

Authors' reply to Anonymous Referee #2 (RC2)

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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
Hyeong-Gyu Kim, Joowan Kim, Sang-Yoon Jun, Seong-Joong Kim, and Damwon So

Referee comments are reproduced in black; our replies are in blue.

Preamble

We thank the referee for a constructive review, and in particular for identifying the principal contribution of the paper. In the referee's view, this lies not in showing that sea ice affects the westerlies but in the dynamical framework through which it does so. We have adopted this framing. The main changes are as follows, and each comment is addressed in detail below.

1. Comparison with paleoclimate evidence on LGM sea ice, SST, moisture and circulation (comment 1)
2. New sea-ice sensitivity experiments in an LGM background, and removal of the claim about tropical cooling (comment 2)
3. Positioning relative to Sime et al. (2013, 2016) (comment 3)
4. Reframing around the dynamical pathway from sea ice to the polar-front jet (comment 4)

Major Comment 1 (paleoclimate evidence)

Referee comment:

1. Lack of engagement with palaeoclimate constraints and observations

My most significant concern is that the study is insufficiently grounded in palaeoclimate evidence. There is very little evaluation against LGM sea-ice and SST reconstructions, and no attempt to compare the simulated circulation changes with available wind-sensitive or moisture-sensitive proxy records.

This omission is important because the long-standing debate over LGM Southern Hemisphere westerlies arises specifically from differences between model behaviour and palaeoclimate interpretations. Without a more detailed discussion of observational constraints, it is difficult to assess whether the simulated wind responses are realistic. At present, the study remains largely detached from the palaeoclimate problem that motivates it.

I therefore strongly encourage the authors to place their simulations within the context of available LGM sea-ice, SST, moisture, and atmospheric circulation

reconstructions, and to discuss whether the imposed surface changes and simulated response are consistent with existing proxy evidence.

Reply:

We thank the referee for this suggestion. Evaluating the simulations against the proxy record is necessary to judge how far the simulated response can be taken as realistic. We have therefore compared them with the paleoclimate evidence on LGM sea ice, SST, moisture and circulation, and will add this comparison to the Discussion, as summarized below.

(a) Sea ice. The coupled LGM agrees with the Gersonde et al. (2005) compilation of winter sea-ice presence or absence at 86 % of core sites, so the winter ice edge is well placed. The overexpansion documented for the CCSM4 model family (Green et al., 2022) appears instead in the concentration within the ice zone, which is too high at the core sites, and in the summer extent, which is too large. Since both CESM 1.2 and the sea ice prescribed in our sensitivity experiments derive from this family, we will describe this as a bias of the model family rather than part of the LGM response, and as a limitation.

(b) SST. At the MARGO core sites (MARGO Project Members, 2009) the simulated LGM cooling of the open ocean agrees in sign with the reconstructions at every site and in magnitude to within about 1 °C on average.

(c) Moisture. As in the proxy record, the mid-latitude land regions become wetter in P – E in the coupled LGM, even though the jet shifts 1.9° poleward, partly because evaporation decreases in the colder climate. The local wetting therefore cannot be attributed to a wind shift alone (Referee 1, Recommendation 2).

(d) Circulation. Reconstructions of the LGM westerlies rely on indirect evidence, inferring the winds through a chain of assumptions from terrestrial moisture or from SST-front positions via model relationships (Kohfeld et al., 2013; Gray et al., 2023). Kohfeld et al. (2013) found the evidence easiest to tie to either stronger or equatorward-shifted westerlies, while noting that several scenarios remain compatible. Our coupled LGM is consistent with the stronger scenario but not with the equatorward one, since its jet shifts poleward. Both the agreement and the disagreement remain uncertain, given this chain of assumptions and other estimates that suggest weaker LGM westerlies (Gray et al., 2023). The disagreement in position is shared by the PMIP models, which also do not reproduce the inferred equatorward shift (Jiang and Yan, 2020), and we will discuss it as an open problem. Our study addresses the mechanism by which sea ice drives the poleward intensification of the westerlies, not their LGM position. Dust will be discussed only qualitatively, since it does not discriminate between the scenarios.

Major Comment 2 (imposed surface forcing experiments)

Referee comment:

2. Problems with the imposed surface forcing experiments

The sensitivity experiments are useful for isolating mechanisms, but I am not convinced that the current experimental design is sufficient to support the broader conclusions being drawn regarding the role of Antarctic sea ice in driving SHW wind changes.

The principal issue is that the expanded sea-ice experiments impose substantial sea-ice changes on unchanged piControl SSTs. Whilst such experiments are useful as idealised perturbations, they are not physically representative of LGM surface conditions, where expanded Antarctic sea ice would have been accompanied by substantial local and regional Southern Ocean cooling.

To support the central interpretation of the manuscript, an additional set of experiments should test whether the diagnosed response remains robust when SST changes are dynamically consistent with the imposed sea-ice expansion. In particular, experiments with combined Antarctic sea-ice and polar/subpolar SST changes appear necessary.

A related issue is that the manuscript repeatedly discusses the role of tropical cooling, yet this mechanism is largely inferred rather than directly tested. If the authors wish to conclude that Antarctic sea ice dominates over tropical cooling in determining the SHW response, then targeted tropical SST sensitivity experiments are required. At present, this comparison remains incomplete

Reply:

(a) Dynamically consistent sea ice and SST. We agree and have conducted four further experiments (ICE0-LGM to ICE75-LGM) in which sea ice is varied within an LGM background whose SST, greenhouse gases, ice-sheet topography and orbital parameters are those of our coupled LGM simulation. The same experiments are reported in our reply to Referee 1 (Recommendation 1). The diagnosed response is robust: at 850 hPa the sensitivity of the jet latitude to the sea-ice edge is -0.44° per degree in this background against -0.35° in the PI-background experiments, and the difference is not significant. The jet also strengthens with sea ice in both backgrounds, by 0.38 and 0.26 m s^{-1} per degree of ice-edge displacement in the PI and LGM backgrounds, respectively. What changes is the jet position, which at the same ice edge lies $1.6\text{--}3.5^\circ$ further equatorward in the LGM background. Sea-ice expansion thus drives the poleward tendency but does not by itself set the LGM position, which reflects the competition between sea ice and the other LGM forcings (cf. Sime et al., 2016).

(b) Tropical cooling. Earlier work has related the equatorward tendency of the coupled PMIP simulations to upper-tropospheric tropical cooling (Chavaillaz et al., 2013; Rojas, 2013). The submitted manuscript inferred an equatorward contribution from the difference between the coupled LGM and ICE100 jet shifts. We agree with the assessment in comment 4 that our experiments do not separate tropical from high-latitude forcing. We will therefore describe the earlier findings on tropical cooling as research background, presenting tropical cooling as a possible opposing influence rather than inferring it from our experiments. The revised manuscript will instead focus on the sea-ice pathway that the experiments isolate.

Major Comment 3 (Sime et al., 2013)

Referee comment:

3. Understanding and referencing of the existing literature

The manuscript cites several relevant studies; however, it does not sufficiently engage with earlier work that addresses many of the same questions.

In particular, the authors should read - and then discuss at several points in their manuscript:

Sime, L.C., Kohfeld, K.E., Le Quéré, C., Wolff, E.W., de Boer, A.M., Graham, R.M., and Bopp, L. (2013). Southern Hemisphere westerly wind changes during the Last Glacial Maximum: model–data comparison. *Quaternary Science Reviews*, 64, 104–120.

This study addresses several aspects that are either absent or only partially treated in the present manuscript. First, it places simulated Southern Hemisphere westerly wind changes within the context of LGM palaeoclimate observations, including a systematic comparison against a large synthesis of SST, sea ice, moisture proxy data and discussion of other relevant palaeo-environmental constraints. Second, it explicitly investigates the sensitivity of Southern Hemisphere westerlies to individual LGM boundary conditions, including sea ice, Southern Ocean SSTs, tropical sea surface changes, greenhouse gases, orbital forcing, and ice-sheet changes. The study identified sea-surface temperature/ice changes, particularly those associated with enhanced Southern Ocean temperature gradients, as a dominant control on simulated wind changes, while also demonstrating an important role for tropical cooling.

As a result, Sime et al. (2013) addresses many of the broader questions that motivate the present manuscript. I therefore encourage the authors to position their contribution more clearly relative to this earlier work, particularly with regard to observational constraints and the interpretation of sensitivity experiments.

Reply:

We have examined Sime et al. (2013, 2016) in detail and will rewrite the Introduction and Discussion around them on the two points the referee raises, the observational constraints and the interpretation of the sensitivity experiments. Sime et al. (2013) reported a poleward displacement of about 2° and a strengthening of about 1 m s^{-1} at 850 hPa under LGM boundary conditions and related them to a steeper Southern Ocean temperature gradient and increased baroclinicity. Sime et al. (2016) then showed across the PMIP3 models that sea-ice expansion shifts the jet poleward when the PI jet lies poleward of 47°S , and proposed that the temperature gradient at the new ice edge acts on developing baroclinic waves.

Our results are consistent with both studies: the PI jet (52.7°S) lies in the range where the sea-ice response operates, and within one model the jet shifts poleward by 0.35° per degree of sea-ice expansion in the PI background and 0.44° in the LGM background, against 0.85° across the PMIP3 models (0.43° without MRI-CGCM3; Sime et al., 2016, Fig. 7b). On observational constraints, Sime et al. (2013) found that the moisture proxies are matched best by the simulation with a small poleward shift and do not require an equatorward one, and our comparison with the moisture proxies (comment 1(c)) follows that approach.

These studies related the jet response to the near-surface temperature gradient and baroclinicity, leaving the eddy response that connects them to be diagnosed. As the referee notes, this diagnosis is where our contribution lies: in the coupled LGM, the expanded sea ice cools the overlying air and sharpens the near-surface temperature gradient, which increases baroclinicity and storm-track activity and alters the EP flux and the residual circulation it drives (Figs. 3 and 5–8; comment 4). We will therefore present the poleward intensification under sea-ice expansion as a response established by Sime et al. (2013, 2016), and our study as the dynamical diagnosis of how sea ice produces it.

Major Comment 4 (framing)**Referee comment:****4. Final comments on framing**

In my view, the principal advance of the present study is not the identification of Antarctic sea ice as a control on LGM westerlies, nor the distinction between tropical and high-latitude forcing – which the current experiments do not demonstrate. Rather, the major contribution is the more detailed dynamical diagnosis linking sea-ice expansion, enhanced baroclinicity, storm-track activity, eddy momentum transport, and strengthening of the polar-front jet. Framing the manuscript more explicitly in this way – alongside considering model-data comparison exercises in any final discussion – would help clarify its novelty and significance.

Reply:

Adopting this framing, we will present the dynamical pathway from sea-ice expansion through baroclinicity, storm-track activity and eddy momentum forcing to the polar-front jet as the principal advance in the abstract, introduction and conclusions, and will make this pathway explicit in the Results. The claim to have distinguished tropical from high-latitude forcing will be removed (comment 2(b)), and the Summary will be moved after the Discussion, as Referee 1 also suggested.

In presenting this pathway we will make the role of each step explicit. The vertical, heat-flux component of the EP-flux divergence transfers westerly momentum downward and intensifies the surface westerlies, as described in the submitted text. The horizontal, momentum-flux component accelerates the flow aloft on the poleward flank of the PI jet and contributes to its poleward displacement. The new experiments enter this framing only at the first step, since their monthly output does not support the eddy diagnostics.

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