

Authors' reply to Anonymous Referee #1 (RC1)

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Dynamical Mechanism behind the Southern Hemisphere Westerly Intensification during the Last Glacial Maximum: A Linkage between Sea-ice and Polar Front Jet
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Referee comments are reproduced in black; our replies are in blue.

Preamble

We thank the referee for a careful and constructive review, and in particular for the two recommendations. The main changes are as follows, and each comment is addressed in detail below.

1. New sea-ice sensitivity experiments in an LGM background (General Comment, Recommendation 1)
2. Comparison with terrestrial moisture proxies and with the modern sea-ice record (Recommendation 2, Specific Comment 1)
3. Revised interpretation of the sea-ice contribution to the LGM shift (General Comment, Technical Correction 1)
4. Clarifications in the Methods, captions and Discussion, with the Summary moved after the Discussion (Specific Comments 2–4, Technical Corrections 2–3)

General Comment

Referee comment:

This paper uses the CESM1.2 Earth System model to examine the mechanisms controlling shifts in the position and intensity of the Southern Hemisphere Westerly winds during the Last Glacial Maximum (LGM). It first examines changes in the SHW between the LGM and pre-industrial (PI) simulations and then conducts a series of sensitivity tests to examine the effects of step-wise sea-ice expansion on changes in the SHW.

The paper demonstrates that the CESM 1.2 model simulates a poleward shift and intensification of the SHW during the LGM, via two mechanisms: (a) the intensification of the meridional temperature gradient, and (b) enhanced baroclinity that intensifies eddy heat fluxes and storm tracks. The authors argue that these factors outweigh the competing factor driving equatorward shifts in the SHW (i.e. cooling of the upper-troposphere in the tropics).

My concern is with the set-up of the sensitivity experiments, which superimpose sea-ice changes on an atmosphere-only PI simulation where the SSTs are prescribed to match modern ocean conditions. The authors use these conditions so that they are solely examining the effects of sea-ice expansion; however, we know

that sea-surface temperatures during the LGM averaged 1.5-5 °C cooler in the Southern Ocean and were as much as 6-8 °C in the zone of the subantarctic zone (see Figure 3, Kohfeld et al., 2013). These substantially cooler SSTs would undoubtedly reduce the surface meridional temperature gradients called upon in these experiments to drive a poleward intensification of the SHW through amplified atmospheric baroclinicity and increased eddy activity. As such, I think that the design of the sensitivity experiments artificially enhances a surface meridional temperature gradient to invoke the anticipated result.

Reply:

As the referee points out, the previous sensitivity experiments expanded sea ice on unchanged PI SSTs, so the surface meridional temperature gradient across the ice edge is sharper than it would be with LGM SSTs.

(a) To directly address the referee's concern, we conducted four additional sensitivity experiments in an LGM background (following Recommendation 1). The SST, greenhouse gases, ice-sheet topography and orbital parameters were set to those of our coupled LGM simulation, and sea ice was prescribed as in the previous experiments, by adding 0, 25, 50 and 75 % of the LGM – PI concentration difference to the PI field. In this background the surface meridional temperature gradient is weaker, yet the sensitivity of the jet latitude to the sea-ice edge is essentially unchanged (-0.44 against -0.35° per degree at 850 hPa, not significantly different). The poleward displacement with expanding sea ice therefore does not depend on the artificially enhanced gradient. What the LGM background changes is the position of the jet, which lies further equatorward (Recommendation 1), rather than its sensitivity to sea ice, and we will make this distinction explicit in the Discussion.

(b) We have also reconsidered how the over-response of the PI-background experiments is described. ICE100, in which LGM sea ice is prescribed on PI SSTs, shifts the jet further poleward than the coupled LGM does (2.7° against 1.9° , Fig. 10). This difference reflects the LGM conditions absent from ICE100, such as the SST, greenhouse gases, ice-sheet topography, orbital parameters and ocean coupling. We will therefore revise the manuscript to state that sea-ice expansion drives the jet poleward and intensifies it, without attributing the net LGM shift to sea ice alone. Our aim is to explain the mechanism of this poleward intensification, not to assess the equatorward influence of the other LGM forcings.

Recommendation 1

Referee comment:

RECOMMENDATION 1: I suspect that the authors could get around this problem with one additional sensitivity experiment in which they select one of their sensitivity tests (e.g., ICE75) and run it again with LGM SSTs prescribed, at least in the Southern Hemisphere. This would allow the authors to isolate the effects of the

artificial surface meridional T gradient imposed by their choice of prescribed conditions.

Reply:

We thank the referee for this suggestion. Rather than prescribing LGM SSTs alone, we conducted four additional experiments (ICE0-LGM to ICE75-LGM) in the LGM background described under the General Comment (a), including ICE75-LGM as the counterpart of the experiment the referee suggests. Each was run for 30 years, with years 6–30 analyzed. We used the full LGM background of our coupled simulation, which includes the LGM SSTs requested here, so that the SST is consistent with the other LGM boundary conditions, as Referee 2 also requested. In this background the sensitivity of the jet latitude to the sea-ice edge at 850 hPa is -0.44° per degree (95 % CI $[-0.62, -0.27]$), against -0.35° in the PI-background experiments (Fig. 10). The jet itself lies $1.6\text{--}3.5^\circ$ further equatorward than in the PI background at the same ice edge, as the referee anticipates, consistent with earlier findings that the LGM forcings other than sea ice displace the jet equatorward (Chavaillaz et al., 2013; Sime et al., 2016). Because the LGM conditions are imposed together, these experiments do not isolate the SST effect, and our conclusion is therefore confined to the sensitivity to sea ice.

Recommendation 2

Referee comment:

RECOMMENDATION 2: Aside from this issue, the analysis of the LGM-PI simulations is interesting and seems sound to me. That said, I suspect that the authors may come up against some challenges, because there is a strong, very vocal contingent in the paleo-community who strongly believes that the SHW shifted equatorward during the LGM. I believe that the data in Kohfeld et al. (2013) are open enough that a poleward shift is possible. The authors have been careful to focus on mechanisms, but I think their argument would be strengthened if they conducted some form of comparison with paleodata, as was done in Sime et al. (2013), showing that even a poleward shift in the westerlies could be consistent with the moisture proxies originally used to infer an equatorward shift in the SHW.

Reply:

We thank the referee for this suggestion. We agree that the poleward shift simulated here disagrees with the equatorward shift commonly inferred from the proxy record, which the PMIP models also do not reproduce (Jiang and Yan, 2020; Gray et al., 2023). Most moisture proxies lie north of the wind maximum (Kohfeld et al., 2013), and few records constrain the latitudes of the sea-ice edge where the mechanism we propose operates, so further proxy records from these latitudes are needed.

Our study aims to explain the mechanism of the poleward intensification rather than to reconstruct the LGM wind position. Nevertheless, whether a poleward shift is

compatible with the moisture proxies bears directly on how our results can be interpreted, and we have therefore examined it. In our coupled LGM simulation the mid-latitude land regions become wetter in P – E even though the jet shifts poleward, and the boundary between the subtropical dry and mid-latitude wet zones moves by only 0.27° despite the 1.9° jet shift. As Kohfeld et al. (2013) noted, the colder glacial climate may also have altered the hydrological cycle independently of the winds, and in our simulation winter evaporation decreases at all the moisture proxy sites examined, whereas sea-ice expansion alone leaves it nearly unchanged. The local wetting therefore cannot be attributed to a wind shift alone, and we will add this comparison briefly to the Discussion. Dust will be discussed only qualitatively, since it does not discriminate between the scenarios.

Specific Comment 1 (Methods: modern sea-ice extent)

Referee comment:

METHODS: Based on Sime et al. (2016) it seems important to know how the CESM 1.2 simulates the modern sea-ice extent. Can you provide a one-sentence clarification?

Reply:

We will add the following sentence to Methods: "In the coupled PI simulation the winter sea-ice edge lies about 2° equatorward of the HadISST climatology for 1979–2008, and the simulated presence or absence of winter sea ice agrees with the modern record at the great majority of the Gersonde et al. (2005) core sites."

Specific Comment 2 (Methods: sea-ice expansion latitudes)

Referee comment:

METHODS: It would be helpful to state in the text the latitudinal expansion of the sea-ice extent in the sensitivity experiments – these values look like they are imbedded in Figure 1 but it would be good to have a one-sentence addition stating them explicitly in the text.

Reply:

We will add the following sentence to Methods: "In JJA the zonal-mean sea-ice edge (0.7 concentration) lies at 63.8 °S in PI and at 60.4, 58.0, 56.0 and 55.4 °S in ICE50, ICE75, ICE100 and ICE125, compared with 56.5 °S in the coupled LGM." At the conventional 0.15 threshold the corresponding edges are 57.5, 51.8, 50.8, 50.3, 49.9 and 51.3 °S, respectively, and this comparison will be given in the revised manuscript.

Specific Comment 3 (Figure captions)

Referee comment:

FIGURE CAPTIONS: It would be useful to indicate in the Figure Captions which figures are using the fully coupled earth-system model and which are based on the sensitivity experiments.

Reply:

We will indicate in every caption whether the figure is based on the coupled or the atmosphere-only experiments.

Specific Comment 4 (L422–424)

Referee comment:

LN 422-424: Many readers/subsequent authors overlook the fact that Kohfeld et al. (2013) left the interpretation of the paleo-data quite open. They actually concluded that a 3-5° equatorward expansion was ONE POSSIBLE interpretation of the paleo data. Kim et al. make this point earlier in the paper (and should here as well); there are several OTHER interpretations that are consistent with the paleodata reconstructions.

Reply:

We thank the referee for this suggestion. Following the conclusion of Kohfeld et al. (2013) that several wind scenarios are compatible with the paleodata, we will rewrite L422–424 to focus on how our result relates to those scenarios, consistent with L57–59. The Discussion will then no longer present our result as contradicting the proxy record itself but test whether it is compatible with that record (Recommendation 2).

Technical Correction 1 (L20)

Referee comment:

Ln 20: Do you mean surface or upper troposphere cooling?

Reply:

Upper-tropospheric cooling is meant, and we will state this explicitly. The abstract will also no longer claim that sea-ice forcing outweighs it (see our reply to Referee 2).

Technical Correction 2 (Structure)

Referee comment:

STRUCTURE: It is unusual and strange to have a section entitled "Summary and Conclusions" BEFORE you begin the Discussion section. I recommend either (a) retitling the section "Summary" and making it part of Section 3, or (b) expanding the section and moving it AFTER the Discussion.

Reply:

We will adopt option (b) and move the expanded Summary after the Discussion.

Technical Correction 3 (L444–446)

Referee comment:

LN 444-446: I'm not actually sure which model-proxy discrepancy you are referring to here. Can you be more specific, because you haven't actually done any data-model comparisons in this paper.

Reply:

The sentence referred to the discrepancy between proxy reconstructions and model simulations of the LGM westerlies discussed in earlier studies (Gottschalk et al., 2019; Kohfeld et al., 2013), not to a comparison of our own. We did not make this clear, and, as the referee notes, the submitted manuscript contained no comparison of its own. We will rewrite the sentence to cite these studies and to refer to the comparisons described in our replies to Specific Comment 1 and Recommendation 2.

References

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