Point by point response to Reviewer 1

We would like to thank Reviewer 1 for helpful comments on our manuscript. Here we have addressed each of the comments and questions in the following format: Each question or comment is re-stated as in the original review of the manuscript in black 'Calibri font'. Our response to each comment/question is indented and written in blue 'Calibri font'.

Firstly, we feel that the way that the paper is set up does not really give a true reflection of the papers findings. The paper claims that abrupt climate events are;

1) a characteristic of glacial climate states, and
2) the results of this study (showing abrupt events occurred at the transition between MIS 11c and 11b) question this and our ideas about our concept of warm climate stability.

Neither of these claims are strictly true.

We edited the abstract, introduction, and conclusions to reflect our findings more clearly.

It has long been known that abrupt climate events occur during interglacials – the 8.2 ka event (along with the pre-boreal oscillation, 4.2 ka event and 2.8 ka event) is a good example of this. Whilst it is likely that none of these were of a magnitude or duration comparable to the Lateglacial Interstadial (i.e. the Younger Dryas) they had transformative effects on ecosystems, surface processes and societies so are still significant. The concept of "warm" climate stability was surely abandoned a long time ago.

- First, we would like to clarify that the main objective in this manuscript is not to claim that our findings are the first to identify high magnitude climate events during interglacial boundary conditions, but instead, our goal is to elucidate their mechanistic links in the climate system specifically involving both surface and deep ocean circulation changes.
- Further, we believe that it is still the predominant paradigm that warm climates are less likely to experience high-magnitude (hemispheric/global) climate events because a large cryosphere is believed to be required as a key antecedent for high-magnitude events to occur and persist (e.g., Zhang et al. 2021). As a result, our understanding of how high-magnitude events did or may occur in the future without NH ice sheets is not well developed. Part of the rationale for the study presented here is that we do not yet appreciate the full scale of antecedent conditions that can lead to high magnitude climate instability.

If the authors are distinguishing between high magnitude (glacial) and low magnitude (interglacial) abrupt events then they need to do so more clearly and, ideally, in a quantified way.

We agree that such a definition would be helpful. In the introduction, we now include a clarification that the maximum range in Holocene SST variability in the SPG does not exceed 3-4 °C (e.g., (Thornalley et al., 2009) while glacial DO events are characterized by SST changes of >6°C (Dokken et al., 2013).

Regardless of how abrupt events are defined, the study presented here doesn't move this argument forward. The events discussed here occurred on the climatic downturn into MIS 11b and, consequently, long after fully interglacial conditions had ceased. They are actually more true of abrupt events under a glacial, or transitional, state in that, as shown in Figure 6, a significant fall in sea level had already been experienced prior to their occurrence. A number of authors have shown that abrupt events occur under fully interglacial conditions during MIS 11c (i.e. Barker et al., 2015; Kandiano et al., 2017). The events described here are more similar to those that occurred during the transition from MIS 5e to 5d that are discussed in the introduction. The occurrence of such events, at interglacial/glacial transitions, are relatively well-known, particularly from the North Atlantic, which slightly detracts from the originality of this study. ***The paper needs to consider the rationale and significance of this work in much greater detail, in terms of how it is discussed in the abstract, introduction and conclusion.***

We agree, there is a growing literature documenting the nature of abrupt events during past interglacial conditions. As clarified above the primary aim of our manuscript is not to prove that high-mag events are possible during low ice conditions but instead to understand how high-magnitude climate events occur (mechanistically) regardless of the background climate state. Here we advance our understanding of the mechanisms that couple the surface climate with the deep ocean during such events. This is/was also clearly stated in lines 86-92. We will edit the *abstract, introduction, and conclusions* to reflect our position more clearly.

With regards to the boundary conditions preceding the described events at 397ka and 390ka, we respectfully disagree with the statement above, that both events described occurred "*long after fully interglacial conditions had ceased".*

- At 397ka, radiative forcing received in June at 65N was 466 W.m^2 and CO_2 concentrations were 259-265 ppmv. Further, the contribution of GIS to global sea levels at 397ka is estimated to have been between 1 and 5 m higher than today (Robinson et al., 2017). MIS 11c at ~397 ka was therefore most similar to preindustrial MIS 1 in terms of eccentricity and CO_2 levels at the time (Ganopolski et al., 2016; Yin and Berger, 2015).
- 390ka coincides with a peak in summer insolation at 65°N (Ganopolski et al., 2016) and greenhouse gases were still at or close to interglacial values (CO2: 259.5 ppmv and CH4: 568 ppbv). As highlighted by the reviewer global sea levels are estimated to have been up to 30m lower than today, placing 390ka during an intermediate cryosphere climate. When describing the event at 390ka we do not claim that this even occurs during interglacial boundary conditions. We acknowledge that the sea level lowering that occurred during the precession minima at 395ka would have led to significant ice build-up leading to positive albedo and atmospheric circulation feedbacks.
- Further, we would argue that it is too simplistic to compare the climate backdrop of 397ka to other glacial inceptions based on varying background climate states. The transition from MIS 5e to 5d, for example, was significantly colder than the transition from MIS11c to 11b due to low radiative forcing, see also (Ganopolski et al., 2016).

Secondly, the Rockall trough, as a system, is a hydrographically unique area with cyclonic re-circulation of sediments. Consequently, changes in sediment characteristics within DSDP 610B could reflect variations in the strength of flow within Rockall Trough and not just actual changes in the strength of WTOW. The authors may have considered this but at the moment the manuscript reads as though the complexity of this location is being ignored and overlooked. *The paper needs to show a much greater consideration of the complexities of the oceanographic processes that operate at DSDP 610B and explain why the proxies record the role of WTOW and not more local processes.*

We agree with the reviewer's comment and have added information on deep-water flow variability in the oceanographic setting. We have included the following points to better characterise the depositional setting and the potential impact on our records.

- Site 610B is located at the downstream end of the Feni Drift which is a contourite deposit formed by southward flowing of deep water (Ellett and Roberts, 1973; Jones et al., 1970).
- Sediments of the Feni drift are deposited by waning, intermittent bottom currents flowing from North to South along the Feni Ridge because density-driven currents keep bathymetry on their right in the Northern Hemisphere (Johnson et al., 2017). Between episodes of current activity normal pelagic and ice-rafted sedimentation continues unhindered (Robinson and McCave, 1994).
- At the depth of 2417m, 610B lies within the influence of lower WTOW. The flow pathway for WTOW is around the northern and western boundary of the Rockall Trough (Johnson et al., 2017). Observations demonstrate that the southward flow of deep WTOW is intermittent on annual timescales but positive on ≥ decadal timescales (Johnson et al., 2017) which is the resolution that we are targeting in this manuscript.
- To the north and west of 610B the central anticyclonic gyre of the Rockall Trough (Johnson, 2012; New and Smythe-Wright, 2001; Smilenova et al., 2020), recirculates water down to 2000m during winter mixing (Smilenova et al., 2020). Given the distance from the gyre (ca

500km) and the deeper depth of 610B, it is unlikely that it influences the sedimentation and flow over the site.

Thirdly, we are not convinced that the cooling that occurred between 397 and 390 ka should be classified as an “abrupt event”. Not only does the event last for some 7,000 years but it is characterised by relatively slow and protracted cooling. This is relatively clearly seen in the SST data presented here where a decline of some 6°C occurs progressively over ca 5 ka.

We argue that the SST record presented here describes a 2-step cooling with a temperature drop of 5.7°C over 1000 years starting at 397.5ka (within dating uncertainties). The onset of this SST cooling, we consider abrupt. Thereafter SSTs are stable for ca 2000 years before a second cooling occurs of 1.8°C over 200 years. Our interpretation for a 2-step rather than a gradual cooling is supported by the ramp function fits shown in figure A2. This method (see also section 2.10) estimates the unknown onset and end of a time interval by weighted least-squares regression by a brute-force search and thereby ensures that onsets and duration of cooling events are chosen objectively. We use a bootstrap simulation of 10,000 resamples to estimate the uncertainty of the results.

The second event that is described is, as the authors acknowledge, is much more typical of an abrupt event (a decline of >6°C in ca 0.5 ka) though this is confidently outside the main interglacial phase and thus does not support their conclusions of high magnitude events during interglacial periods.

As stated above we have edited the abstract, introduction, and conclusions to reflect our findings more clearly.

The change in grain size data for the first event is more dramatic and has much in common with the second event, however, this elicits a very different response in SST values and this is not really acknowledged or addressed.

The phasing of the response between overflows and SST is actually very similar when considering the 2-step nature of the cooling event recorded at 397ka (also described above).

It is also quite important for the authors to discuss the discrepancy in the SST data of late MIS 11c between DSDP 610 and M23414. From 403 ka to 398 ka there is an offset of up to 6$_{o}$C between the two sites, significantly greater than the modern temperature gradient between these two localities. Again this isn’t discussed but is fundamental to an acceptance of the data and ideas presented here.

The difference between the two events need to be discussed and explored in much greater detail, whilst the validity of the SST estimates for DSDP 610 need to be discussed in more detail, particularly with reference to the record from M23414.

We thank the reviewer for pointing out this discrepancy and we have investigated this issue.

1.) The SST data from M23414 that we show in Figure 6 was first published in Kandiano et al. (2007). When investigating the methods used to derive SSTs we noted that the data published consists of average values combining three different methods to infer summer SSTs using: Transfer Function Technique (TFT; (Imbrie and Kipp, 1971), Modern Analogue Technique (MAT; (Prell, 1985)) and Revised Analogue Method (RAM; (Waelbroeck et al., 1998)). For all methods SSTs were calculated using the North Atlantic subset of the core-top database as compiled by (Pflaumann et al., 2003). This includes 947 core tops and assumes that the assemblages represent summer SST.
2.) The ForCenS Databased used here, has several advantages over the Pflaumann dataset. (1) It combined four existing key foraminifera compilations (CLIMAP, MARGO, Brown University, & ATL947) and pulls in PANGAEA & NOAA paleoclimatology data. (2) It restricted data synthesis to data generated using the CLIMAP methodology, meaning a minimum count of 300 specimens over 150um (3) ForCenS applied strict procedures to remove duplications and outliers, before going through taxonomic standardization (4) Out of the 6,984 initial records, the database contains 4,205 records from unique sites and informative technical and true replicates.
3.) _The explanation for Offset:_ The offset between (Kandiano and Bauch, 2007) and the ForCens generated SST values is mostly due to the fact that ForCenS uses the WOA98 ***annual SST*** dataset to generate SST reconstructions, while (Kandiano and Bauch, 2007)

used summer SST. We argue that the choice of the annual SST dataset is justified particularly during interglacial boundary conditions, because foraminifera bloom twice at subpolar latitudes (Chapman, 2010), once in spring and once in late summer. The assemblages preserved in marine sediments would therefore reflect multiple seasons similarly to the signal preserved in geochemical proxies based on planktonic foraminifera (Leduc et al., 2010). 2010). *We corrected the axis information in Figure 6 to Annual SST for our dataset and report Kandiano et al. 2007 as summer SST*

Figures: Some general points on uniformity of font sizes, writing (610B – this study) or (610B) or (this study) rather than a combination of the 3

Figure 1

Indicating which branch of ISOW is WTOW would be helpful for the reader, particularly as this is the focus of your study. It may also be helpful to include other labels (DSOW, other ISOW branches, NADW etc but not necessary). The grey site label names on a grey background are something I'd advise to change for legibility.

WTOW is derived from overflows entering the Rockall Trough via the Wyville Thompson Ridge, which saddles the Scottish continental shelf and the Faroe Bank. We included a label on the map to clarify. Grey site labels and names are now in white.

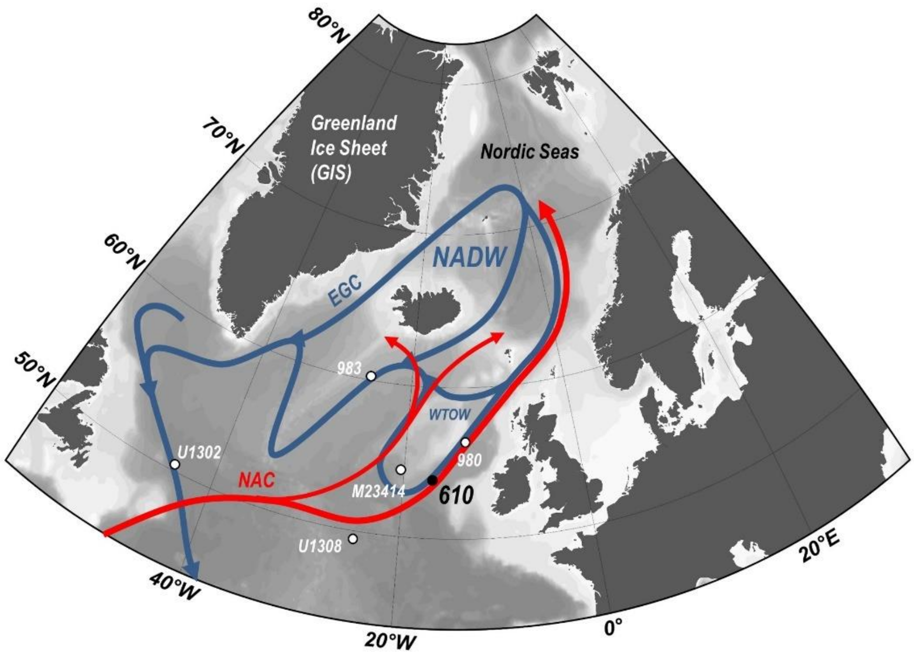


Figure 1 Revised Figure 1 with recommendations from Reviewer 1

Figure 2

- In some figures you have labelled the data for this study and in figure 2 you have not. I'm assuming those not labelled relate to DSDP 610 in this study?
  We have standardized the reference to new data to *This study – 610B*
- You've plotted N.incompta + N.deutertrei % together from Kandiano et al 2007 but you've listed this as sub-polar (following Kucera et al 2007), but Deutertrei is a sub-tropical species. You also don't talk about this in the text so wondered why it is plotted?
  The reason they are plotted together is that they are reported in this way in Kandiano et al. 2007. They are reported in Figure 2 for consistency and information for the reader.
- The two shades of each colour may be difficult for colour Colour blind people so symbols may help with this.

We added symbols to the Kandiano et al. 2007 data

- The graph feels busy – it might benefit from extending horizontally
  We have extended it horizontally

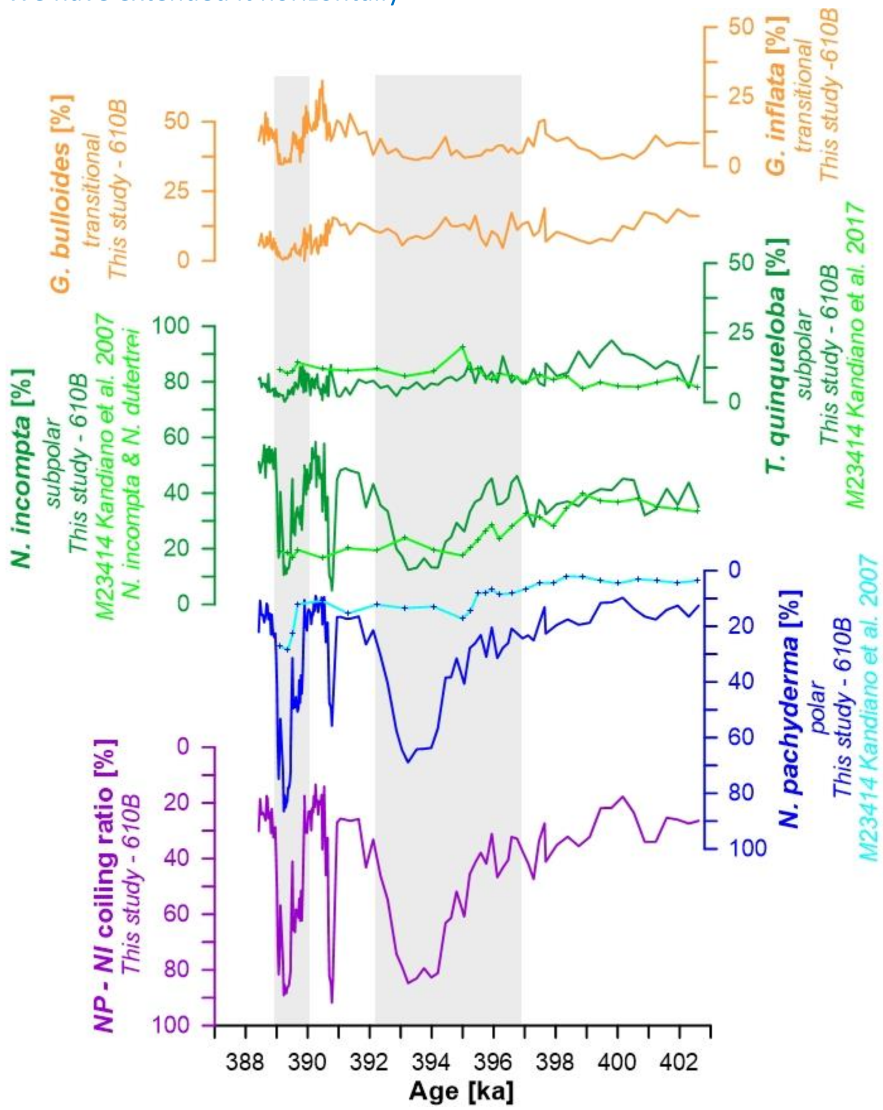


Figure 2 Revised Figure 2 as recommended by Reviewer 1

Figure 5

- IRD for 983 is in grey in the axis and appears black in the graph
  We have corrected the colour in the figure caption from grey to black
- The range of font sizes looks untidy
  All font sizes have been unified to size are standardized

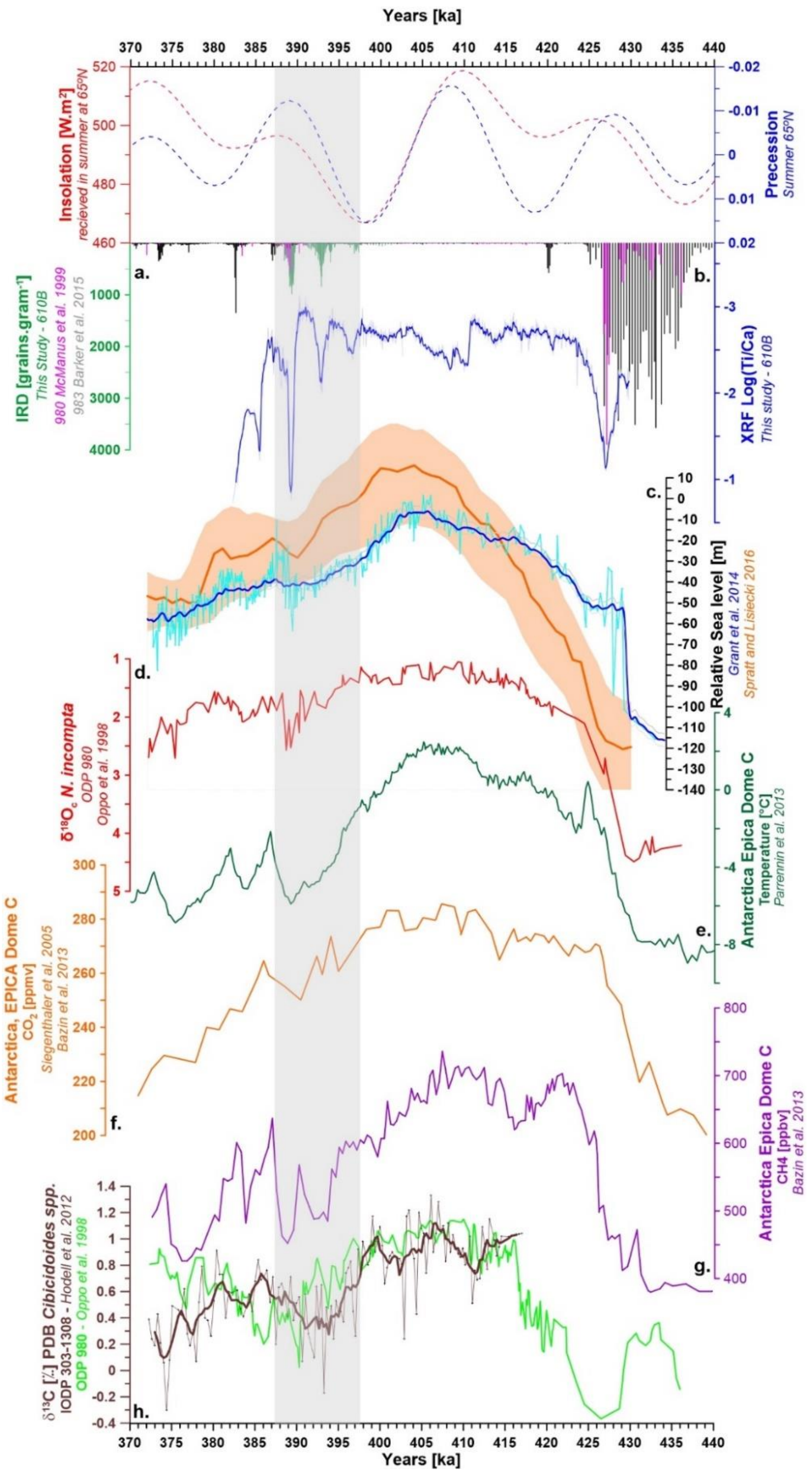
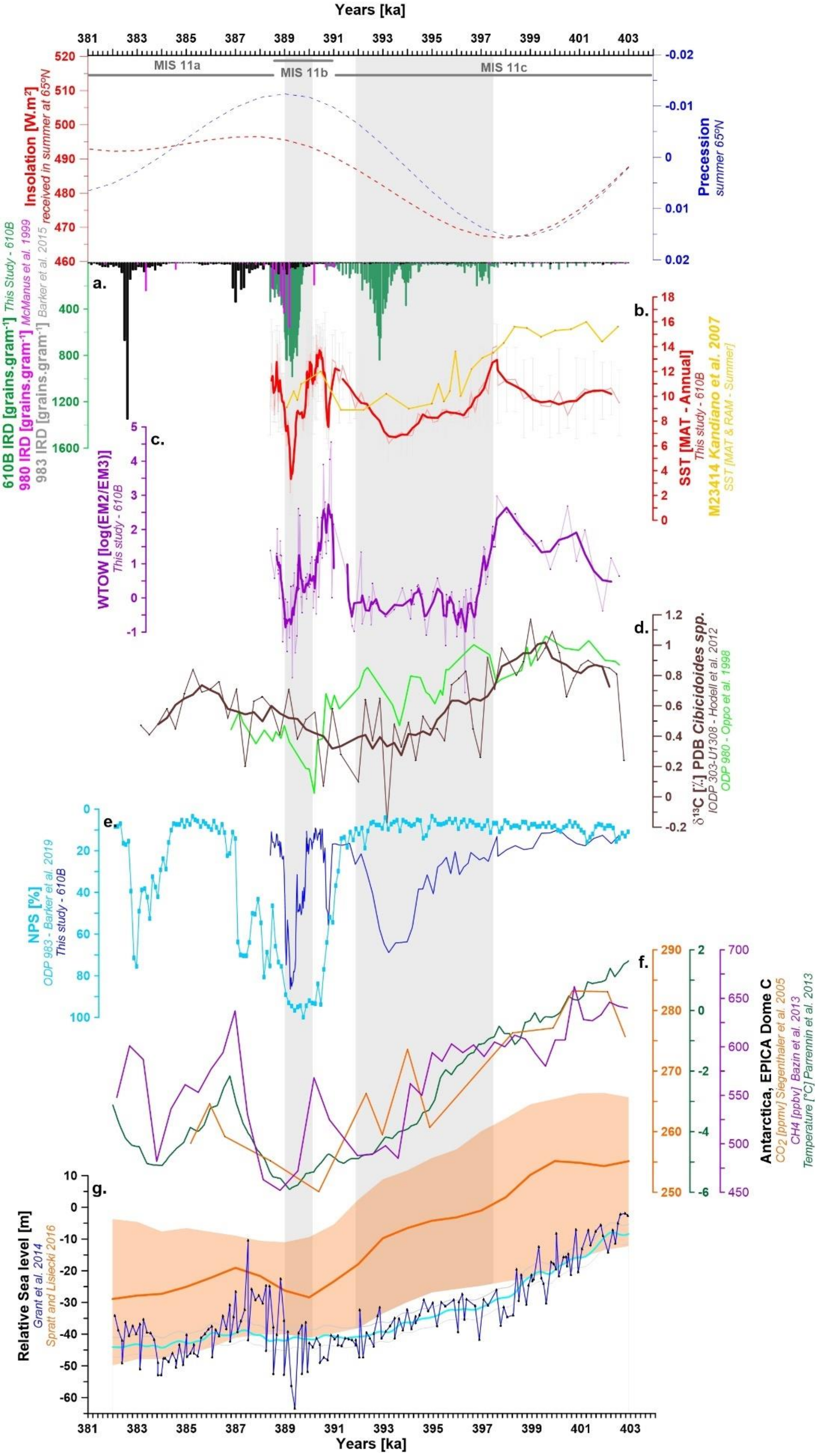


Figure 6

- IRD for 983 is in grey in the axis and appears black in the graph
  We have corrected the colour in the figure caption from grey to black
- The NPS % from barker et al 2015 was updated in the barker et al 2019 paper. There aren't any major changes in %, though some minor peaks are smaller in the data you have used (e.g., ~ 394ka)
  We have replaced the Barker et al. 2015 with the Barker et al. 2019 dataset.



Years [ka]
MIS 11a
MIS 11b
MIS 11c
Insolation [W.m²]
received in summer at 65°N
Precession
summer 65°N
610B IRD [grains.gram⁻¹] This Study - 610B
980 IRD [grains.gram⁻¹] McManus et al. 1999
983 IRD [grains.gram⁻¹] Barker et al. 2015
a.
b.
SST [MAT - Annual]
This study - 610B
M23414 Kandiano et al. 2007
SST [MAT & RAM - Summer]
c.
WTOW [log(EM2/EM3)]
This study - 610B
d.
δ¹³C [‰] PDB Cibicidoides spp.
IODP 303-U1308 - Hodell et al. 2012
ODP 980 - Oppo et al. 1998
e.
NPS [%]
ODP 983 - Barker et al. 2019
This study - 610B
f.
Antarctica, EPICA Dome C
CO₂ [ppmv] Siegenthaler et al. 2005
CH4 [ppbv] Bazin et al. 2013
Temperature [°C] Parrennin et al. 2013
g.
Relative Sea level [m]
Grant et al. 2014
Spratt and Lisiecki 2016
Years [ka]

Age Model

Is the age model for ODP 983 tied to DSDP 610B in any particular way or just placed on a timescale with 2 different models (+ associated uncertainties)?

No, the two cores are not tied or tuned to each other and for IODP 983 we are using the AICC2012 as published in (Barker et al., 2015) and in (Barker et al., 2019).

I ask as the LR04 age model for ODP 983 places the increase in NPS % at ~ 395 ka – 389 ka and a second 387-385 ka which is much closer to the authors claims for these events (in both duration and timing). The authors also seem to have tied their core to LR04 so I wonder why (it seems) they have not tied ODP 983 to this.

In Barker et al. 2015 three Age models were proposed for 983 (1) The EDC3 Age model (2) the alternative ice core age model (AICC2012; (Bazin et al., 2013),(Veres et al., 2013)) and (3) an absolute age model (GICC05/NALPS/China) based on (Barker and Diz, 2014; Barker et al., 2011; Cheng et al., 2009). Only the later more dated age model places the increases in NP% at 395 and 385, while the EDC3 and AICC2013 place the first excursion at 390Ka as shown in figure 6.

Text:

Some general points line by line through the text. The piece in general would benefit from some sub-headings to organise the flow as presently sections seem to overlap considerably.

- Line 74-75 – would cite Barker et al 2015 "icebergs not the trigger for NA cooling events" (they reference the paper later but they do not cite it here)
  We have added the reference here
- Line 80-84 – quantifying importance of NADW to AMOC and quoting overall contribution from WTOW would be good
  We have added the contribution of WTOW to the total overflow to the manuscript
- Line 90 – Global average temperature difference between MIS 11 and MIS 1 would be good
  According to (Robinson et al., 2017) Summer temperature anomalies at the height of MIS 11 (411ka) were 2.8 ±0.7°C relative to the present. By 403ka, anomalies were at 0 ±1°C relative to the present. By 397ka Summer temperature anomalies had dropped to -2°C.
- Line 109 – add space between reference and 'today'.
  The space was added
- Line 85 – 115. This seems muddled. It seems to be a descriptive piece setting out the conditions during MIS 11 but starts and ends with talk about orbital similarities as a justification for looking at MIS 11. I would have set out the orbital similarities prior to then describing MIS 11.
  This section was restructured according to the reviewer's suggestion.
- Line 347 – 350 – the authors state that the offset is 9 samples (4.5cm), 320 years. Firstly, from the graph, it doesn't look like all 9 of these samples have been run so this is confusing wording
  We assure the reviewer that all 9 samples were analysed and are shown
- Line 404 – random 'o' in the sentence
  This was deleted
- A good paper to cite on surface waters in the Nordic seas being unusually cold
- and fresh in MIS 11 https://www.frontiersin.org/articles/10.3389/fmars.2018.00251/full#h7 which is absent in the bibliography.
  This reference was added
- The reference list needs to be checked there are a number of typos throughout and some repetition (i.e., McManus et al., 1999 is included twice).
  We have checked the reference list throughout.

END Reviewer 1

References used:

Barker, S., Chen, J., Gong, X., Jonkers, L., Knorr, G., and Thornalley, D.: Icebergs not the trigger for North Atlantic cold events, Nature, 520, 333, 2015.

Barker, S. and Diz, P.: Timing of the descent into the last Ice Age determined by the bipolar seesaw, Paleoceanography, 29, 489-507, 2014.

Barker, S., Knorr, G., Conn, S., Lordsmith, S., Newman, D., and Thornalley, D.: Early interglacial legacy of deglacial climate instability, Paleoceanography and Paleoclimatology, 34, 1455-1475, 2019.

Barker, S., Knorr, G., Edwards, R. L., Parrenin, F., Putnam, A. E., Skinner, L. C., Wolff, E., and Ziegler, M.: 800,000 years of abrupt climate variability, science, 334, 347-351, 2011.

Bazin, L., Landais, A., Lemieux-Dudon, B., Kele, H. T. M., Veres, D., Parrenin, F., Martinerie, P., Ritz, C., Capron, E., and Lipenkov, V.: An optimized multi-proxy, multi-site Antarctic ice and gas orbital chronology (AICC2012): 120-800 ka, Climate of the Past, 9, 1715-1731, 2013.

Chapman, M. R.: Seasonal production patterns of planktonic foraminifera in the NE Atlantic Ocean: Implications for paleotemperature and hydrographic reconstructions, Paleoceanography, 25, PA1101, 2010.

Cheng, H., Edwards, R. L., Broecker, W. S., Denton, G. H., Kong, X., Wang, Y., Zhang, R., and Wang, X.: Ice age terminations, science, 326, 248-252, 2009.

Dokken, T. M., Nisancioglu, K. H., Li, C., Battisti, D. S., and Kissel, C.: Dansgaard-Oeschger cycles: Interactions between ocean and sea ice intrinsic to the Nordic seas, Paleoceanography, 28, 491-502, 2013.

Ellett, D. and Roberts, D.: The overflow of Norwegian Sea deep water across the Wyville-Thomson Ridge, 1973, 819-835.

Ganopolski, A., Winkelmann, R., and Schellnhuber, H. J.: Critical insolation–CO 2 relation for diagnosing past and future glacial inception, Nature, 529, 200-203, 2016.

Imbrie, J. and Kipp, N. G.: A new micropaleontological method for quantitative paleoclimatology: application to a late Pleistocene Caribbean core. In: The Late Cenozoic Glacial Ages, Turekian, K. K. (Ed.), Yale Univ. Press, New Haven, 1971.

Johnson, C.: Tracing Wyville Thomson Ridge overflow water in the Rockall trough, 2012. Aberdeen University, 2012.

Johnson, C., Sherwin, T., Cunningham, S., Dumont, E., Houpert, L., and Holliday, N. P.: Transports and pathways of overflow water in the Rockall Trough, Deep Sea Research Part I: Oceanographic Research Papers, 122, 48-59, 2017.

Jones, E., Ewing, M., Ewing, J., and Eittreim, S.: Influences of Norwegian Sea overflow water on sedimentation in the northern North Atlantic and Labrador Sea, Journal of Geophysical Research, 75, 1655-1680, 1970.

Kandiano, E. S. and Bauch, H. A.: Phase relationship and surface water mass change in the Northeast Atlantic during Marine Isotope Stage 11 (MIS 11), Quaternary Research, 68, 445-455, 2007.

Leduc, G., Schneider, R., Kim, J.-H., and Lohmann, G.: Holocene and Eemian sea surface temperature trends as revealed by alkenone and Mg/Ca paleothermometry, Quaternary Science Reviews, 29, 989-1004, 2010.

New, A. L. and Smythe-Wright, D.: Aspects of the circulation in the Rockall Trough, Continental Shelf Research, 21, 777-810, 2001.

Pflaumann, U., Sarnthein, M., Chapman, M., d'Abreu, L., Funnell, B., Huels, M., Kiefer, T., Maslin, M., Schulz, H., Swallow, J., Kreveld, S. v., Vautravers, M., Vogelsang, E., and Weinelt, M.: Glacial North Atlantic: Sea-surface conditions reconstructed by GLAMAP 2000, Paleoceanography, 18, 1065, 2003.

Prell, W. L.: Stability of low-latitude sea-surface temperatures: an evaluation of the CLIMAP reconstruction with emphasis on the positive SST anomalies. Final report, Brown Univ., Providence, RI (USA). Dept. of Geological Sciences, 1985.

Robinson, A., Alvarez-Solas, J., Calov, R., Ganopolski, A., and Montoya, M.: MIS-11 duration key to disappearance of the Greenland ice sheet, Nature communications, 8, 16008, 2017.

Robinson, S. G. and McCave, I. N.: Orbital forcing of bottom-current enhanced sedimentation on Feni Drift, NE Atlantic, during the mid-Pleistocene, Paleoceanography, 9, 943-972, 1994.

Smilenova, A., Gula, J., Le Corre, M., Houpert, L., and Reecht, Y.: A persistent deep anticyclonic vortex in the Rockall Trough sustained by anticyclonic vortices shed from the slope current and wintertime convection, Journal of Geophysical Research: Oceans, 125, e2019JC015905, 2020.

Thornalley, D. J. R., Elderfield, H., and McCave, I. N.: Holocene oscillations in temperature and salinity of the surface subpolar North Atlantic, Nature, 457, 711-714, 2009.

Veres, D., Bazin, L., Landais, A., Toyé Mahamadou Kele, H., Lemieux-Dudon, B., Parrenin, F., Martinerie, P., Blayo, E., Blunier, T., and Capron, E.: The Antarctic ice core chronology (AICC2012): an optimized multi-parameter and multi-site dating approach for the last 120 thousand years, Climate of the Past, 9, 1733-1748, 2013.

Waelbroeck, C., Labeyrie, L., Duplessy, J. C., Guiot, J., Labracherie, M., Leclaire, H., and Duprat, J.: Improving past sea surface temperature estimates based on planktonic fossil faunas, Paleoceanography, 13, 272-283, 1998.

Yin, Q. and Berger, A.: Interglacial analogues of the Holocene and its natural near future, Quaternary Science Reviews, 120, 28-46, 2015.