nature portfolio

Peer Review File

Role of land-ocean interactions in stepwise Northern Hemisphere Glaciation

REVIEWER COMMENTS

Reviewer #1 (Remarks to the Author):

Review of Zhong et al, NComms -24-09239-T

I enjoyed reading this paper and apologize for taking extra time because of other obligations; but I didn't want to pass up the opportunity for reviewing this one. The more we learn about the climate evolution of the arctic the more complex it becomes so this paper adds new layers and new connections to our understanding of the earth system. They argue that the increasing aridification of parts of Central Asia (Taklimakan desert) and eastern Asia and increasing westerly winds impacted the onset of Northern Hemisphere glaciation (they call oNHG starting 3.6 Ma) and intensification (iNHG, starting 2.7 Ma). I also took the time to read some of the background papers including one by Hall et al 2024 that just came out in the last week or so -- this paper is not completely cited in the references because its rather new but critical to questions about gateways to the arctic.

I will frame my comments using the line numbers.

Line 32 : sediments provide a unique archive FOR RECONSTUCTING windblown dust

Extended data Figure 1 should be in the main paper as Figure 2 and then make Fig 2 into 3. You leap right to the extended figures before getting to figure 2. So I suggest a reorganization of the important data figures.

Line 84: what is clearly western and central N. Pacific for figure 2. Central would be IODP 1208 but not sure what you are comparing. Figure 2 does not contain data from 882 or 885?

Line 87: Arctic ocean IRD at 3.6 and 3.3 Ma are single points, not a trend. But definitely a big shift after 2.7 Ma.

Line 97: Scaling of dust with ice volume? Should you plot 2a vs the data in e and f to confirm that?

Line 106: What is the significance of the yellow arrows in Ext Data figure 3. Add to the caption the significance of the gateways ?

Line 114: spelling of “account”. And here you are referring to modeled open and closed

Bering strait. The new Hall et al. 2024 paper argues that the strait was open for mPWP so I assume that is the direction you are taking here. See my notes below about the confusing Fig3 and clarifying the difference maps. Not sure your point is clear in the paper.

Line 122: Narrowing of Indonesian through way….here you should note Yellow arrows on Ext data figure 3.

Line 133: You are not clear to me what is driving increased dust at 3.6 Ma? Is it a CO2 threshold or uplift of Himalayas ?

Line 150: we analyze the climate modeling…? Not clear to me that the Haug and Tiedemann paper tests to mPWP and I have not read Prudhomme et al. in a journal I haven't heard of before.

Line 154 -- remove "in". not needed.
Line 155 – Glaciation started in SW Alaska with uplift of the coastal ranges as early as 7 Million yrs ago. So likely ice there in M2 agreed.

Line 158 – Alaskan "coastal" glaciers were …..
Line 161 -- Your Fig 4 C iNhg is likely too big. The tills that are >2.4 Ma in Nebraska suggest a large extent and likely low lying wetbased ice sheet. The proposal of Clark e tal 2024 for an LGM sized ice sheet is highly controversial and would force one to throw out all of the well documents continental shelf stratigraphy but people like Ken Miller.

Figure 4, d-f line 172. Seems the magnitude of difference here for d,e,f would be easier to see if you kept the x- axis the same. Or can you add the wind speed today? And line 173 I can't see what you mean about seasonal increase in Winds? You say "stronger throughout the year", but the axes are latitude vs wind speed. Some information missing here in this paragraph.

Line 179 – What is the Y-axis in figure Extended Data SFig 7? Assume its annual mean temp in degrees C. Please add axes to figures. Please also add elevation of these pressures. (1.5 km, 5.5 km, and 20 km because you mention middle troposphere height in line 183. Remember not all readers are atmospheric scientists.

Line 188 – MIS M2 is not a larger Northern Hemisphere ice sheet if you see Fig 4B. It is bigger than PlioMip 1 but is the M2 expansion in Figure 4b enough? Seem you are saying it is.

Line 207-210- Shifts in vegetation in figure SFig8 convincing for 8e and g but not for f given that there are 3 spikes to C4 equal to what is at 2 Million in lower resolution sampling.

Line 506 – The paper is rather confusing about testing an open and closed Bering strait. Figure 3 the word changes should be anomalies as in the last line of the caption. I can't tell from the text if you think an open or closed Bering strait increases the wind speeds. Please clarify in the caption and also in the Mode1 discussion lines 463-466.

Line 476 – here it sounds like you performed Mode 2 with only Prism3 open Bering strait. Correct?

I suggest the paper needs some moderate corrections for clarity. This paper will join a suite of papers looking for additional causes and feed backs for the onset of NH glaciation. With some clarity in the model outcomes the paper will be more understandable and more impactful.

Reviewer #2 (Remarks to the Author):

This is an interesting paper on the nature and forcings behind glacial climatic cycles. I think there a lot of merit in the paper. I have specific comments on the dust aspects of this paper and I focus on this below.

Line 527 "but with an LGM ice-sheet configuration". Please define the LGM here: Last Glacial Maximum

The role of dust as an indicator of the state of the global hydrological cycle is well known in the study of Pleistocene glaciations and associated glacial cycles. It would be useful to refer to the key papers on this matter, which are currently not cited in your paper. These include:

Lambert, F., Delmonte, B., Petit, J.R., Bigler, M., Kaufmann, P.R., Hutterli, M.A., Stockler, T.F., Ruth, U., Steffensen, J.P., Maggi, V., 2008. Dust¬–climate couplings over the past 800,000 years from the EPICA Dome C ice core. Nature 452, 616-619.

Lambert, F., Bigler, M., Steffensen, J.P., Hutterli, M., Fischer, H., 2012. Centennial mineral dust variability in high-resolution ice core data from Dome C, Antarctica. Climate of the

Past 8, 609-623.

Ruth, U., Bigler, M., Rothlisberger, R., Siggaard-Andersen, M.L., Kipfstuhl, S., Goto- Azuma, K., Hansson, M.E., Johnsen, S.J., Lu, H.Y., Steffensen, J.P., 2007. Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate. Geophysical Research Letters 34 (3), L03706. doi:10.1029/2006GL027876.

These papers highlight how dust is a strong indicator of glbola climate change as recorded in the polar ice core records, especially Antarctica. The Ruth et al. 2007 paper is especially relevant to your manuscript.

The role of dust in global glacial cycles in the Pleistocene is also reviewed in these papers:

Hughes, P.D. and Gibbard, P.L., 2018. Global glacier dynamics during 100 ka Pleistocene glacial cycles. Quaternary Research, 90(1), pp.222-243.

Hughes, P.D., Gibbard, P.L. and Ehlers, J., 2020. The "missing glaciations" of the Middle Pleistocene. Quaternary Research, 96, pp.161-183.

The Pleistocene is important because the records are better resolved than the Pliocene. The Pleistocene glacial cycles were also much more pronounced and large-amplitude compared with the Pliocene. So, some comparison is very relevant.

Line 141: The two papers above highlighted how the global ice volume record in benthic isotopes is dominated by the Laurentide Ice Sheet over North America. So, it would be more precise to state after "global ice volume, as represented by the benthic oxygen isotope record (Fig. 2a)". that "This was largely driven by changes in the Laurentide Ice Sheet in the Pleistocene glacial cycles (Hughes et al. 2020) and this is likely to have been the case in the Pliocene too".

Responses to the suggestions and comments by Reviewer 1

Thank you very much for your constructive comments and suggestions. Here is our point-by-point response:

1. I enjoyed reading this paper and apologize for taking extra time because of other obligations; but I didn't want to pass up the opportunity for reviewing this one. The more we learn about the climate evolution of the arctic the more complex it becomes so this paper adds new layers and new connections to our understanding of the earth system. They argue that the increasing aridification of parts of Central Asia (Taklimakan desert) and eastern Asia and increasing westerly winds impacted the onset of Northern Hemisphere glaciation (they call oNHG starting 3.6 Ma) and intensification (iNHG, starting 2.7 Ma). I also took the time to read some of the background papers including one by Hall et al 2024 that just came out in the last week or so -- this paper is not completely cited in the references because its rather new but critical to questions about gateways to the arctic.

Response: We really appreciate these feedbacks on our work, and thank you very much for your review work. We cannot find the latest published paper of Hall et al., 2024. However, we have added a new reference on the "Timing and consequences of Bering Strait opening: New insights from $^{40}Ar/^{39}Ar$ dating of the Barmur Group ((Tjörnes Beds), Northern Iceland" (Hall et al., 2023, Paleoceanography and Paleoclimatology). The Bering Strait gateway tends to cool the North Atlantic-Arctic region and promotes formation of sea-ice, in comparison with a closed gateway scenario. We added some discussion about the impact of the Bering Strait opening/closing in the Lines 121-140.

2. Line 32: sediments provide a unique archive FOR RECONSTUCTING windblown dust

Response: Changed accordingly in Line 33.

3. Extended data Figure 1 should be in the main paper as Figure 2 and then make Fig 2 into 3. You leap right to the extended figures before getting to figure 2. So I

suggest a reorganization of the important data figures.

Response: We have added the former Figure S1 to the main text Figure 2.

4. Line 84: what is clearly western and central N. Pacific for figure 2. Central would be IODP 1208 but not sure what you are comparing. Figure 2 does not contain data from 882 or 885?

Response: We moved Figure S1 to become Figure 2 to the main text. We compare ODP Site 1208 (36.1°N, 158.2°E, 3,346 m water depth) and Site 885/886 (44.7°N, 168.2°W, 5,709/5,714 m water depth) in the western and central North Pacific, respectively. Site 885/886 is located downwind of Asia and is sufficiently far from the continent to preclude riverine inputs and ice-rafted debris influences. In order to compare with the central North Pacific record clearly, we now refer to Figure 2b in Lines 86-88.

5. Line 87: Arctic ocean IRD at 3.6 and 3.3 Ma are single points, not a trend. But definitely a big shift after 2.7 Ma.

Response: We agree with your comments. The IRD record of Hole 911A provides a regional view on the extent of the northern Svalbard/Barents Sea Ice sheet, but more importantly offers insight into a full sequence of long-term and major trends in the evolution of NHG in the Arctic region. We recognized three IRD events between ~4 and ~2.5 Myr ago: (1) during the onset of NHG (~3.6 Myr ago); (2) during marine isotope stage (MIS) M2, the first large-scale glaciation (3.3 Ma); (3) during glacial MIS G6/4 around 2.7 Myr ago. We compared the IRD maxima with Zr/K ratios, illustrating enhanced supply of glacially derived coarse-grained material from northern Svalbard (Figure R1). In general, our dust flux changes correspond to ice-rafted detritus (IRD) peaks in the Arctic Ocean at the onset of NHG (~3.6 Myr ago), MIS M2 (~3.3 Myr ago) and the pronounced increase after 2.73 Myr ago (Fig. 3c). We made modifications in Lines 88-89 to better elucidate this context.

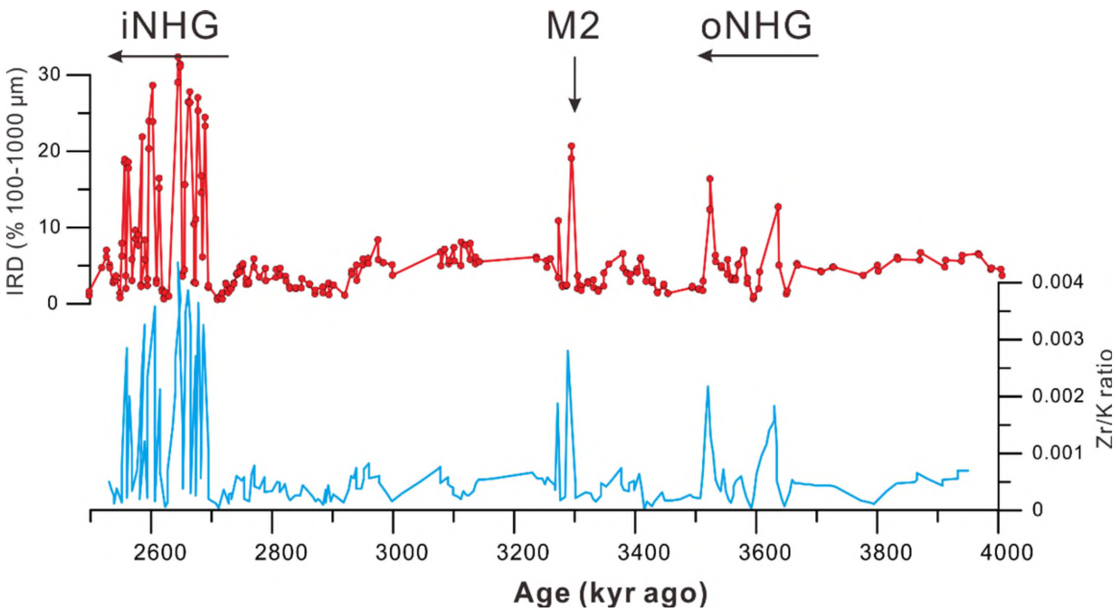

Fig. R1. IRD (wt.%) and Zr/K ratio in bulk sediments of Hole 911A (Knies et al., 2014). The onset of the Northern Hemisphere Glaciation (oNHG) at ~3.6 Myr ago, the MIS M2 glaciation at ~3.3 Myr ago, and the intensification of NHG (iNHG) at ~2.7 Myr ago are highlighted.

6. Line 97: Scaling of dust with ice volume? Should you plot 2a vs the data in e and f to confirm that?

Response: Thank you for this comment. We have now realized that this phrase should be used rigorously and is not suitable for our sentence. We want to express that the change in dust generally corresponds to the change in ice volume. Therefore, we change this "varied proportionally" to "align with" in Lines 99-101.

7. Line 106: What is the significance of the yellow arrows in Ext Data figure 3. Add to the caption the significance of the gateways?

Response: In the model 1 (3.6~3.3 Myr ago), we suggest the Bering Strait and Indonesian Throughflows might have contributed to cooling the northern high latitudes. We utilized the model simulations to further predict that the weaker AMOC, influenced by the inflow of Pacific water through an open Bering Strait. In this case, it have reduced northward heat transport, leading to a steepening of meridional temperature gradient in the Northern Hemisphere. Moreover, modeling studies suggest that restriction of the Indonesian Gateway from 4 and 3 Myr ago caused by the northward movement of the Australian Plate and the emergence of the Halmahera region caused a major switch in the Indonesian Throughflow source water. In this scenario, warm saline waters sourced from the South Pacific via the Halmahera region were cut off when the Bird's Head uplifted, leading to a switch to less saline North Pacific water (Cane and Molnar, 2001; Brierley and Fedorov, 2016).

Recent modelling study by Tan et al. (2022) found that the narrowing of the Indonesian seaway may also increase the meridional gradient of sea surface temperature in the North Pacific, leading to cooling over the northern high latitudes. To avoid ambiguity in the figure caption regarding the yellow arrows, we have added some descriptions related to the opening and restriction of the Bering Strait and Indonesian Gateways. Please see the modifications in Supplementary Figure 2.

8. Line 114: spelling of "account". And here you are referring to modeled open and closed Bering strait. The new Hall et al. 2024 paper argues that the strait was open for mPWP so I assume that is the direction you are taking here. See my notes below about the confusing Fig3 and clarifying the difference maps. Not sure your point is clear in the paper.

Response: We agree with this comment and added some clarifications in Lines 135-137. In regards to the relationship between Bering Strait evolution and the onset of Northern Hemisphere Glaciation, we added some new discussions to the main text. Pleases see the modifications in Lines 121-140.

9. Line 122: Narrowing of Indonesian through way….here you should note Yellow arrows on Ext data figure 3.

Response: We added new figure captions to explain the yellow arrows, and we update the grey arrows in Supplementary Figure 2.

10. Line 133: You are not clear to me what is driving increased dust at 3.6 Ma? Is it a CO_2 threshold or uplift of Himalayas?

Response: We would like to express our gratitude to the Reviewer for this insightful comment. Our conclusions suggest that neither a CO_2 threshold nor the uplift of the Himalayas was the driving mechanism behind the increased dust flux at 3.6 Ma. Instead, the opening of the Bering Strait facilitated a weakened AMOC state and a steepening of the meridional temperature gradient in the Northern Hemisphere. Such a steepened gradient would induce a strengthening of the mid-latitude jet stream and westerly winds in the mid to lower troposphere, facilitating the transport of Asian dust into the North Pacific. We have modified Lines 121-140 to better elucidate this aspect of our findings.

11. Line 150: we analyze the climate modeling…? Not clear to me that the Haug and Tiedemann paper tests to mPWP and I have not read Prudhomme et al. in a journal I haven't heard of before.

Response: Thank you very much for this important comment. We meant to state that our climate modeling results represent the climate of the mPWP, MIS M2 and iNHG based on the Mode 2 simulation as outlined in the Method section. The references of Haug et al. (1998) and Prud'homme et al. (2021) were deleted in Lines 178-180.

12. Line 154: remove "in". not needed.

Response: Done as suggested.

13. Line 158 – Alaskan "coastal" glaciers were …..

Response: We modified this sentence in Line 184-187.

14. Line 161 -- Your Fig 4 C iNhg is likely too big. The tills that are >2.4 Ma in Nebraska suggest a large extent and likely low lying wetbased ice sheet. The proposal of Clark et al., 2024 for an LGM sized ice sheet is highly controversial and would force one to throw out all of the well documents continental shelf stratigraphy but people like Ken Miller.

Response: Yes, we agree with that. The size of the ice sheet was likely nor as big as the LGM, as indicated by the evidence you provided as well as the sea level reconstruction of Miller et al. (2020), in which the sea level decline in the late Pliocene is much weaker than in the LGM.

At this juncture, it's important to clarify that our simulation is an ideal sensitivity setup outlined by Tan et al. (2018). The original motivation for this simulation was to explore possible climate feedback as the Laurentide ice sheet expanded, as suggested by some studies (Balco and Rovey, 2010). Due to the unconstrained extent of the ice sheet and the computational resources required for the climate simulations, we apologize for not conducting new and multiple sensitivity experiments for different ice sheet sizes.

Additionally, to avoid misunderstanding by the readers, we have amended the previous sentence in Lines 164-165 as follows: "We note that this might be probably an overestimation of Northern Hemisphere ice volume (Fig. 5c), but it may represent a possible scenario for the extent of the Laurentide ice-sheet as reported previously. We chose this rather extreme scenario to investigate the sensitivity of the atmospheric circulation to changes in ice sheet extent under Pliocene boundary conditions. Please refer to the modifications in Lines 188-193.

15. Figure 4, d-f line 172. Seems the magnitude of difference here for d,e,f would be easier to see if you kept the x- axis the same. Or can you add the wind speed today? And line 173 I can't see what you mean about seasonal increase in Winds? You say "stronger throughout the year", but the axes are latitude vs wind speed. Some information missing here in this paragraph.

Response: Because the magnitude of the wind speed varies considerably at different pressure levels, using the same x-axis is not a suitable for this plot. Instead, we have added in Figure R2 (black line in e, f, g) the modern zonal wind simulated with the same model. As shown in that figure the modern zonal wind at 850 hPa and 500 hPa is similar to the MIS M2 scenario, as their NHIS extents are comparable. However, it's worth noting that the boundary conditions (topography, bathymetry, land-sea mask and vegetation) differ in the modern experiment compared to the other three "Pliocene" experiments. Therefore, we have chosen not to include the modern results in our paper to maintain readability and clarity of the results.

Regarding the second comment, we compare the mean annual, summer and winter results, and we find that the zonal wind speed are stronger at 850hPa and 500hPa throughout the year. We apologize not including the supplementary seasonal results in this context initially, and we have now added this information.

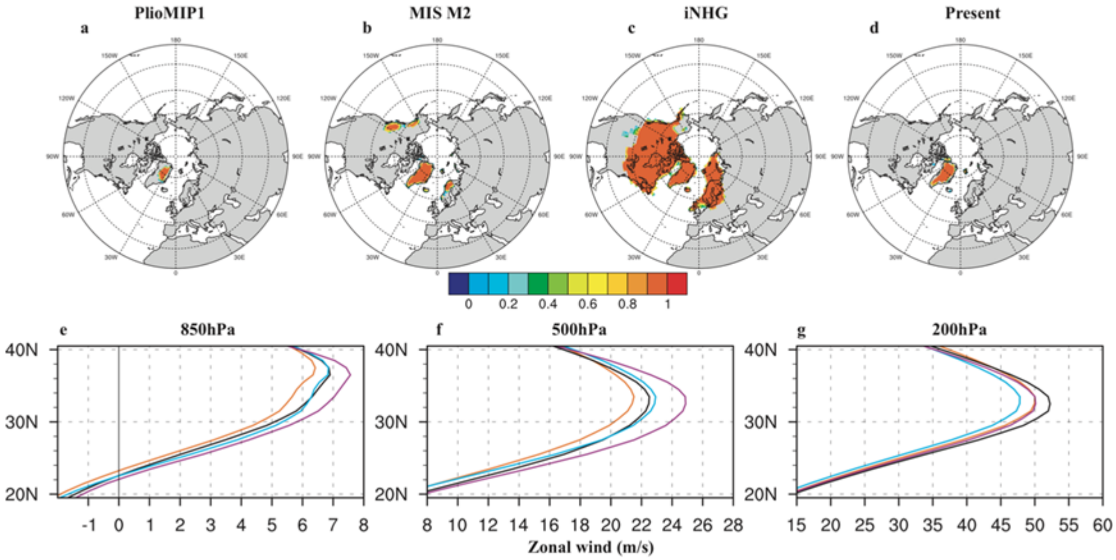

Figure R2. Modelled ice sheet and zonal wind changes under four climate conditions. The shaded colour in a, b, c, d indicates the land ice fraction. The average zonal wind at different pressure levels (e, f, g) is calculated for longitudes between 120°E and 150°E, corresponding to the dominant dust source region in the North Pacific. The orange, blue, purple and black curves represent PlioMIP1, MIS M2, iNHG and present simulations, respectively. The 850 hPa, 500 hPa and 200 hPa pressure levels generally correspond to altitudes of ~1.5 km, ~5.5 km and ~12 km, respectively, but can vary due to the air conditions and geographic location.

16. Line 179 – What is the Y-axis in figure Extended Data SFig 7? Assume its annual mean temp in degrees C. Please add axes to figures. Please also add elevation of these pressures. (1.5 km, 5.5 km, and 20 km because you mention middle troposphere height in line 183. Remember not all readers are atmospheric scientists.

Response: Indeed, Fig. S7 displays the mean annual air temperature in degrees C. We have added axes to that figure and also added the altitudes according to these pressure levels. However, the actual altitude corresponding to a given pressure level varies a lot depending on factors such as temperature and geographical location. We have clarified that in the legend of Figure 5 of the main text (previously Figure 4 of the main text).

17. Line 188 – MIS M2 is not a larger Northern Hemisphere ice sheet if you see Fig 4B. It is bigger than PlioMip 1 but is the M2 expansion in Figure 4b enough? Seem you are saying it is.

Response: In fact, MIS M2 is a significant glaciation for this period. It is clearly evident in the benthic stable oxygen isotope ($\delta^{18}O$) based on sea level reconstructions (Westerhold et al., 2018; Miller et al., 2012; Naish et al., 2009). However, the extent of the NHIS during M2 as considered in this study may not be large enough, as the reconstructed sea level drop for during M2 is between 20 and 60 meters. The NHIS of MIS M2 simulated by Tan et al (2017) is in the lower range of this estimate, but all favorable conditions of the M2 period for ice growth were considered.

18. Line 207-210- Shifts in vegetation in figure SFig8 convincing for 8e and g but not for f given that there are 3 spikes to C4 equal to what is at 2 Million in lower resolution sampling.

Response: We deleted graph f in Figure S8 and updated the Figure S8 in the supporting information accordingly.

19. Line 506 – The paper is rather confusing about testing an open and closed Bering strait. Figure 3 the word changes should be anomalies as in the last line of the caption. I can't tell from the text if you think an open or closed Bering strait increases the wind speeds. Please clarify in the caption and also in the Mode1 discussion lines 463-466.

Response: Our finding is that an open Bering Strait increases ocean-atmospheric-land teleconnections, thereby enhancing the mid-latitude jet stream and westerly winds in the mid to lower troposphere, which in turn facilitates the transport of Asian dust into the North Pacific.

To clarify our conclusion, we have modified the Mode 1 simulation description in the Methods sections in Lines 342-353.

We also changed “changes in” to “anomalies” in the Figure 4 caption, following Reviewer #1’s suggestion. We also highlight in the caption that anomalies indicate “the difference between open BS and closed BS conditions (i.e., open BS climate minus closed BS climate)”.

20. Line 476 – here it sounds like you performed Mode 2 with only Prism3 open Bering Strait. Correct?

Response: Yes, all three simulations for Mode 2 (PlioMIP 1, MIS M2, iNHG) use the boundary conditions of PlioMIP phase, in which the Bering Strait is set to open.

21. I suggest the paper needs some moderate corrections for clarity. This paper will join a suite of papers looking for additional causes and feed backs for the onset of NH glaciation. With some clarity in the model outcomes the paper will be more understandable and more impactful.

Response: We would like to extend our sincere appreciation to the Reviewer for their support. We have endeavored to better clarify and explain our model outcomes to enhance understandability and impact.

References

Balco, G. & Rovey, C. W. Absolute chronology for major Pleistocene advances of the Laurentide Ice Sheet. *Geology* **38**, 795-798 (2010).

Brierley, C. M. & Fedorov, A. V. Comparing the impacts of Miocene–Pliocene changes in inter-ocean gateways on climate: Central American Seaway, Bering Strait, and Indonesia. *Earth and Planetary Science Letters* **444**, 116–130 (2016).

Cane, M. A. & Molnar, P. Closing of the Indonesian seaway as a precursor to east African aridification around 3–4 million years ago. *Nature* **411**, 157–162 (2001).

Hall, J. R., Allison, M. S., Papadopoulos, M. T., Barfod, D. N., & Jones, S. M. Timing and Consequences of Bering Strait Opening: New Insights from $^{40}Ar/^{39}Ar$ dating of the Barmur Group (Tjörnes Beds), Northern Iceland. *Paleoceanography and Paloclimatology* **38**, e2022PA004539 (2023).

Knies, J., et al. Effect of early Pliocene uplift on late Pliocene cooling in the Arctic–Atlantic gateway. *Earth and Planetary Science Letters* **387**, 132–144 (2014).

Miller, K. G., et al. Cenozoic sea-level and cryospheric evolution from deep-sea geochemical and continental margin records. *Science Advances* **6**, eaaz1346 (2020).

Naish, T., et al. Obliquity-paced Pliocene West Antarctic ice sheet oscillations. *Nature* **458**, 322-328 (2009).

Tan, N., et al. Exploring the MIS M2 glaciation occurring during a warm and high atmospheric CO_2 Pliocene background climate. *Earth and Planetary Science Letters* **472**, 266–276 (2017).

Tan, N., et al. Recognizing the Role of Tropical Seaways in Modulating the Pacific Circulation. *Geophysical Research Letters* **49**, e2022GL099674 (2022).

Tan, N., et al. Dynamic Greenland ice sheet driven by pCO_2 variations across the Pliocene Pleistocene transition. *Nature Communications* **9**, 4755 (2018).

Westerhold, T., Rohl, U., Donner, B., & Zachos, J. C. Global Extent of Early Eocene Hyperthermal Events: A New Pacific Benefit Foraminiferal Isotope Record From Shatsky Rise (ODP Site 1209). *Paleoceanography and Paleoclimatology* **33**, 626-642 (2018).

Responses to the suggestions and comments by Reviewer 2

We would like to thank the Reviewer for her/his constructive comments and suggestions.

1. Line 527 "but with an LGM ice-sheet configuration". Please define the LGM here: Last Glacial Maximum.

Response: We modified this sentence in Line 371.

2. The role of dust as an indicator of the state of the global hydrological cycle is well known in the study of Pleistocene glaciations and associated glacial cycles. It would be useful to refer to the key papers on this matter, which are currently not cited in your paper. These include:

Lambert, F., Delmonte, B., Petit, J.R., Bigler, M., Kaufmann, P.R., Hutterli, M.A., Stockler, T.F., Ruth, U., Steffensen, J.P., Maggi, V., 2008. Dust¬–climate couplings over the past 800,000 years from the EPICA Dome C ice core. Nature 452, 616-619.

Lambert, F., Bigler, M., Steffensen, J.P., Hutterli, M., Fischer, H., 2012. Centennial mineral dust variability in high-resolution ice core data from Dome C, Antarctica. Climate of the Past 8, 609-623.

Ruth, U., Bigler, M., Rothlisberger, R., Siggaard-Andersen, M.L., Kipfstuhl, S., Goto- Azuma, K., Hansson, M.E., Johnsen, S.J., Lu, H.Y., Steffensen, J.P., 2007. Ice core evidence for a very tight link between North Atlantic and east Asian glacial climate. Geophysical Research Letters 34 (3), L03706. doi:10.1029/2006GL027876.

These papers highlight how dust is a strong indicator of glbola climate change as recorded in the polar ice core records, especially Antarctica. The Ruth et al. 2007 paper is especially relevant to your manuscript.

The role of dust in global glacial cycles in the Pleistocene is also reviewed in these papers:

Response: Done as suggested.

3. Hughes, P.D. and Gibbard, P.L., 2018. Global glacier dynamics during 100 ka

Pleistocene glacial cycles. Quaternary Research, 90(1), pp.222-243.

Hughes, P.D., Gibbard, P.L. and Ehlers, J., 2020. The "missing glaciations" of the Middle Pleistocene. Quaternary Research, 96, pp.161-183.

The Pleistocene is important because the records are better resolved than the Pliocene. The Pleistocene glacial cycles were also much more pronounced and large-amplitude compared with the Pliocene. So, some comparison is very relevant.

Line 141: The two papers above highlighted how the global ice volume record in benthic isotopes is dominated by the Laurentide Ice Sheet over North America. So, it would be more precise to state after "global ice volume, as represented by the benthic oxygen isotope record (Fig. 2a)". that "This was largely driven by changes in the Laurentide Ice Sheet in the Pleistocene glacial cycles (Hughes et al. 2020) and this is likely to have been the case in the Pliocene too".

Response: We agree with your comments on the importance of Pleistocene glacial cycles. We have modified the Lines 99-103 concerning this point.

Responses to the suggestions and comments by Reviewer 1

Thank you very much for your constructive comments and suggestions. Here is our point-by-point response:

This is my second review of the paper and they seem to have addresses most or all of my concerns. I am attaching a file with most of my comments in BOLD, highlighting some lingering issues with the paper that are mostly editorial or mislabeling of figures.

Response: Thank you for your suggestions in our manuscript. According to your comments in BOLD, we made some modifications in the revised version.

(1) We added “that” in Line 31.

(2) In regards to the mislabeling of figures, we have checked our figures and made some modifications in context.

(3) We changed “was” as “were” in Line 102.

(4) We added “temporally distinct” in Line 111.

(5) We change “Mode 1” as “Mode 1 (3.6–3.3 Ma)” in Line 112.

(6) We added “persistently” in Line 126.

(7) We added “persistent” in Line 145.

(8) We added “in the North Atlantic” in Line 146.

(9) We change the Fig. 3g in Line 172.

(10) We added “Northern Hemisphere” and “events” in Line 227.

(11) We added “as early as 5.5 Ma” in Line 346.