Oice profile are superimposed to the BØlling-AllerØd warm phase followed by the Younger-Dryas cooling (Björck et al., 1998) while the 65°N insolation during those events is equivalent to the one observed during the sequence of events 15-17. Finally, rebound-type events tend to be associated with long GIS intervals characterized by a slow cooling. We speculate that the rebound at the end of the GIS could be explained by an enhancement of the AMOC. Indeed, a progressive cooling could increase sea ice formation and reduce precipitation amount/runoff, increasing salinity in the North Atlantic region.

-P152 line 16: Following my last point, if we are more generally interested in why only certain GIS events have a 'precursor' event we should include other events such as GIS 24, which starts when insolation is as high as for GIS 23 and yet no precursor is observed. Do the authors have an explanation for this? We could also question the Bølling transition and the end of the YD, which occur when insolation is 'high' but do not have precursor events.

» We now include GIS 24 in the discussion about time periods with strong 65°N insolation and the B-O transition and the end of YD: Instead of trying to find an explanation for the occurrence of precursor-type peak events specifically, we think that it is more relevant to discuss in a more general way the occurrence of such abrupt variability as observed also during GIS24, the sequence of events 15-17 or during the transition between the Bolling and the Younger Dryas. Thus we propose a new organisation of this section:

The influence of the Milankovitch insolation forcing on the sub-millennial variability can also be explored (Figure 5). During MIS 5, the GIS 21 precursor-type event and GIS 24 are both in phase with two relative maxima in summertime insolation at 65°N while the GIS 23 precursor-type event occurs during a relative strong 65°N insolation and lags the preceding insolation maximum only delays by ∼2.5 kyrs (Figure 5). During MIS 3, we again observe that precursor-type events GIS 14 and 16 are associated with secondary insolation maxima. On the contrary, GIS 11 and 12 are not preceded by a precursor and occur at a time without a marked anomaly in 65°N summer insolation. Our data therefore suggest a link between high 65°N insolation and the presence of a sub-millennial scale climatic variability in addition to the GS-GIS succession. This hypothesis also applies to the last deglaciation. Indeed, centennial-scale variations in the NorthGRIP δ18Oice profile are superimposed to the BØlling-AllerØd warm phase followed by the Younger-Dryas cooling (Björck et al., 1998) while the 65°N insolation during those events is equivalent to the one observed during the sequence of events 15-17.

-P153 lines 2-9: The authors describe 6 GIS events as having rebounds yet 3 of these (GIS 11, 12 and 16) do not follow the pattern suggested by the authors (i.e. decreasing insolation leading to rebound event). This does not lend support to their argument. Also, insolation is increasing before the ‘rebound event’ of GIS 23. Can the authors’ mechanism account for this? It is interesting that rebound events tend to be associated with longer GIS intervals. Could a rebound event ‘simply’ be a subsequent GIS event that the preceding event ‘runs into’

» The link with insolation is indeed difficult to strongly support from our data since we miss an absolute timescale and our comparison may be wrong with several kyrs uncertainties. Still, we think that this link with insolation should be explored later especially for the very long GIS of MIS 5 associated with very significant variations in local summer insolation (the precession/local summer insolation variations are clearly muted during MIS 3). In the absence of a robust chronology, we agree that we do not have more convincing arguments and removed this discussion in the present manuscript.

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Finally we propose the following sentences:

Finally, rebound-type events tend to be associated with long GIS intervals characterized by a slow cooling. We speculate that the rebound at the end of the GIS could be explained by an enhancement of the AMOC. Indeed, a progressive cooling could increase sea ice formation and reduce precipitation amount/runoff, increasing salinity in the North Atlantic region.

-P155 line 18 (Fig 7): The observation of a breakdown of the seesaw model for AIM 2 and 18 is very interesting and must ultimately be related to the severe glacial conditions prevalent during these times. This would be a good opportunity for the authors to include some discussion of their records in a wider context e.g. with respect to marine records, which clearly demonstrate the peculiar conditions during MIS 2 and 4.

» In the new version of the paper, we put our results in a wider context discussing of the peculiar conditions during MIS2 and MIS4 as shown as well in marine records or speleothems.

Modifications in the text:

The specific behaviour observed for AIM 2 and AIM 18 is not consistent with the same thermal bipolar seesaw pattern (Figure 8). In fact, AIM 2 and AIM 18 warming periods are shorter than the corresponding northern stadial phases, ∼700 yrs for each instead of GS durations of 4 kyrs and 5 kyrs respectively. This highlights that Antarctic warming does not systematically start with the beginning of a GS. Climate conditions of MIS 2 and MIS 4 were particularly cold as recorded in both marine (Bond et al., 1993; Chapman and Shackleton, 1998; de Abreu et al., 2003) and terrestrial records (e.g. Genty et al., 2003; Genty et al., 2006) and associated with vast ice sheets (Waelbroeck et al., 2002). Numerous studies have already shown that millennial scale climatic variability was reduced during MIS 2 and MIS 4 in relation with ice sheet volume (e.g. McManus et al., 1999; Schulz, 2002 ; Wang and Mysak, 2006; NorthGRIP c. m., 2004; Margari et al., 2010). Our study suggests that the bipolar see-saw was also affected during these cold periods. Several explanations can be proposed for this particular see-saw pattern: A first possibility could be that the expansion of the Antarctic ice sheet and sea-ice during these two particular periods would increase the isolation of Antarctica and therefore decrease the heat received by the continent from the Southern Ocean (Levermann et al., 2007). A second possibility is linked to the AMOC activity. Marine records have revealed that the AMOC structure and dynamic was different over MIS 4 and end of MIS 2 compared to MIS 3 and MIS 5 in both hemispheres (e.g. Gherardi et al., 2009 ; Govin et al., 2009; Guihou, 2009). This particular configuration may have lead to an AMOC not strictly in an "off" mode during the whole GS. The AMOC might have been significantly reduced for the entire cold period in the North during GS 3 and 19 but could have collapsed just a few hundred years before the end of the cold phase.

-Minor comments: P151 line 12: Suggest change to 'Here we present some of the possible mechanisms: : :'

»Done

-P152 line 16: maximum (not maxima).

»Done

-Table 2: GS durations given using GICC05 age scale to 50ka (should be 60ka?)

» GICC05 timescale is available until 60 ka. However, GS durations are given for event 18 and 19 that are older than 60 ka. That's why we use ss09sea timescale (NorthGRIP c. m., 2004). To make it clearer we made the following modifications in the legend of Table 2:

[e] GS durations are given (1) on the GICC05 age scale for GS 2 to GS 12 (Blunier et al., 2007; Svensson et al., 2008), (2) on ss09sea age scale for GS 18 to GS 20 (NorthGRIP c. m., 2004) and (3) on the EDML-NorthGRIP synchronised timescale for GS 21 to GS 24 (Capron et al., 2010). GS duration is defined by the interval between the midpoint of the stepwise temperature change at the start and end of a stadial.

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The errors associated with stadial duration are estimated by using different splines through the data that affect the width of the DO transitions and are linked to visual determination of maxima and minima during transitions. No estimate of GS is given where the beginning of the GS is hard to pinpoint due to the particular structure of events and the corresponding events are labeled with #.

-Figure 2: Axis labels are confusing – better to have consistency between each plot. – Also GIS 21 is labelled GIS 20 andGIS 23 is labelled GIS 21.

» We made some modifications on Figure 2 and we hope that it makes it clearer.

We thank you for your review.

Interactive comment on Clim. Past Discuss., 6, 135, 2010.

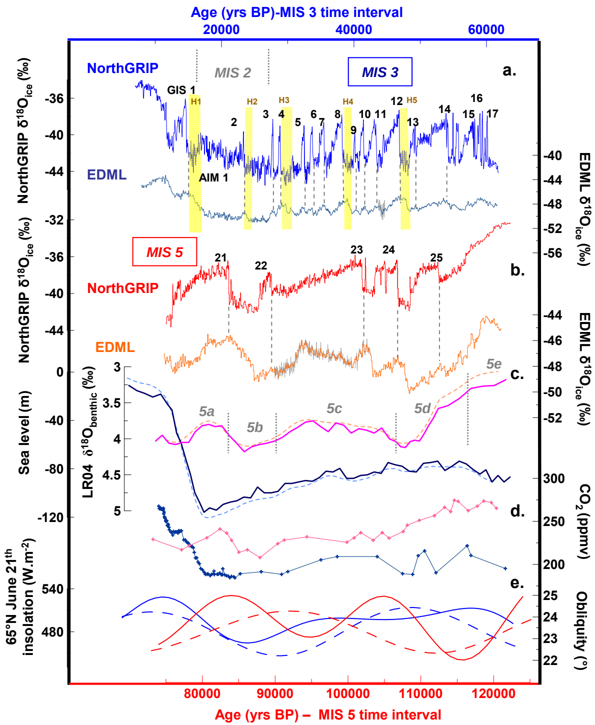

Fig. 1. Figure 1

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Interactive Comment

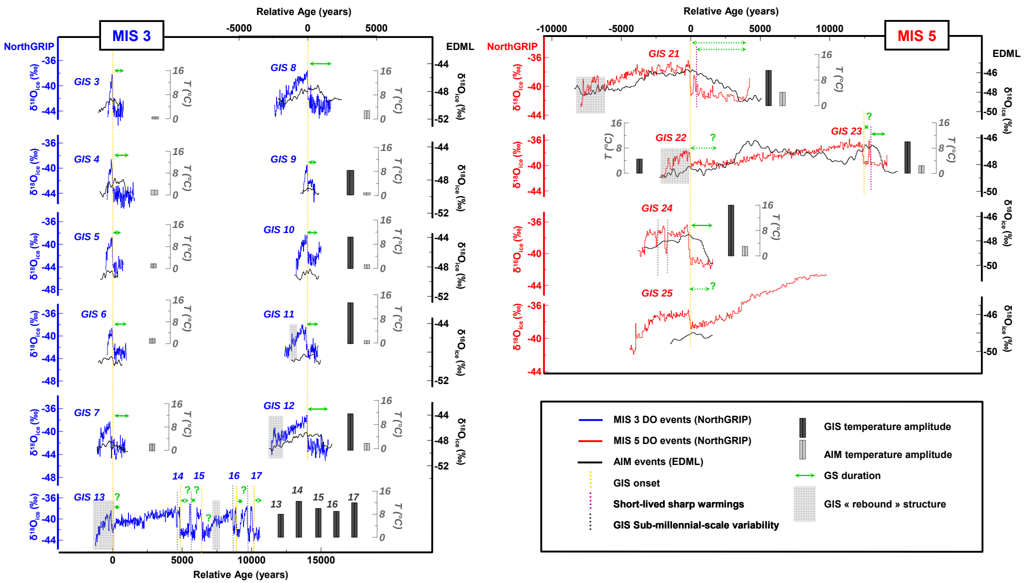

Fig. 2. Figure 2

Full Screen / Esc

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Interactive Discussion

Discussion Paper

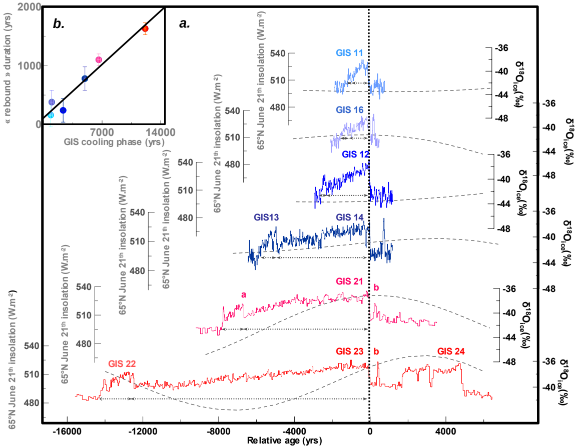

Fig. 3. Figure 5