Comment on cp-2021-103: Abrupt climate changes and the astronomical theory, by
Rousseau, Bagniewski and Ghil

Linda Hinnov

OVERVIEW

Thank you to reviewer 3, Dr. Hinnov, for their comments and suggestions that we are using in the revised version of our manuscript.

The authors carry out recurrence analysis of two paleoclimate proxies from the North Atlantic core U1308, covering the past 3.2 million years. One proxy represents global ice volume and deep ocean temperature, and the other proxy represents ice raft debris deposition. They also analyze the NGRIP water ice $d^{18}O$ record representing temperature at the top of the Greenland ice sheet for the past 110,000 years. The authors identify thresholds in RP topology that coincide with previously inferred paleoclimate transitions.

RECOMMENDATION

The authors attempt to accomplish two things at once: (1) review the history of Cenozoic climate change research,

Not so at all. If we intended to do so, we would have covered much more ground than is covered in the present manuscript.

and (2) newly analyze the past 3.2 million years of climate change with recurrence plots. This does not work very well,

Of course, as we only focused on the past 3.2 Myr and not at all on the entire 66 Myr of the Cenozoic era.

and in my estimation (1) should be abandoned, and (2) should be singularly pursued with its novel and illuminating possibilities.

We beg to differ on Reviewer #3's point (1), as per above, and do not exactly understand what they mean by their point (2).

There are dozens of vaguely relevant facts and factoids

Factoids are not well defined in scientific terminology and sound a bit insulting, which we're sure was not the intent of the reviewer.

mentioned only once and never tied to anything else in the paper, such as the long commentary on the history of the astronomical theory of climate change, and the description of the unused change-point method of one of the co- authors. These could easily be removed from the paper.

What reviewer 3 names "relevant facts and factoids" correspond to the observations we have made after performing the analysis of the U1308 and NGRIP datasets using a method that appears to be rather novel in paleoclimatology, despite several papers published as lead or co-author by N. Marvan. As indicated in our reply to Reviewer #1, although the title of the manuscript is "Abrupt climate changes and the astronomical theory," we didn't intend to submit a complete review paper on the astronomical theory, which is the object of the entire Special Issue to which this paper was submitted. Instead, we just wanted to sketch the evolution of ideas on the specific aspect of abrupt climate changes through a selected subset of papers, while injecting some of our own thinking and recent results. Such a selection cannot be entirely devoid of personal preferences.

The CENOGRID recurrence analysis by Westerhold et al. (2020) provides a convenient starting point, in that the RP topology there is governed by major climate reorganizations. The authors could pick up on that as a lead into their discussion of climate reorganizations and thresholds over 0-3.2 Ma and over the Last Glacial Cycle (0-100,000 years bp).

We thank Reviewer #3 for this remark, since this is exactly what we did. In fact, the CENOGRID recurrence analysis by N. Marvan in Westerhold et al. (2020), does show major climate reorganization, but in Fig. 2B of that paper, the recurrence plot (RP) in the upper right corner corresponding to the last 3.3 Myr doesn't show any particular pattern. This is the reason why we decided to investigate the last 3.3 Ma through the high-resolution core U1308, as well as the NGRIP $\delta^{18}O$ record.

It would be helpful to discuss the meaning of the various patterns in the recurrence plots. For example, in the NGRIP recurrence plot (Figure 4), there is a region with a highly periodic signature, from 30 ka to 60 ka, that does not occur anywhere else. Turning one's head 45º so that the diagonal is in the vertical position has a powerful effect on visualization. It would be interesting to point out this and other features along all three of the analyzed time series.

We are now discussing the RPs according to the analysis of the recurrence rate (RR), following up on the suggestions for clarification of Reviewers #1 and #2. Doing so allows us to robustly distinguish the significant thresholds from the others. In particular, our RR analysis allows us to identify 58.9 ka and 47 ka (b2k) as significant transitions, and discuss 38.3 ka, too.

Finally, much is discussed about modeling DO and Bond cycles, but the recurrence plots have a very limited role in these discussions. It would be helpful to show how these recurrence analyses supplement our knowledge about millennial-astronomical climate change connections.

Thanks to Reviewer #3 for this valuable suggestion that we are using in revising our manuscript.

COMMENTS

The comments below are linked to line numbers. Additional editorial suggestions (blue and red

markings) and comments (yellow sticky notes) are provided in the annotated version of “cp-2021-103-LAH.pdf”.

Abstract

Most the text here is information that is better suited for the Introduction. The results of the present study should be summarized here.

Lines 12-18: Rephrase perhaps as follows: Abrupt climate changes are defined as sudden climate changes that took place in tens to hundreds of years and/or recurred at millennial time scales, involving processes that are thought to be internal to the climate system. By contrast, astronomically forced climate changes involve parameters that are external to the climate system and whose multi-millennial quasi-periodic variations are well known from astronomical theory.

Thanks to Reviewer #3 for this valuable suggestion. We have rephrased these lines accordingly.

Line 26: What is a Bond cycle? This should be defined earlier in the text, prior to the introduction of "amended Bond cycle".

We have removed the word “amended” and the sentence now reads as follows: ” Combining the HE, IRD and DO observations, we study a complex process giving rise to the observed millennial-scale variability that subsumes the abrupt climate changes of the last 0.9 Myr. This process is characterized by the presence of Bond cycles, which group DO events and the associated Greenland stadials into a trend of increased cooling, with IRD events embedded into every stadial, the latest of these being an HE

1 Introduction

The Introduction includes an unexpected and long historical commentary on the astronomical theory of climate change, which can be abbreviated considerably by deleting Lines 49-95 in favor of focusing on the intersection of abrupt and astronomical climate changes.

As we indicated in our replies to the two previous reviewers, we did not mean to provide a complete review of the astronomical theory of climate: such a review is given by other papers in this Special Issue. Instead, we just wanted to sketch the evolution of ideas on the specific aspect of abrupt climate changes through a selected subset of papers, while injecting some of our own thinking and recent results.
We prefer to keep the presentation here as is and have modified the Abstract as suggested by Reviewer #3.

Most of the Abstract as presently written would be relevant here.

Please see the previous relevant replies.

Other topics that could improve the introduction:

• Explain the connection between CENOGRID, U1308 and NGRIP (referring to Fig. 1)

Figures 1a,b,c are discussed in detail in Sec. 2 and in the caption of the figure. We fail to see the point of lengthening the Introduction by bringing the figure into it.

• Comment on the recurrence plots of CENOGRID by Westerhold et al. (2020) as a way to introduce recurrence analysis, and application of the methodology in the work here.

Following Reviewer #2's suggestion and your own later on, we will restructure the paper, if accepted, by including a Materials and Methods section, in which both the datasets and the methods used are described. Doing so clarifies the paper's structure. Concerning the recurrence analysis, we think it better to guide the reader towards the key papers describing the method, namely Eckman et al. (1987) and Marvan et al. (2007, 2013).

• Previous work on astronomically paced ice volume link to millennial scale climate variability.

Lines 39-43: Change to something short like this (with apologies for suggesting some of my publications): Geological data indicate that the Earth has experienced astronomically paced climate changes throughout its history (reviews by Hinnov, 2013, 2018).

We have added these two references after the citations of Berger (1977) and Laskar (2011). Now the sentence reads as follows: "These changes reflect the variations in the Earth's axis of rotation – namely in its precession and tilt — and in the geometry of the Earth's orbit around the sun, i.e., in its eccentricity, driven by gravitational interactions within the solar system (Berger, 1977; Laskar et al., 2011; Hinnov, 2013, 2018)"

2 The Past 3.2 Myr History of the Northern Hemisphere Climate

Lines 115-116: Briefly describe the "new relationship" between the carbon cycle and climate proposed by Turner (2014).

Following Reviewer #3's suggestion, the sentence now reads as follows: " which corresponds to a new relationship between the carbon cycle and climate. Indeed, the negative excursions in $\delta^{13}C$ were associated with negative ones in $\delta^{18}0$ during most of the Cenozoic since 66 Ma. A shift occurred, though, in the Plio-Pleistocene, at about 5 Ma, with negative $\delta^{13}C$ excursions associated with positive $\delta^{18}0$ ones (Turner, 2014). Such a shift appears to be related to a dichotomy in the response of the marine and terrestrial reservoirs of the carbon cycle dynamics to orbital forcings."

Line 118: Include the geographic coordinates of the U1308 site (49.87N, 24.24W) and NGRIP (75.1 N, 42.32 W).

Thank you. The sentence now reads as follows: "… particularly well described in the North

Atlantic core U1308 at (49.87N, 24.24W) (Hodell and Channell, 2016), while the last climate cycle is well represented by the Greenland NGRIP ice core at (75.1N, 42,32W) (NGRIP community, 2004). The U1308 core…".

Lines 120-123: Rephrase, perhaps as follows: …and reflect the benthic marine d^{18}O record stack of 57 marine cores from the world's oceans (Lisiecki and Raymo, 2005).

We have clarified our sentence as follows " The variations in the benthic $\delta^{18}O$ mostly indicate varying periodicities through time that correspond to periodicities in the orbital parameters of Earth's climate (Hodell and Channell, 2016; see suppl. fig. S1), as also pointed out by Lisiecki and Raymo (2005) from the stack oxygen isotope record they produced using 57 marine records from the world's oceans".

Lines 156-158: The statement here is perplexing, when there are hundreds of quantitative studies of Cenozoic paleoclimate proxy records, especially of the past 3 million years, that have been made over the past 50+ years. These lines could be deleted.

We acknowledge that the statement could be confusing and therefore we have removed these lines.

Line 158: At this point a new section should be started entitled, "Materials and Methods" which should continue from Lines 158-181, and add text here about the time series being investigated. It looks like NGRIP is also analyzed (Fig. 4) and should be introduced here.

As mentioned earlier and following the recommendation of Reviewer #2, too, we will restructure the manuscript, if accepted, including such a new "Materials and Methods'" section. Thank you.

Line 182: This should be the start of a section entitled "Results".

Correct. Thank you.

Lines 201-205: The meaning of "sea level variations of about 25-50 m below the present-day" is unclear. Does "below" mean that sea level was below present-day sea level (of 0 m)

Yes, exactly this is what the available dataset used by van de Wal et al. (2011) shows. We consider that it is worth reproducing the figure published in Climate of the Past. However, checking the available dataset, we changed 50 m to 70 m. The sentence now reads as follows: "The interval 2.8 to 1.2 Ma shows glacial–interglacial sea level variations of about 25–70 m below the present-day value."

or that the sea level variations during 2.8-1.2 Ma were 25-50 m smaller in amplitude compared to 1.2 Ma to present? Same confusion for "After 1.25 Ma…etc".

We have added "value" after "present day" and the sentence reads now: "After 1.25 Ma, the

sea level changes decreased to about 70–120 m below the present-day value",

3 Millennial-Scale Variability

Line 220: Is there a reliable reference for the increase of IRD at 1.5 Ma?

We are referring here to our own results and to those published by Hodell and Channell (2016) about the bulk carbonate $\delta^{18}O$.

Lines 229-233: Strong DO cycles found in GISP2 and GRIP ice $d^{18}O$ (also in marine core MD95-2042) over the Last Glacial Cycle occur in a very narrow frequency band centered on 1/(1470 yr) (Hinnov et al., 2002). Schulz (2002) and Rahmstorf (2003) likewise noticed that DO cycles have a persistent 1470 yr period, and that if a DO warming event was missed, one then occurred in the future at a multiple of 1470 yr. So, the phrase "DO cycles of variable duration" needs further explanation/qualification. When/where are there submillennial DO cycles? Or, is this meant to indicate the short events that occur within DO cycles (shown in Fig. 5)?

If one considers the original DO cycles, including the DO interstadials and the associated Greenland stadials, one can notice that these DO cycles don't have the same duration. Computing the duration of these original cycles by using the limits published by Rasmussen et al. (2014), one gets an average of 4045 yr ± 3179 yr. Therefore, it is difficult to trust the persistent 1470-yr period claimed by Schultz (2002) and Rahmstorf (2003).

Lines 253-263: This passage describes ongoing work by Bagniewski et al. on a new method using a Kolmogorov-Smirnov test to identify abrupt transitions ("change points") in time series, available as a short presentation at https://www.essoar.org/pdfjs/10.1002/essoar.10506097.1 However, it is unclear if the test has been used anywhere in this paper. Is it used to identify the transitions shown by the vertical "threshold" lines in Figs. 2, 3 and 4? (Apparently not.) I propose to remove this from the paper.

The new method is in press in Chaos *and was indeed used to determine the major transitions in U1308 and NGRIP. In the marine core, the method proposes objective dates for the marine isotope stratigraphy, which Hodell and Channell (2016) linked to the astronomical parameters. In the NGRIP record, this method allows one to also objectively determine the abrupt transitions as presented by Rasmussen et al. (2014). However, the complementary recurrence analysis allows one to select among these abrupt transitions the ones that are related to important changes in the system, allowing us therefore to associate the astronomical theory of climate and the millennial variability. We will clarify this point in the new "Materials and Methods" section of the revised version. Moreover, we are adding 2 supplementary figures showing the abrupt transitions detected by the new method in both the two U1308 records and the NGRIP δ18O record.*

Lines 264-266: The work of Hinnov et al. (2002) on methane-linked GISP2 and Byrd included statistically constrained spectral coherency analysis to demonstrate the global reach of the DO cycles, as well as what at the time were called the "Antarctic warming" cycles (with a 4.44 kyr

period), each with interesting lead-lag relationships.

We are adding the reviewer's reference. "Moreover, Hinnov et al. (2002) also carried out […]"

Lines 268-269: How will this statement that Antarctic warms before Greenland - who said that; Hinnov et al. (2002) did, but who else? –

Well, the seminal paper of Blunier and Brook (Science, 2001) did but this lead-lag relationship was better supported by the WAIS Divide project members (Nature, 2016), by comparing the NGRIP and WAIS ice cores.

be reconciled in the next paragraph that argues that Greenland climate leads Antarctica by approx. 200 years.

In the same WAIS (2016) paper, the authors indicate that "We find that on average the DO cooling signal is transmitted as fast to Antarctica as the DO warming signal is (our sensitivity study suggests a difference in propagation time of 10689 years). This implies that the north-to-south propagation time is independent of the AMOC background state; that is, it is independent of whether the AMOC is in the weak or strong overturning state."

Lines 273-275: Consider mentioning the results of the never-cited Hinnov et al. (2002): coherency analysis reveals a time lead of Byrd DO (Antarctic) cycles over GISP2 DO (Greenland) cycles by 384±70 yr (2s level), and of the North Atlantic benthic DO (AABW) cycles over planktonic DO cycles by 208±33 yr (2s level).

Yes, pls. see above.

Line 285: What is meant by "subsumed by the 65ºN summer insolation"?

Since the word "subsumed" does not seem to be familiar to Reviewer #3, we will drop the end of this sentence, "whether subsumed by the 65ºN summer insolation curve or not." What is meant is that orbital forcing acts in complex ways at different seasons and different latitudes, which are not really subsumed — see Merriam-Webster or other standard English dictionary — by this particular curve.

4 DO events and Bond cycles

Lines 300-301: The recurrence plot of NGRIP shows very pronounced well defined patterns, whereas those of the U1308 $d^{18}O$ records are harder to understand.

We have revised the recurrence plots of NGRIP and U1308 by adding the plot of the recurrence rate below the recurrence plot, and identifying the significant transitions as defined by their prominence. Please see the replies to Reviewers #1 and #2, as well as the attached figure.

Lines 343-344: It is not clear what the difference between the traditional Bond cycle (e.g., Alley, 1998) and the "amended" Bond cycle proposed here. A figure contrasting the two models would be helpful, e.g., add Figure 1 of Alley (1998) next to current Fig. 6a.

In the traditional Bond cycle as sketched by Alley, the DOs show a clear decreasing trend in the warming intensity and the last stadial includes an HE. This is precisely what we have reproduced in our Figure 5, with a reference to the long cooling trend indicated in the Bond et al. (1992) paper. In the "amended" Bond cycle, we include the fact that all stadials include an IRD event whose amplitude culminates in the last stadial and corresponds to an HE, the massive iceberg discharge, as illustrated in Fig. 6a.

5 Concluding Remarks

Lines 407-408: Here it is stated that this paper is an "overview of millennial-scale climate variability over the last 3.2 Myr." But the authors really only discussed millennial scale climate for the past 0.1 Myr (the Last Glacial Cycle).

Not quite so. We have tried to demonstrate with our analysis that millennial-scale climate variability started at least at about 0.9 Ma, when DO-like events are clearly present, although Reviewer #2 suggested to let such events start at about 1.3 Ma.

Lines 420-421: Here it is indicated that millennial scale variability has been observed in glacial periods previous to the Last Glacial Cycle, "at least since 0.8-0.9 Ma." There was mention of EPICA modeling of Greenland suggesting that DO cycles should have continued throughout the past 800 ka – but has geological evidence been recovered yet?

Yes, please see previous reply and comments by Reviewer #2, cp-2021-103-AC5+Suppl.

There is a new report of millennial scale variations in MIS 19 Interglacial, 0.760 to 0.790 Ma (Head, 2021), so limiting the discussion to glacials only may not be sufficient or accurate. Finally, where did HEs first appear in the record?

We will indicate more clearly in the revised paper, if accepted, that we are addressing the millennial climate variability during glacials only, as related to the occurrence and expansion of NH ice sheets, while millennial variability during interglacials relies on other mechanism(s). Concerning HEs, they first appear by 0.65Ma, as indicated in the original manuscript at lines 144-154 and 335-341.

Figures

Figures 2 and 3: In Figure 2, the top of the figure has the title "Recurrence U1308 benthic δ180"; in Figure 3, the top of the figure has the title "Recurrence U1308 bulk carbonate δ180". These are helpful designations and could be included in the figure captions. In both figures, there is a blue curve called "Cibicidoides sp. δ18O bulk (VDP)" and presumably this is analyzed only in Figure 2 and is the U1308 benthic δ18O. There is a green curve called "δ18O bulk carb (PDB)" and this is

analyzed only in Figure 3. I recommend showing only the relevant time series in these two figures (blue curve in Figure 2 and green curve in Figure 3).

These figures have been corrected and are included in the reply to Reviewer #1, cp-2021-103-AC4+Suppl. We have decided to keep both benthic and bulk carbonate $\delta^{18}O$ curves to help the reader locate where the selected transitions occur in the record under study and to what features they correspond in the companion record.

Figures 2-4: Remove the sentence: "The RP web site is http://www.recurrenceplot.tk" and add once in the text where the recurrence plot method is discussed.

Done, thank you.

Figure 6a: This "amended Bond cycle" illustration should be enhanced by adding the "traditional Bond cycle", e.g., Figure 1 of Alley (1998) to highlight the differences.

The traditional Bond cycle is presented in Figure 5.

Figure 6b: Add locations of U1308 and NGRIP.

Done, thank you.

Other

Upper vs. Late, Lower vs. Early is always confusing: geologists are very particular in the use of this terminology: Upper and Lower refer to rock, and Late and Early refer to time. In this paper, there is no comprehensive description of a stratigraphic section in terms of a rock/sediment formation, therefore only the "time" terms should be used, i.e., Early and Late. (Middle is conferred to both rock and time.)

Done, thank you.

NEW REFERENCES

Hinnov, LA, 2018. Chapter 1: Cyclostratigraphy and Astrochronology in 2018, in Montenari, M., ed., Stratigraphy and Timescales, 3, 1-80.

Hinnov, LA, 2013. Cyclostratigraphy and its revolutionizing applications in the Earth and Planetary Sciences, 125th Anniversary Volume, Geological Society of America Bulletin, 125, 1703-1734.

Hinnov, L.A., Schulz, M., Yiou, P. 2002. Interhemispheric space-time attributes of the Dansgaard-Oeschger oscillations between 0-100 ka, Special Volume: Decadal to Millennial Climate Change, Quaternary Science Reviews, 21, 1213-1228.

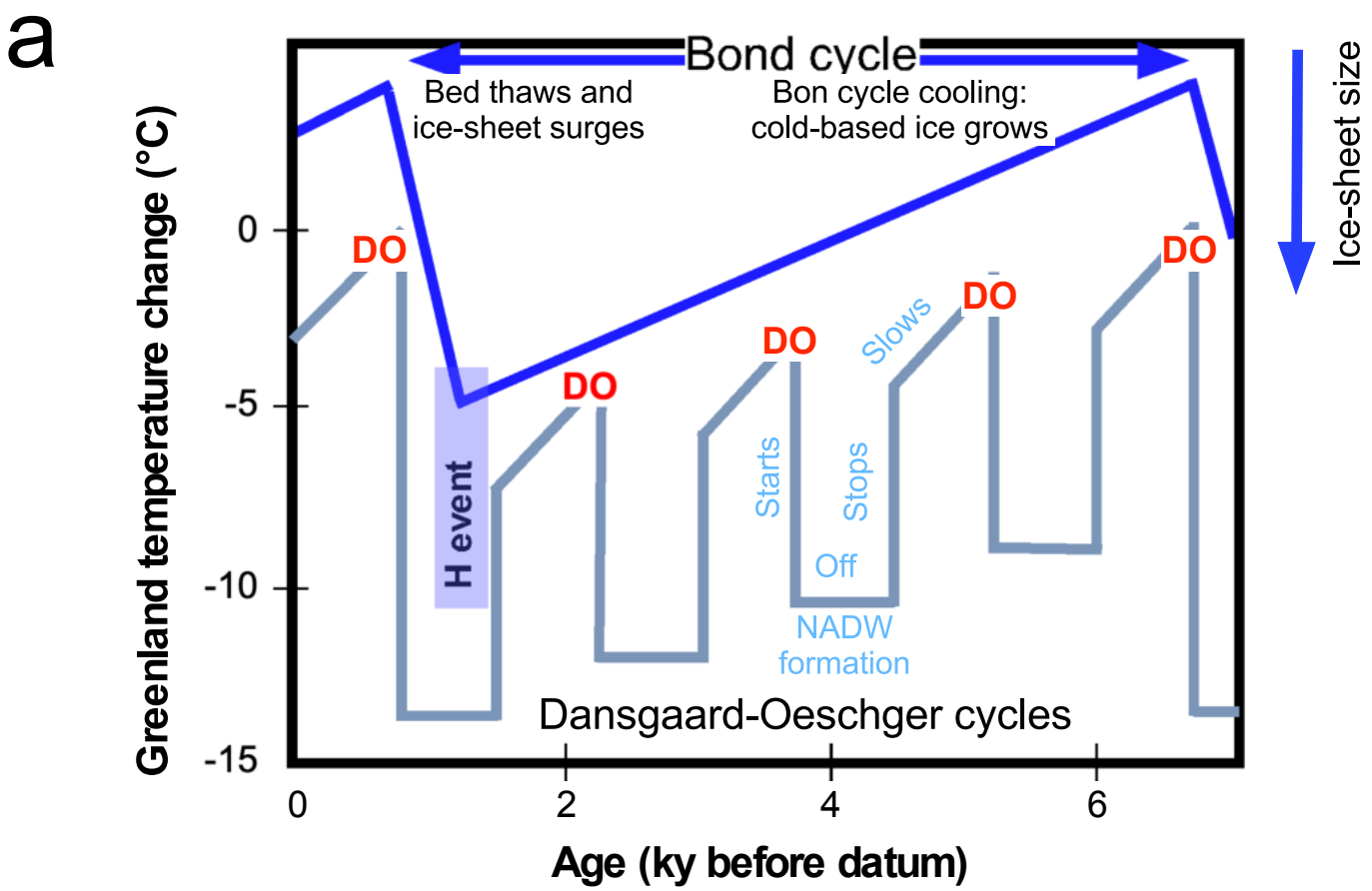
Head, M, 2021. Review of the Early–Middle Pleistocene boundary and Marine Isotope Stage 19, Progress in Earth and Planetary Science, 8:50, doi:10.1186/s40645-021-00439-2

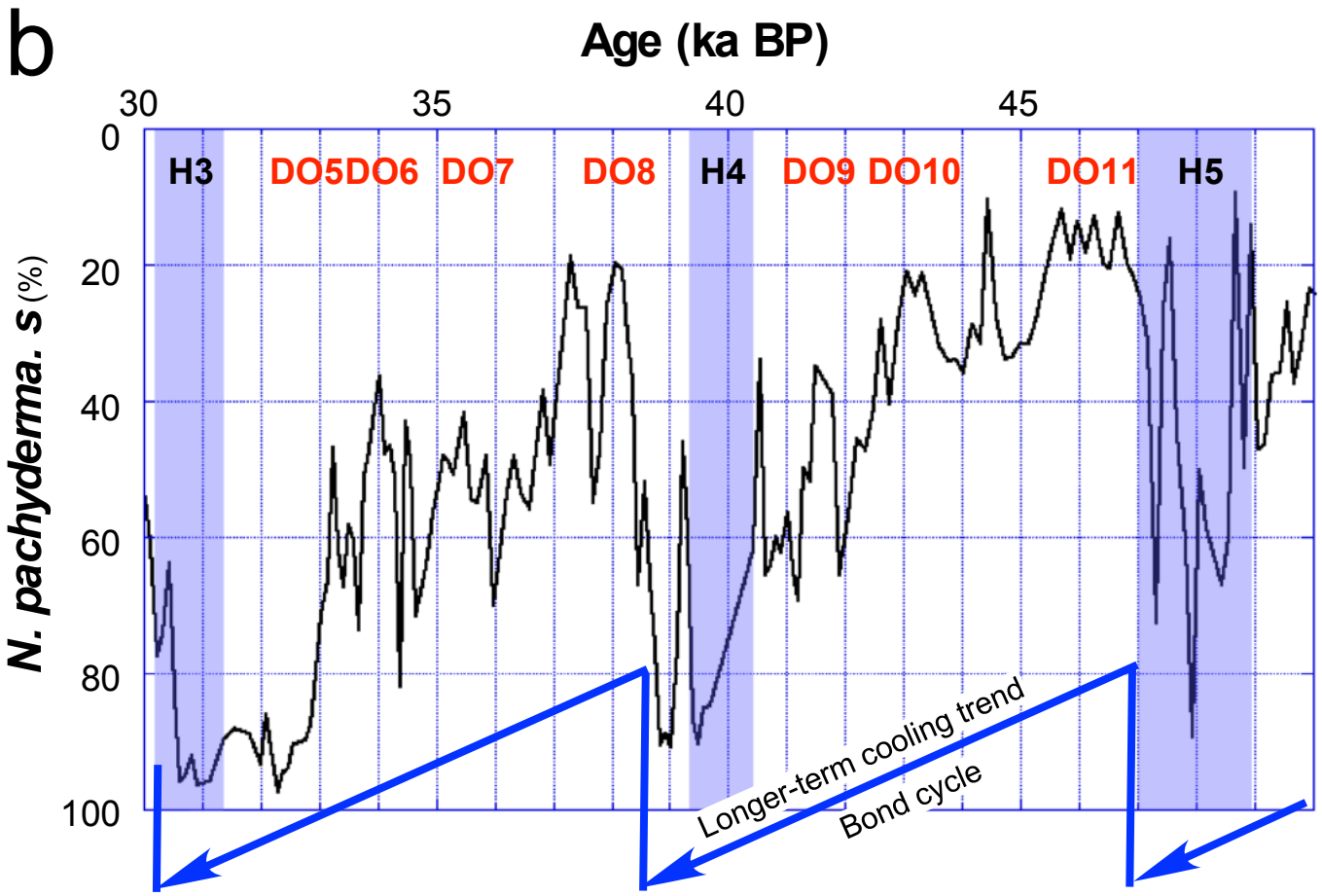
Rahmstorf, S., 2003. Timing of abrupt climate change: a precise clock, Geophysical Research Letters, 30:10, 10, 1510, doi:10.1029/2003GL017115

All these references have now been included. Thank you.

We have included the revised figures 5 and 6, as well as two supplementary figures that show the results of applying the KS methodology to the U1308 benthic and NGRIP oxygen isotope records.

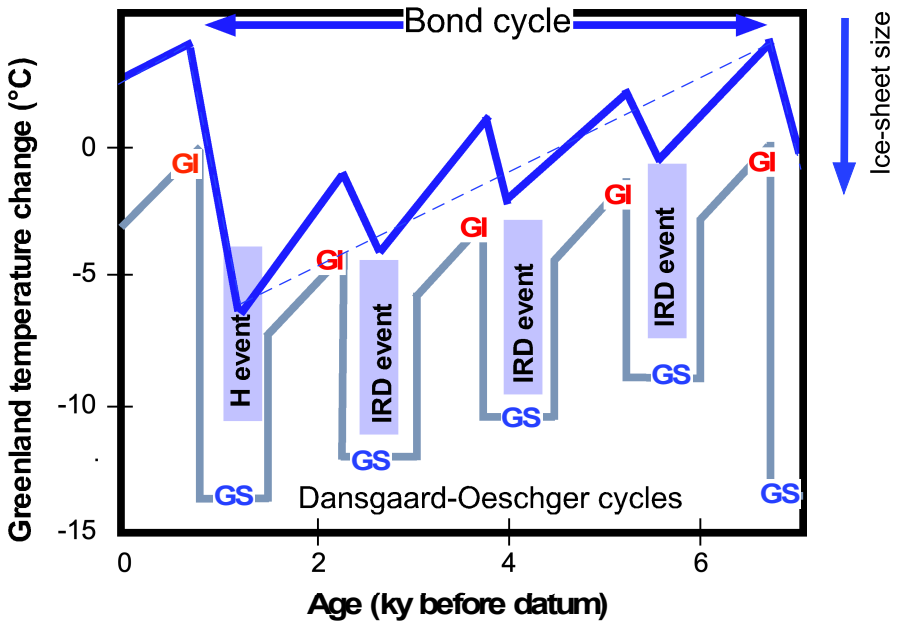
revised Fig. 5



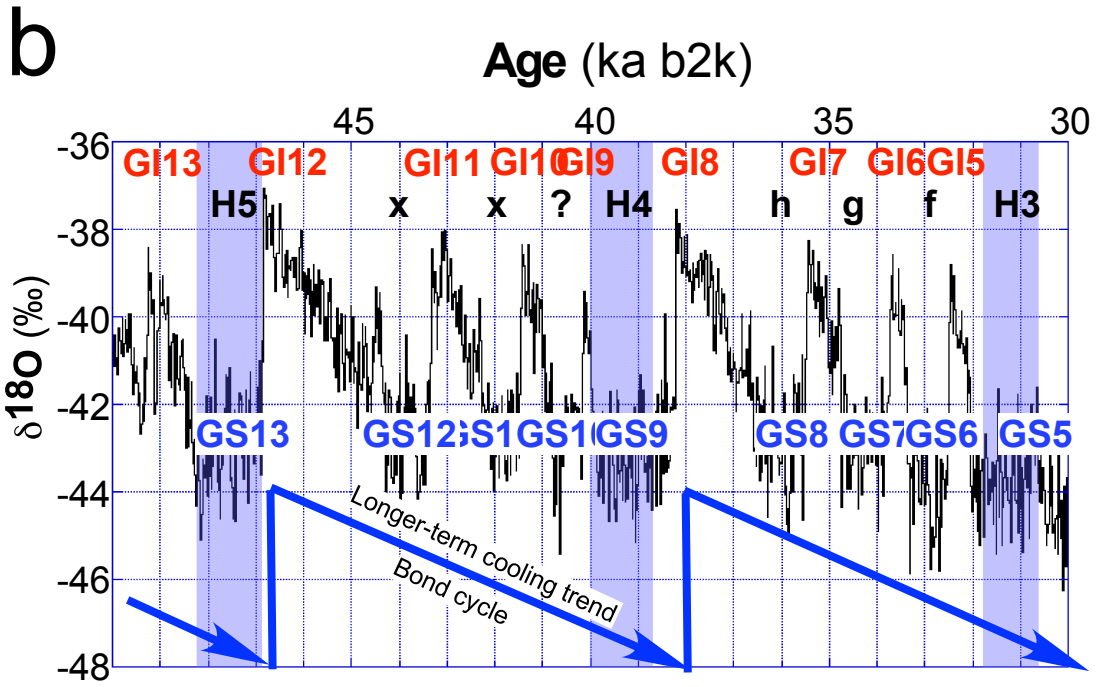


revised Fig. 6

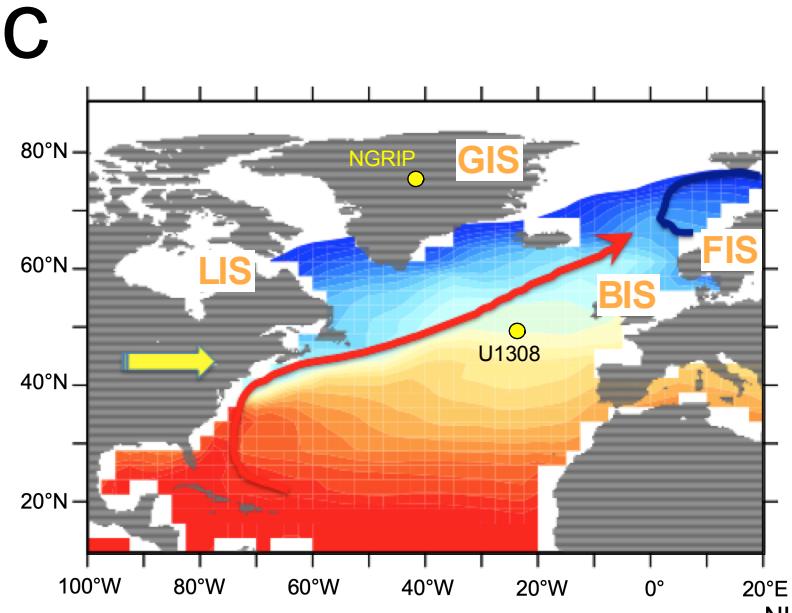
a



b



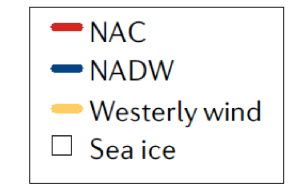
c

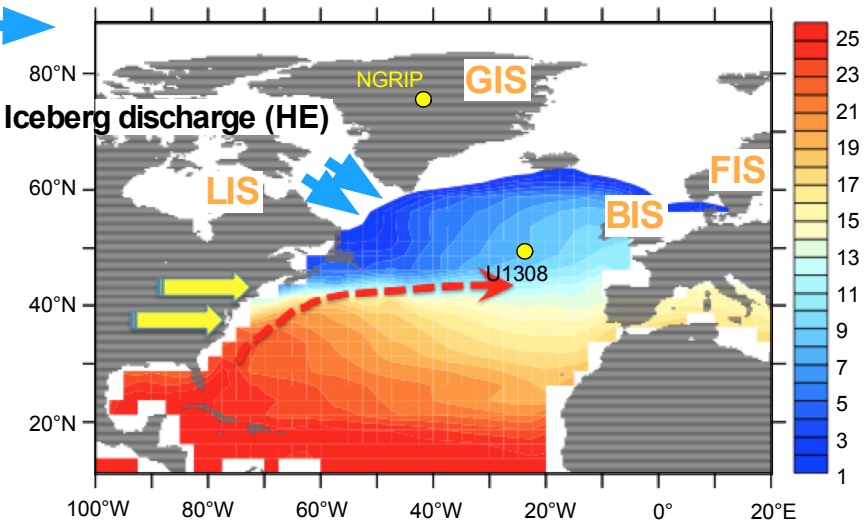


Greenland Interstadial

N Atlantic westerlies increase
Sea ice decreases
Salt transport to NA
-> NADW strenghens
Re-growth of NH ice sheets

High Ice shelves destabilization (high decrease in elevation) through subsurface warming
Strong NH ice sheets Ice streaming 'HE)
Sea ice increases
-> NADW weakens

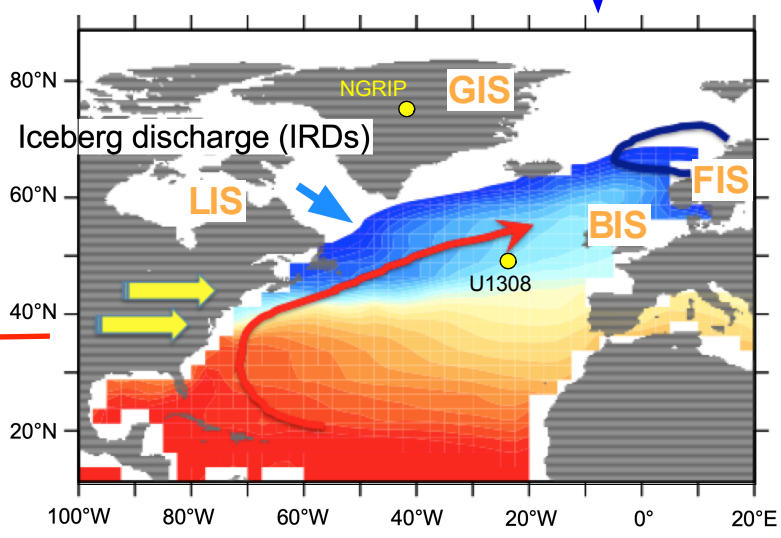




Heinrich Stadial

NH ice sheets destabilize (low decrease in elevation) through subsurface warming
Ice streaming increases
Sea ice increases (IRDs)
-> NADW weakens

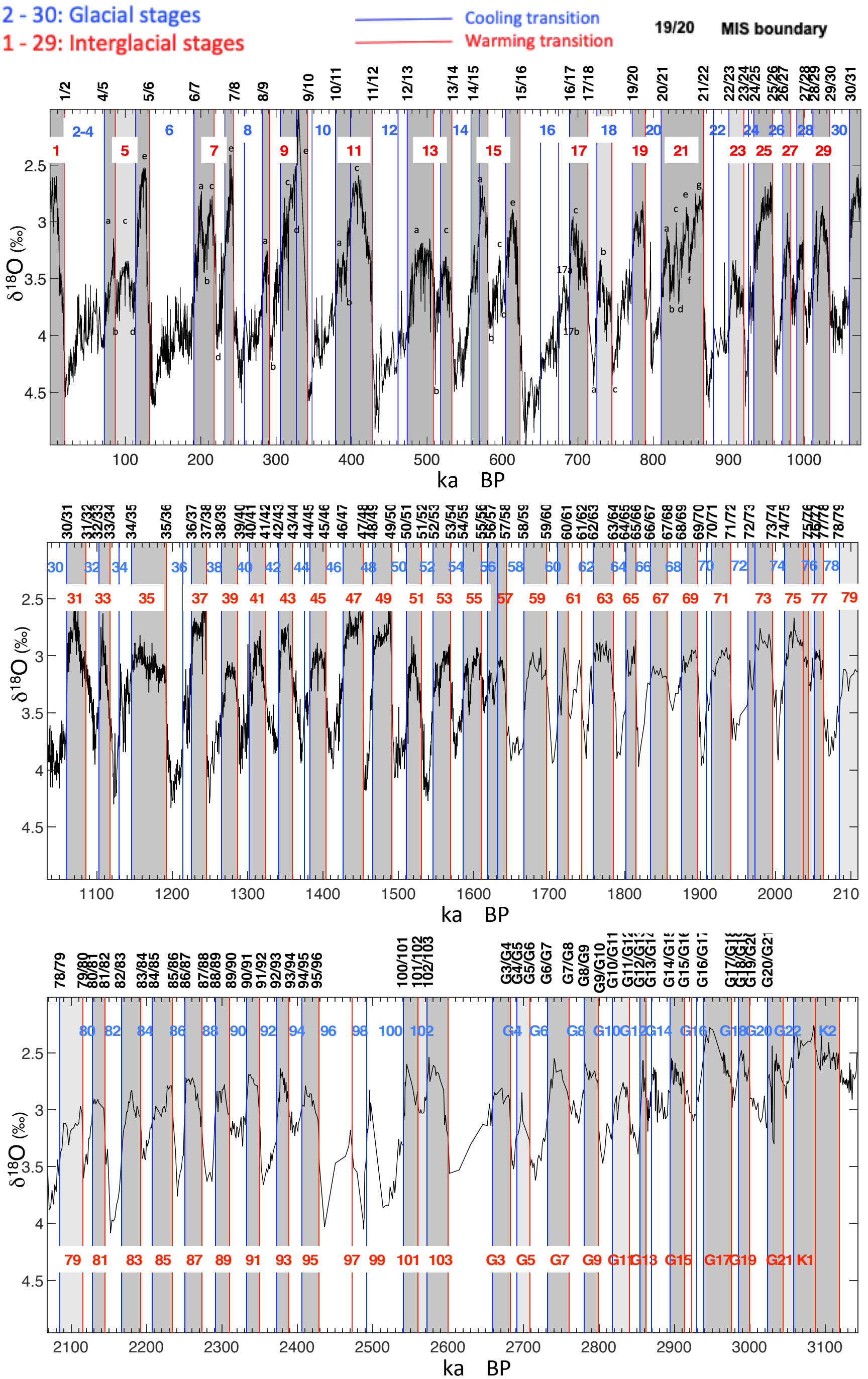
N Atlantic westerlies increase
Sea ice decreases
Salt transport to NA
-> NADW strenghens
Re-growth of NH ice sheets



Greenland Stadial

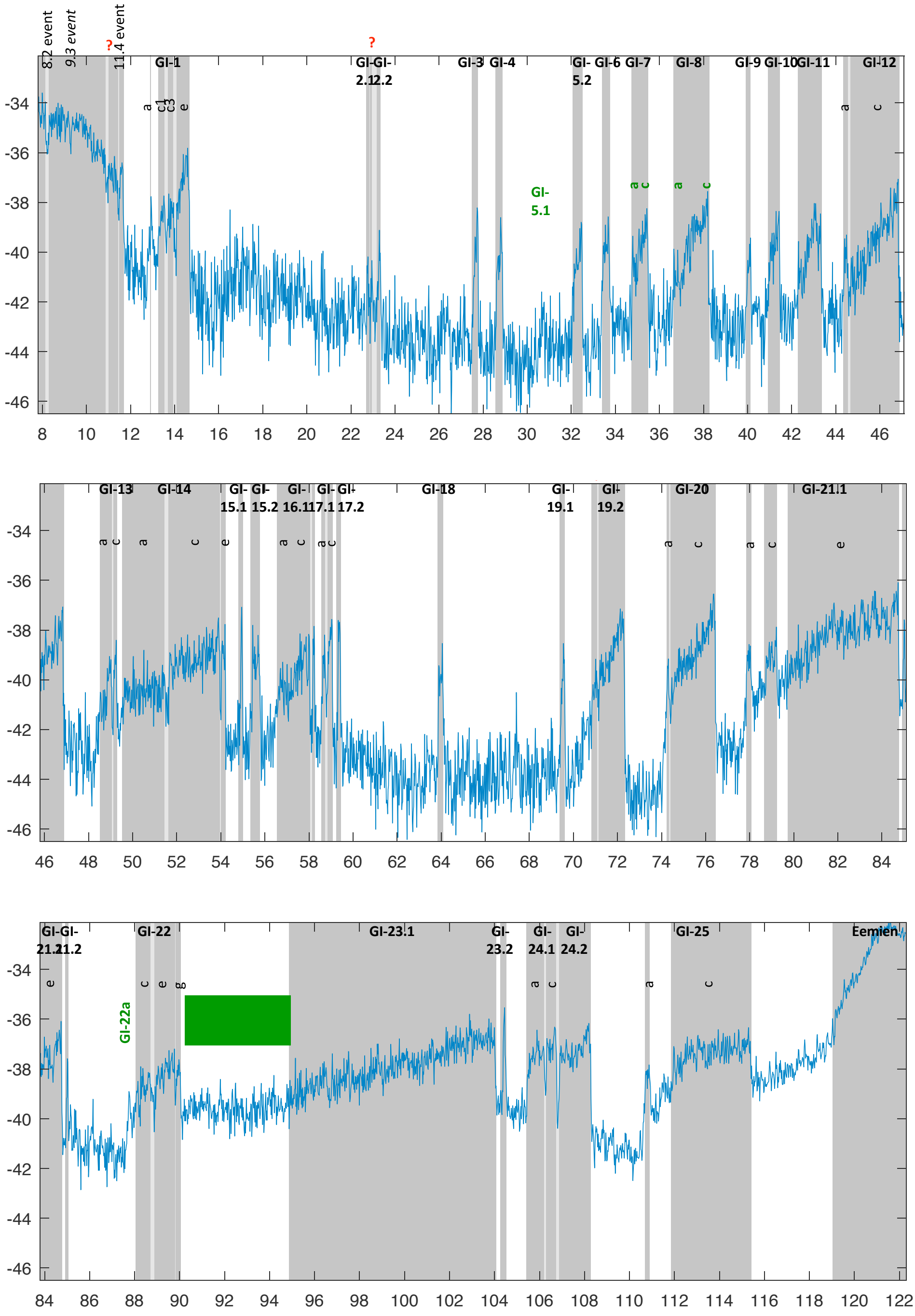
supplementary Figure 1

Detection of Abrupt transitions from benthic $\delta^{18}O$ in U1308 with the K-S method



MIS boundaries from Lisiecki & Raymo (2005). Paleoceanography, PA1003, doi:10.1029/2004PA001071 and odd MIS from Hodell and Channel (2016) Climate of the Past, 12, https://doi.org/10.5194/cp-12-1805-2016.
Substage numbering from Railsback et al. (2015). Quaternary Science Reviews 111. https://doi.org/10.1016/j.quascirev.2015.01.012.

supplementary fig. 2



Annotation in green and green box: disagreement betwen Rasmussen et al (2014) observations and the KS test results.
Question mark in "red" event not labelled in Rasmussen et al. (2014)