Alexandre Pohl (CNRS, France)

General evaluation

Sun et al. use CESM 1.2.2 and the ice-sheet model ISSM to simulate Late Ordovician land ice under an atmospheric CO2 concentration of 6 times the preindustrial value. They run different experiments: forcing ISSM with the CESM monthly output in an offline setup, leading to an ice sheet of small extent; the same simulation but using an asynchronous coupling method allowing this time the ice sheet to reach ~40 ° S, plus two additional simulations where the maximum ice-sheet extent is imposed in CESM with fixed sea-surface temperatures (SST) one the one hand, and with a slab mixed-layer ocean on the other hand.

In terms of land-ice extent and volume, the results are mostly similar to the previous attempt of Pohl et al. (2016). However, the authors focus here on the impact of the ice sheet on climate. They show that an ice sheet reaching the middle latitudes induces an overall warming over most of the ocean. Warming in the Southern Hemisphere arises from changes in atmospheric circulation and radiative budget (as demonstrated in the slab simulations, which include no [changes in] ocean dynamics); warming in the Northern Hemisphere arises from changes in the deep ocean-circulation and ensuing modifications in the oceanic heat transport. I think this manuscript constitutes a very welcome contribution. Attempts to simulate Late Ordovician land ice are few, and I think our 2016 paper was the only one so far including climate-ice-sheet feedbacks. Therefore, it is excellent to see these results obtained independently using other climate and ice-sheet models. The asynchronous coupling method, involving no less than 80 steps, is impressive, and the additional simulations using the slab model and the prescribed SST are clever and helpful. The focus on the impact of land ice on climate is interesting. The paper is also very well written and I had great pleasure reading it. Overall, I strongly encourage publication of the study by Sun et al., after revisions. To complement my evaluation, I would suggest sending the manuscript to an expert in atmospheric science, since I am not competent to properly evaluate this aspect.

Thank you for your kind words. In response to your insightful comments, we will thoroughly revise the manuscript. We address your comments point by point below.

- **Impact of albedo.** Section 3.3 insists a lot on the role of katabatic winds (see also the abstract, lines 12-14, lines 384-387). While I did find this section interesting, I think that the primary role of albedo change in driving land-ice growth is critically missed. My expectation is that changes in albedo are the primary driver of land-ice expansion in the asynchronously coupled simulations. I think that demonstrating the opposite would imply repeating the asynchronously coupled simulation without albedo change. As far as I'm concerned, I think it is not worth the effort considering the amount of work involved and expected outcome (but will happily leave this decision to the authors), and would instead revise the manuscript to insist more on the first-order importance of albedo. I also think that, as we proposed in 2016, the strong temperature gradient at the middle latitudes is key in stabilizing the land-ice front there.

1. **Regarding the supplementary experiment:**

We sincerely thank you for this critical point that albedo change could be the primary driver of land-ice expansion. Following this excellent suggestion, we have performed a new coupled experiment, where we disabled the "land surface type feedback" by repeating the asynchronously coupled simulations without surface type change. The results of the time series are shown in the figure below.

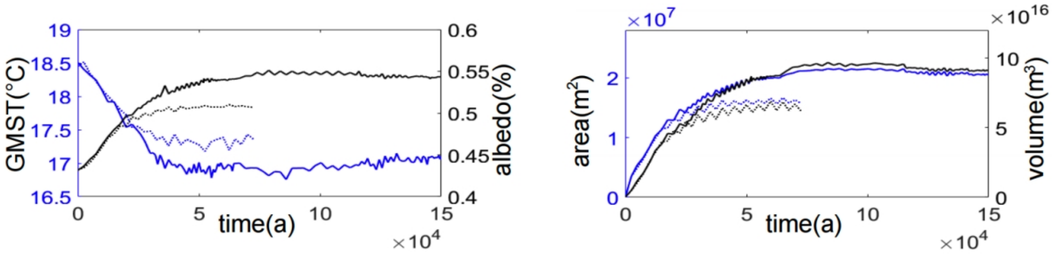


Figure R1. Temporal evolution of GMST, global annual mean land surface albedo, ice-sheet area, and ice-sheet volume. Solid lines show the fully coupled experiment, while dashed lines show the supplementary experiment in which the ice-sheet area was set to 0 during coupling. The left panel shows the evolution of global mean surface temperature (GMST, °C; black) and global annual mean land surface albedo (%; blue), and the right panel shows ice-sheet area (m2; blue) and ice-sheet volume (m3; black).

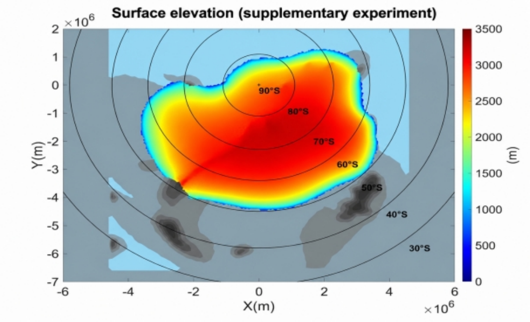


Figure R2. Surface elevation of the ice sheet in the supplementary experiment. The figure shows the final ice-sheet surface elevation(m) of the coupled simulations without surface type change.

The results were revealing. As the Reviewer anticipated, the absence of albedo change did reduce the final extent of land-ice expansion, confirming its important role. Nevertheless, substantial land-ice growth still occurred. The growth of this portion of the ice sheet can be understood as a result of the ice sheet topographic uplift: as the ice sheet surface elevates, temperatures decrease and effectively suppress ablation; simultaneously, the towering ice sheet topography drives strong downslope katabatic winds (as mentioned in main text Sect. 3.3), transporting cold air from the summit to the margins, lowering marginal temperatures to further suppress ablation; last but not least, the elevated, low-temperature environment leads to an expansion of snow cover in the climate model, in which case the snowfall process built in to the CESM and associated snow-albedo feedback partially compensates for the lack of ice-albedo feedback. We believe that here, at least during the supercontinental period, topographic feedback is very important, even more important than the ice-albedo feedback (note that we are not referring to the overall snow-ice-albedo feedback here, because we can not rule out snow-albedo feedback in the simulations).

Overall, the albedo effect is indeed important, and the effect of surface elevation is also significant, both in terms of its impact on large-scale global circulation (the effects of stationary waves) and in more localized aspects (katabatic winds). We intend to emphasize the importance of topography while still discussing albedo. Therefore, we do not plan to treat ice-albedo feedback as a first-order factor; instead, we essentially regard both as important, and we want to particularly stress that during this period, topographic feedback may be even more significant. We chose to dedicate substantial space in the main text to circulation changes, in part because your previous work has successfully elaborated on the abledo effect. Additionally, our main conclusions regarding ocean warming are, after all, directly related to atmospheric processes. Taking all these factors into account, we decided to revise and expand the discussion to clarify and explicitly acknowledge the role of the albedo effect. A time series of the global annual mean land surface albedo will also be included in Fig. 3 (Figure R1 here), and a clear correlation between the two is evident. At the same time, we observe that even without the influence of ice-albedo, the ice sheet still advances significantly and covers a much larger area than the OFFLINE ice sheet, which clearly demonstrates that topographic feedback plays a crucial role. Therefore, taken together, we conclude that it is the combined effect of albedo and topography that supports ice sheet growth in the coupled simulation.

This comparative discussion was indeed omitted from our previous paper; in the revised paper, we will provide brief but conclusive additions to this section and include the results of the supplementary experiments mentioned above. We would be very happy to continue discussing this part with you.

2. the strong temperature gradient at the mid-latitudes:

I also fully agree. As you proposed in 2016, the strong temperature gradient at the mid-latitudes is key in stabilizing the land-ice front there. Building on that, we have added the following discussion: "And as the ice sheet expands, the ice front reaches sufficiently low latitudes, where the surface temperatures sustain high ablation rates. Under such conditions, the enhanced melt counteracts further margin advance, consistent with the negative feedback mechanism described earlier, in which ice-sheet expansion into ablation-prone zones can offset mass gain and finally stabilize the ice sheet. The strong mid-latitude temperature gradient thus could play a key role in stabilizing the land-ice front."

We have included these similar discussions in Sect. 3.3 and 3.4 when discussing the temperature patterns.

- **Equilibrium of the deep-ocean circulation under full glacial conditions?** The authors discuss the changes in the deep-ocean circulation. This is interesting, but I'm not convinced that the latter reached a steady-state following land-ice growth. My understanding is that CESM was integrated for 800 years after land ice *started* to grow would it change the results to integrate CESM for another, say, 1000 years once the ice sheet reaches its final steady state? The response to this question may largely impact the simulated SST change.

We sincerely appreciate your insightful comment regarding the equilibrium state of the deep-ocean circulation. We shared your concern and fully acknowledged that this could potentially affect the simulated SST changes. In fact, a test addressing this concern had already been conducted before the original submission. Specifically, after the coupled ice sheet reached its equilibrium, the climate model was further integrated for 1000 years under the fixed ice-sheet configuration (Fig. R4). The results confirmed that the deep-ocean circulation had already reached a quasi-equilibrium state in the original simulation. We regret that this test was not explicitly described in the earlier manuscript. We have detailed this method in the revised manuscript and updated the corresponding figures and discussion.

The following description has been added to the methods of Sect. 2.3: “After the coupled ice sheet reached its equilibrium state, the climate model was further integrated for an additional 1000 years to allow the deep ocean to approach a steady state.”

We have also updated the images that use this data (not shown).

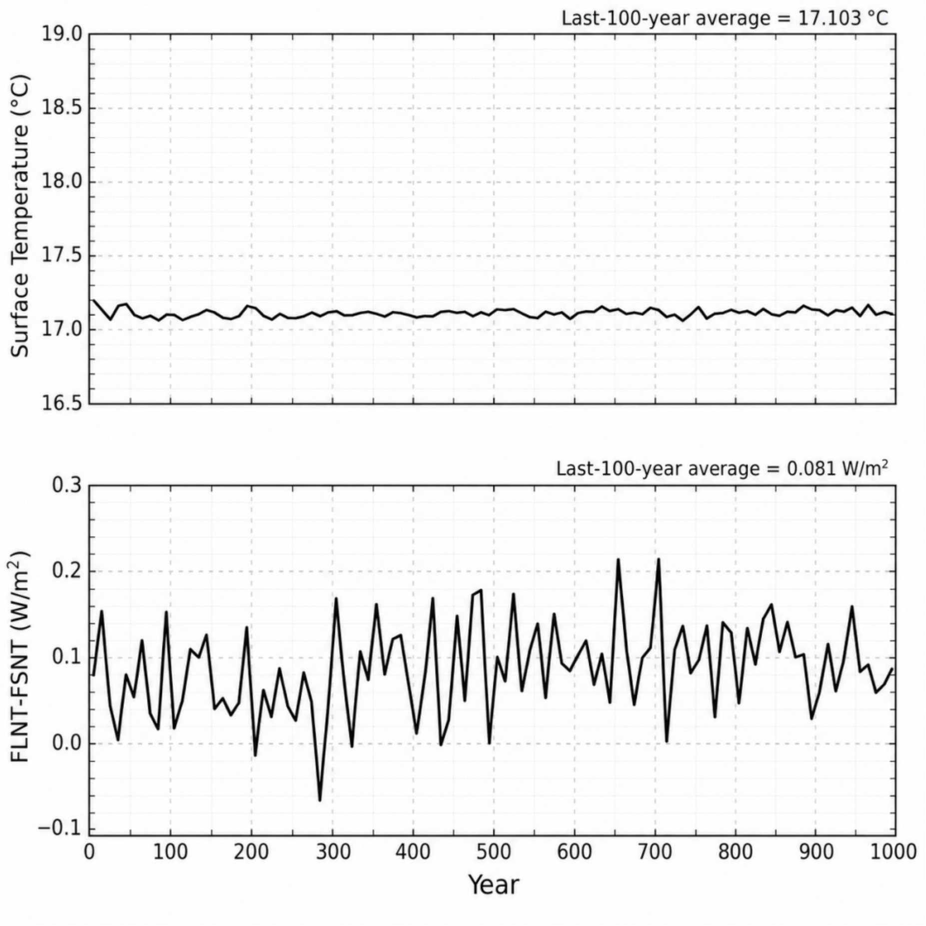


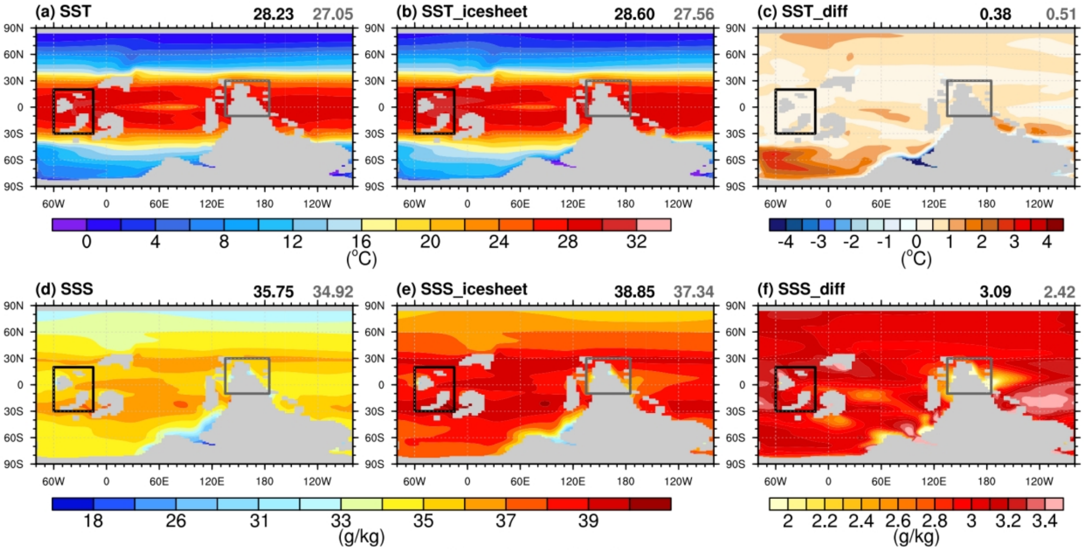
Figure R3. Extended climate-model integration under fixed equilibrium ice-sheet conditions. The upper panel shows GMST, and the lower panel shows the net top-of-atmosphere radiative imbalance, FLNT − FSNT, in W m−2. FLNT is the outgoing longwave radiation, and FSNT is the net absorbed shortwave radiation.

In fact, the ice sheet model reached equilibrium by ~80 ka, and we continued the coupled simulation for some time afterward (~70 ka), during which there were actually very few changes (the climate model ran for approximately 300 years). The 300 years, combined with the 1,000 years the climate model ran independently, means that the climate model has been running in a steady state for 1,300 years. These results demonstrate that even with the substantially extended integration, the fundamental characteristics and strength of the ocean circulation remain essentially unchanged. This confirms that the original 800-year simulation already provides a good representation of the equilibrium state, and our previous conclusions are reliable.

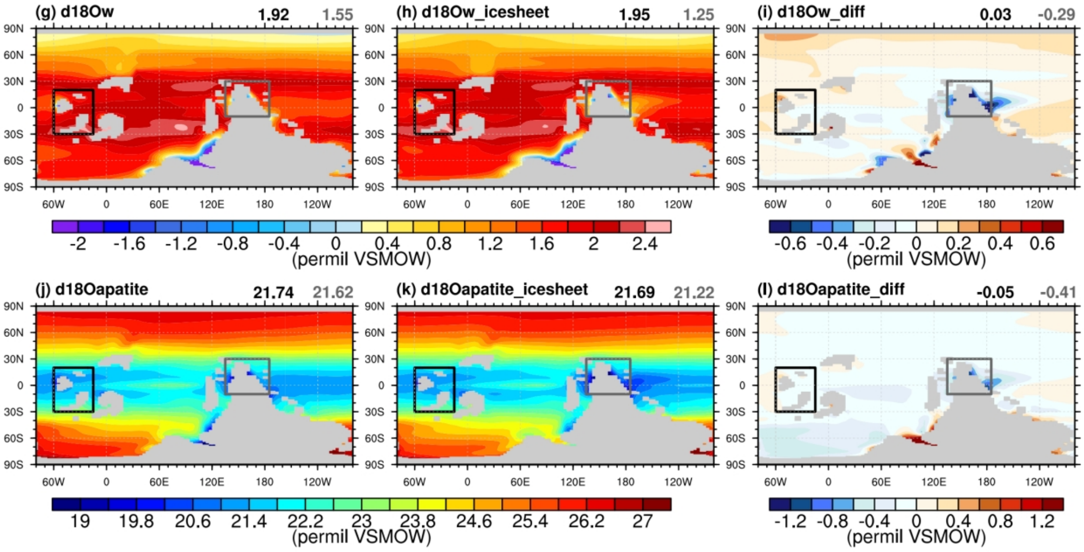
- **Further discussion of the impact of land ice on the low-latitude geochemical record.** The authors demonstrate a small change in tropical SST in response to land-ice growth (Fig. 5i). I think it would be useful to discuss the expected imprint on the geochemical record; for instance, the authors could extract the SST change at Anticosti Island, and combine this number with the expected global ocean salinity change arising from land-ice growth (+ regional simulated pattern), to convert these numbers into a $\delta^{18}O_{apatite}$ change, and ensuing apparent SST imprint of land-ice growth. I think this could be a very short yet extremely interesting discussion for the community, the details of which may be provided in the supplement.

We thank the reviewer for this helpful suggestion. Following this advice, we have added a new supplementary analysis to evaluate how land-ice growth may be recorded in low-latitude phosphate oxygen-isotope records. Specifically, we extracted the simulated SST and SSS responses from two low-latitude regions corresponding to possible Ordovician oxygen-isotope records from Laurentia, including the Anticosti Island region, and Gondwana (Trotter et al. 2008). Because land-ice growth in our coupled experiments does not explicitly remove freshwater from the ocean reservoir, we further estimated the global salinity increase expected from the transfer of seawater to land ice using salt conservation. This correction increases the global mean salinity from 35.03 to 38.00 g/kg and produces an approximately 2~3 g/kg increase in surface salinity in the coupled ice-sheet experiment.

We then converted the simulated SST and corrected SSS fields into $\delta^{18}O_w$ and $\delta^{18}O_{apatite}$ using published salinity–$\delta^{18}O_w$ and phosphate paleotemperature relationships (Railsback et al. 1989). This analysis shows that, when the background seawater oxygen-isotope composition, $\delta^{18}O_0$, is held fixed between the two experiments, the combined effects of the small tropical SST response and the salinity correction produce only a minor $\delta^{18}O_{apatite}$ change in the low-latitude regions. In contrast, if the growth of land ice is allowed to enrich the global ocean $\delta^{18}O_0$, the low-latitude $\delta^{18}O_{apatite}$ signal becomes substantially larger. This result indicates that a positive shift in low-latitude $\delta^{18}O_{apatite}$ records during glaciation does not necessarily require an equivalent tropical cooling, but may instead largely reflect the ice-volume effect on the isotopic composition of the ocean reservoir.



Constant d18Ow



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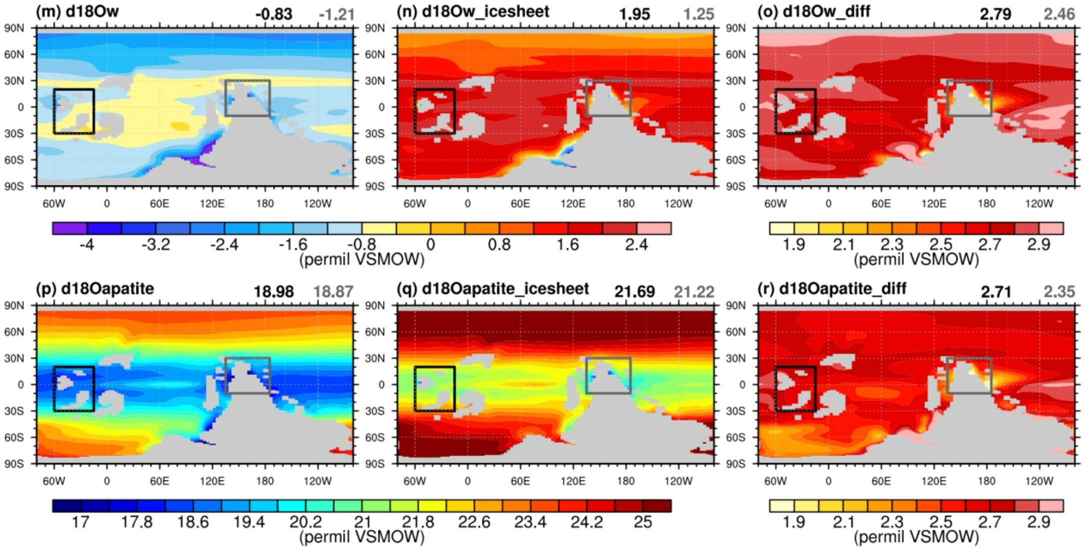

Figure R4 (Fig. B2 in the main text). Simulated and calculated effects of land-ice growth on low-latitude oxygen-isotope records. Left, middle, and right columns show the uncoupled ice-sheet experiment, the coupled ice-sheet experiment, and their differences, respectively. Rows 1 and 2 show simulated SST (a–c) and SSS (d–f). In the coupled ice-sheet experiment, SSS has been corrected for the global salinity increase expected from the transfer of seawater to land ice based on salt conservation. Rows 3 and 4 show the calculated surface $\delta^{18}O_w$ (g–i) and $\delta^{18}O_{apatite}$ (j–l), assuming a fixed background seawater oxygen-isotope composition, $\delta^{18}O_0$, between the two experiments. Rows 5 and 6 show the same calculations for $\delta^{18}O_w$ (m–o) and $\delta^{18}O_{apatite}$ (p–r), but allowing $\delta^{18}O_0$ to vary with land-ice volume. The black and dark-gray boxes denote low-latitude regions corresponding to possible Ordovician oxygen-isotope records from Laurentia, including the Anticosti Island region, and Gondwana, including Australia, respectively. The black and dark-gray numbers in the upper-right corner of each panel indicate the area-weighted mean values within the black and dark-gray boxes, respectively.

In the main text, we added the following in Sect. 3.4:

“To further evaluate the potential imprint of land-ice growth on low-latitude geochemical records, we calculated the expected changes in surface $\delta^{18}O_w$ and $\delta^{18}O_{apatite}$ from the simulated SST and SSS fields (Fig. B2). The two low-latitude regions corresponding to possible Ordovician oxygen-isotope records from Laurentia, including the Anticosti Island region, and Gondwana, including Australia, respectively (Trotter et al. 2008). In both regions, coupling to the ice sheet produces only a small SST change (Fig. B2c), consistent with the weak tropical temperature response discussed in the main text.”

In Appendix B, we added:

“To further evaluate the potential imprint of land-ice growth on low-latitude geochemical records, we calculated the expected changes in surface $\delta^{18}O_w$ and $\delta^{18}O_{apatite}$ from the simulated SST and SSS fields (Fig. B2). The black and dark-gray boxes in Fig. B2 denote two low-latitude regions corresponding to possible Ordovician oxygen-isotope records from Laurentia, including the Anticosti Island region, and Gondwana, including Australia, respectively (Trotter et al. 2008). In both regions, coupling to the ice sheet produces only a small SST change (Fig. B2c), consistent with the weak tropical temperature response discussed in the main text.

In our coupled ice-sheet experiments, land-ice growth does not explicitly remove freshwater from the ocean reservoir. Therefore, to estimate the salinity effect associated with the transfer of seawater to land ice, we applied a global salinity correction based on salt conservation. This correction increases the global mean ocean salinity from 35.03 to 38.00 g/kg, and results in an approximately 2~3 g/kg increase in SSS in the coupled ice-sheet experiment (Fig. B2e, f). Surface $\delta^{18}O_w$ was then estimated from SSS using an icehouse salinity–$\delta^{18}O_w$ relationship (Railsback et al. 1989):

If S>S0:

$$\delta^{18}O_w = \delta^{18}O_0 + 0.35(S - S_0)$$

If S<S0:

$$\delta^{18}O_w = \delta^{18}O_0 + \frac{\Delta fw}{S_0}(S - S_0)$$

where $\Delta fw = 21.0$ for the icehouse case. Here, S_0 and $\delta^{18}O_0$ denote the global mean salinity and the background oxygen-isotope composition of seawater, respectively. Surface $\delta^{18}O_{apatite}$ was then calculated using the phosphate paleotemperature equation (Lécuyer et al. 2013):

$$T(°C) = 117.4 - 4.5(\delta^{18}O_{apatite} - \delta^{18}O_w)$$

When $\delta^{18}O_0$ is held fixed between the uncoupled and coupled ice-sheet experiments, the large global salinity correction produces only a small change in $\delta^{18}O_w$ (Fig. B2i). Consequently, the calculated $\delta^{18}O_{apatite}$ difference remains small in the low-latitude Laurentian region, less than 0.1‰ in the black box (Fig. B2l). This indicates that the direct effects of the simulated tropical SST response and the salinity correction alone are insufficient to generate a large low-latitude $\delta^{18}O_{apatite}$ excursion.

We also tested an alternative case in which $\delta^{18}O_0$ is allowed to vary with land-ice volume. In this case, the uncoupled experiment is assigned a more depleted background $\delta^{18}O_w$ value to represent an ice-free ocean reservoir ($\delta^{18}O_0$ = −1.08‰ (Grossman and Joachimski 2022)), whereas the coupled ice-sheet experiment accounts for the enrichment of oceanic $\delta^{18}O$ caused by the storage of ^{16}O-rich water in land ice. Under this assumption, the calculated $\delta^{18}O_w$ and $\delta^{18}O_{apatite}$ values are substantially lower in the uncoupled experiment (Fig. B2m, p), and the resulting $\delta^{18}O_{apatite}$ increase exceeds 2.3‰ in the low-latitude regions (Fig. B2r). This larger signal reflects the ice-volume effect on the global ocean oxygen-isotope reservoir rather than local tropical cooling.

These results suggest that land-ice growth has only a small direct impact on low-latitude $\delta^{18}O_{apatite}$ through changes in tropical SST and regional salinity. However, low-latitude oxygen-isotope records may still show a large positive excursion if land-ice growth substantially enriches the background $\delta^{18}O$ of seawater. Therefore, a positive shift in low-latitude $\delta^{18}O_{apatite}$ during the Late Ordovician glaciation does not necessarily imply an equivalent tropical SST cooling. Instead, it may partly or largely reflect the global ice-volume effect on seawater $\delta^{18}O$.

We note that the estimate of $\delta^{18}O_0$ for the Late Ordovician remains uncertain. In our calculation, the background seawater $\delta^{18}O_0$ is estimated from an approximately linear relationship between global ice-sheet volume, inferred from sea-level change (Miller et al. 2020), and reconstructed $\delta^{18}O_w$ values derived from benthic $\delta^{18}O_c$ and Mg/Ca records in the Cenozoic (Lear et al. 2020). Extrapolating this relationship to the Late Ordovician may introduce uncertainties, particularly because the ice sheet during the Hirnantian glaciation may have been substantially larger than the range constrained by Cenozoic observations (Cocks and Torsvik, 2021; Bergmann et al., 2025). In addition, the oxygen-isotope composition of the global ocean may have evolved toward more negative values in early Paleozoic oceans (Isson and Rauzi 2024; Veizer and Prokoph 2015), which would also affect the absolute values of the calculated $\delta^{18}O_w$ and $\delta^{18}O_{apatite}$. These uncertainties may partly explain why the calculated $\delta^{18}O_{apatite}$ values are more enriched than some geological records."

- **Discussing land-ice extent.** The sedimentary record of the glaciation suggests that the ice sheet may have reached ~30° S during the Hirnantian (see Fig. 2c), while the ice sheet simulated at 6 PAL pCO2 reached ~40° S. This difference should be described and it should be clearly stated that the conclusions of the paper may be different with an ice sheet reaching lower latitudes. In this regard I disagree with lines 184-185 stating that 'result closely matches the distribution of glacial tillites in the geological record'. Please revise. The references for the paleogeographical reconstructions and tillite database should also be provided in Fig. 2. I also disagree with lines 374-376 (also lines 399-402): modeling results would need to be ground-truthed with Middle Ordovician data for these statements to be supported.

We fully agree that the discrepancy between the simulated ice-sheet limit (~40°S) and the geological evidence suggesting glaciation reached ~30°S must be explicitly acknowledged.

In the revised manuscript, we have made the following changes:

✧ Added a description of the ice-sheet extent discrepancy. We now clearly state in the text that the simulated ice sheet does not reach the full equatorward extent indicated by some sedimentary records. We have replaced "closely matches" with more cautious phrasing that acknowledges the partial agreement while noting the remaining discrepancy.

✧ Added the reference (Cocks and Torsvik, 2021) for paleogeographic reconstructions and the tillite database in the caption of Fig. 2 in the main text.

✧ The statements in question extended beyond what can be reliably supported by our modeling results alone, as they would require validation against Middle Ordovician geological data that are currently unavailable. Accordingly, we have deleted lines 374–376, lines 399–402, and all related speculative discussions from the revised manuscript. The revised discussion is now strictly focused on the ice sheet-climate interactions, which represent the primary contribution of this study.

- **Sensitivity to orbital changes.** I strongly disagree with lines 196–197. The sensitivity of the ice sheet to orbital forcing was not quantified. Please delete. Accordingly, future work should also consider orbital changes (lines 199–200).

We acknowledge that this statement was indeed too arbitrary and have removed the relevant passage.

- **Impact of topography vs. albedo.** I wonder about the contribution of land-ice topography vs. albedo to simulated southern hemisphere warming. Additional slab-ocean simulations could be used to quantify these respective contributions. This is clearly just a suggestion to further improve the manuscript, nothing mandatory of course.

We thank you for this very helpful suggestion. Following this advice, we have conducted additional slab-ocean sensitivity experiments to isolate the respective contributions of land-ice topography and land-ice albedo. The experimental design and results are now presented in a new section in the revised manuscript, Section 3.5, entitled “Relative contributions of ice-sheet topography and albedo”.

Specifically, we performed two additional slab-ocean experiments. In the first experiment, ALB_ONLY, the full glacial ice-sheet albedo obtained from the coupled ice-sheet experiment is prescribed, while the surface topography is kept at the ice-free condition. In the second experiment, TOPO_ONLY, the full glacial ice-sheet topography is imposed, while the ice-sheet area is kept to zero so that the associated albedo effect is removed. The contribution of ice-sheet albedo is therefore diagnosed from the difference between ALB_ONLY and CTRL, whereas the contribution of ice-sheet topography is diagnosed from the difference between TOPO_ONLY and CTRL. All experiments were integrated for 300 years, and the climatological means over the last 100 years were used for analysis.

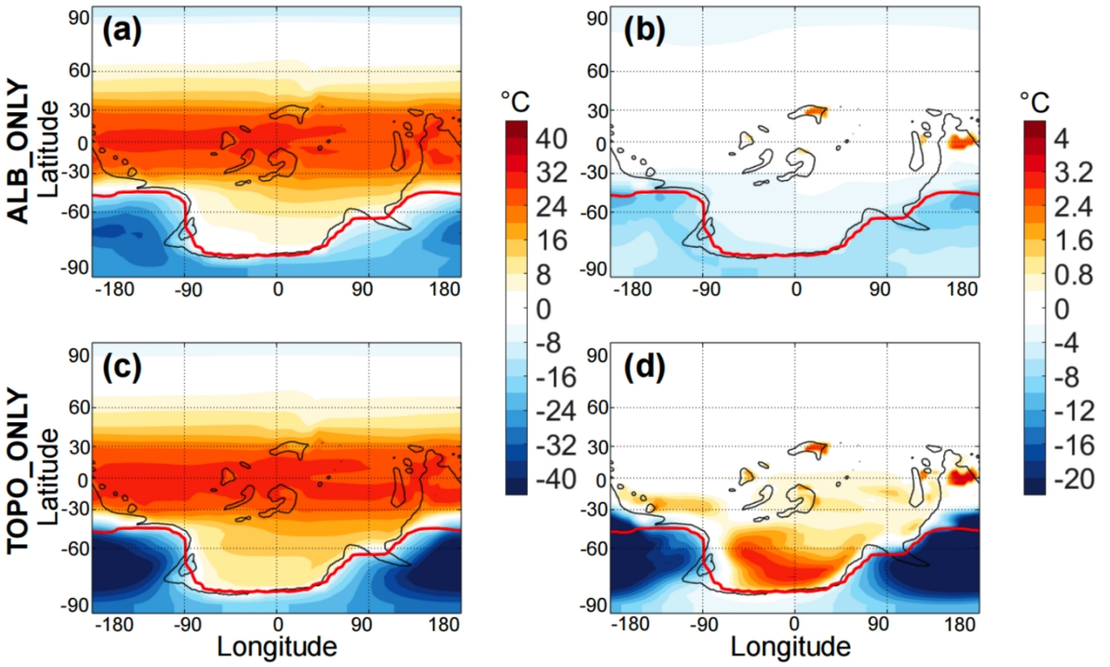

Figure R5. Surface temperature responses in the slab-ocean sensitivity experiments isolating ice-sheet albedo and topography effects. Left panels (a, c) show the climatological annual mean surface temperature in the ALB_ONLY (a) and TOPO_ONLY (c) experiments. Right panels (b, d) show the differences relative to the CTRL, highlighting the temperature response exclusively due to ice-sheet albedo (b) and topography (d). The red contour in each panel denotes the ice-sheet margin in the full glacial configuration.

These additional simulations provide valuable insights into the mechanism of the simulated Southern Hemisphere warming. The results show that ice-sheet topography is the primary contributor to the Southern Hemisphere ocean warming in our simulations. The elevated ice sheet acts as a mechanical barrier to atmospheric flow and generates a stationary wave response, which allows the topographic forcing to influence regions far beyond the ice-sheet margin. In contrast, the ALB_ONLY experiment produces a more modest and geographically confined temperature response, mainly over the ice-covered land region, with only weak cooling elsewhere.

We have also clarified in the revised manuscript that this result does not diminish the importance of ice-sheet albedo in the coupled ice-sheet evolution. During the transient growth of the ice sheet, the ice-albedo feedback remains a important positive feedback: increased ice extent raises surface albedo, reduces absorbed shortwave radiation, cools the surface, and promotes further ice growth. Without this feedback, the coupled model would not produce an ice sheet of comparable magnitude. The relatively weaker equilibrium temperature response in ALB_ONLY compared with TOPO_ONLY therefore indicates that, once the ice sheet has reached its steady-state extent, the direct radiative effect of ice albedo is relatively local, whereas the topographic effect can propagate more broadly through atmospheric dynamics.

- **Title.** What about revising the title to insist on the main message rather than on the methods? For instance, ‘Limited impact of Late Ordovician ice sheet on tropical ocean temperatures’ or similar?

Fully agreed. We have revised the title accordingly to highlight the main message of our study. The new title reads: “Ocean warming cauced by Late Ordovician glacial onset in a coupled climate-ice sheet simulation.” We believe this title more effectively conveys the key finding to readers.

- **The Ordovician mystery.** The authors refer to an Ordovician mystery (line 23). I would suggest avoiding such phrasing, since I think there is not such mystery anymore (the growth of an ice sheet under a high pCO2 was resolved many years ago by considering the lower solar luminosity).

Thank you for pointing this out. We have removed the sentence "This period is considered one of the most unique, contradictory, and enigmatic, with dramatic environmental changes" from the revised manuscript.

- **Anchoring the simulations in the geochemical record.** I think it would be good to give rapidly in the manuscript the tropical SST, and compare it with geochemical records, to give the reader an idea of what kind of climatic state is illustrated in the simulations. Otherwise, statements like ‘the climate condition is comparable to that of reconstruction’ (lines 168–169) are poorly supported. An overview of sea-ice extent may also help (as for now, statements like the one of lines 387–388 are unsupported).

To ground our simulations in the geochemical record, we first compare our simulated tropical SST with proxy reconstructions. Our simulation yields a tropical SST of 28.2 °C, which is in close agreement with the reconstruction of Trotter et al. (2008). We will also point out this comparison directly in the relevant sections of the main text. And we will also talk and show that our pCO_2 adjustment simulations show that Arctic sea ice is widespread when pCO_2 falls below 3X (GMST=13.5 °C), whereas high-latitude sea ice in the Southern Hemisphere does not begin to form until pCO2 drops to ~1X (GMST=8 °C).

It should be noted that our global mean temperature is fitted to the Scotese curve (Li et al., 2022; Scotese et al., 2021); the tropical temperature can also serve as an additional indicator for assessing the climatic conditions here.

- **Line 29.** The sedimentary record suggests that the ice sheet may have approached 30°S.

Revised accordingly. Thank you.

- **Lines 31–32**: I do not think that the fact that SST approach modern levels can be used to infer icehouse conditions when the configuration of the continents was so different. I think this is misleading.

We have removed the sentence in question: "reaching temperature conditions of present-day levels, thereby entering an icehouse state."

- **Line 37** (and elsewhere, e.g., line 176): what is a ‘super ice sheet’? I suggest to rephrase throughout.

We have replaced "super ice sheet" with "continental ice sheet" throughout the manuscript.

- **Lines 82–83**: ‘achieving a high level of agreement with geological records’. I do not think this statement is supported.

We have removed this statement.

- **Dome-like geometry.** The simulated ice sheet seems to have a maximum thickness in its center, hence aligning with our 2016 results but contrasting with the alternative modeling results of Lowry et al. (2014). Since there is no general consensus, it may be interesting to rapidly discuss the geometry of the ice sheet in light of the results obtained here?

We have added a discussion comparing our simulated dome-like ice-sheet geometry with the contrasting results of Lowry et al. (2014), whose simulations show ice flowing from the coast toward the continental interior, with maximum elevation near the coastline. We also briefly discuss possible reasons for this discrepancy, as shown in the revised manuscript main text:

"The overall shape of the ice sheet is dome-like, centered on the interior of the supercontinent, constrained by continental boundaries in the high latitude and the 40° S line in the mid-latitude continental interior. Notably, in our simulation with $pCO_2 = 6$ PAL, large ice shelves do not form in any of the time periods, even around the high-latitude polar seas. This coincides with the absence of large-scale sea ice. Our configuration is consistent with the earlier results of Pohl et al. (2016), but contrasts markedly with Lowry et al. (2014), in which ice sheets flow from the coast toward the continental interior, with the highest elevation located near the coastline. Importantly, the coastal-to-interior flow pattern obtained by Lowry et al. (2014) is at odds with the glacial sedimentary record (e.g., Fielding et al., 2008). Lowry et al. (2014) acknowledged this discrepancy in their discussion, noting that their application of uniform topography likely contributed to this pattern, as the absence of elevated interior regions removes the effect of lapse-rate cooling that would otherwise favor ice accumulation. Moreover, high topography can also act as an ice nucleation center and modify atmospheric heat transport and precipitation through its influence on stationary wave patterns. (e.g., Fiorella and Poulsen, 2013). This suggests that the inclusion of realistic surface elevation is essential for accurately capturing ice sheet geometry. "

- **Lines 192–193.** Please provide the land-ice volume and extent as numerical values in addition to the calculated sea-level drop for purposes of future inter-model comparison (+ does the calculated sea-level drop account for isostatic adjustments?); please also provide a detailed comparison with 'previous reconstructions' (line 193) or at least provide references to support this statement.

The sea-level drop was calculated by simply dividing the simulated ice volume by the global ocean surface area, without accounting for isostatic adjustments. We acknowledge that this is a simplification and have noted this as a caveat in the revised text, as shown in the revised manuscript main text:

"The total volume of the ice sheet (~9.0×10^{16} m^3) obtained here corresponds to a sea level drop of ~210 m, higher than the levels during the LGM but consistent with previous reconstructions (Montañez and Poulsen, 2013; Bergmann et al., 2025). The equivalent sea-level drop is estimated by dividing the total ice volume by the global ocean surface area and we must acknowledge that this sea level drop estimate does not account for isostatic adjustments and therefore carries uncertainties."

- **Line 207.** The statements of a 'much lower coupling frequency (200 ka)' is not correct (the coupling frequency is muss less than the one used here, but difficult to estimate due to the modeling setup we used). The ‘coarser resolution’ statement referring to the FOAM atmospheric resolution is also erroneous, since we forced our ice-sheet model with the higher-resolution LMDZ output; please consider deleting as well to avoid misleading the reader.

We have deleted the statement "and with a much lower coupling frequency (200 ka) and coarser model resolution (4.5°×7.5°)" and apologize for these inaccuracies.

- **Fig. 3.** Please clearly state that the black contour represents the ice-sheet edge, and that bottom row represents the ice-sheet surface elevation. In think it may be instructive to also include an additional figure showing land-ice thickness in the supplement.

We have clarified in the text that the black contour denotes the ice-sheet edge and the bottom row represents ice-sheet surface elevation. An additional figure showing land-ice thickness has been added to the supplementary material.

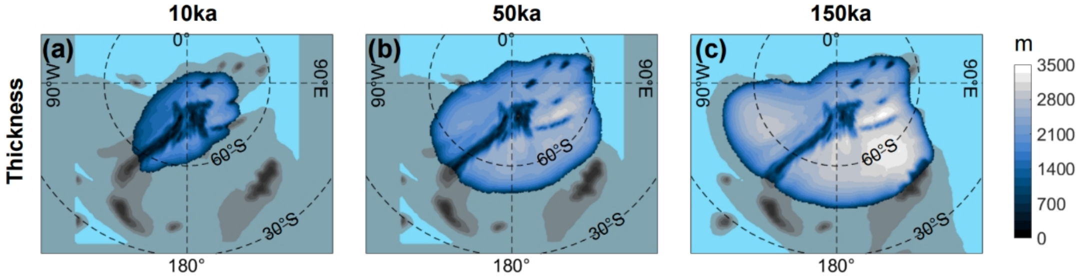

Figure R6 (Fig. S* in the supplementary materials). land-ice thickness in case CP. Three snapshots from the coupled framework simulation at (a) 10 ka, (b) 50 ka, and (c) 150 ka. Latitude is shown at 30° intervals.

- **Line 264.** ‘warm air started to blow towards the ice sheet’. I cannot see this in Fig. 4l. Is the 0°C isotherm also lacking in Fig. 4, upper row?

We acknowledge that our previous statement was somewhat speculative, and we have revised the text accordingly. The revised passage now reads (lines): "When the ice sheet expands to ~42° S (red curves in Fig. 4i–l), the katabatic winds remain strong in austral winter, but become negligible in summer, and the surface winds reverse direction from downslope to upslope over the ice surface between 170° S and 165° W. The high summer ablation at mid-latitudes prevents the ice sheet from further expanding."

The 0°C isotherm (blue contour) is present in the upper row of Fig. 4. The red contour (ice-sheet extent) is absent from the control experiment because there is no ice sheet in this simulation. The caption has been clarified accordingly: "The 0°C isotherm and ice-sheet extent are indicated by the blue and red contours, respectively."

- **Line 276.** Throughout (and notably in figure captions), I suggest to avoid using the term ‘control’ for the ‘offline’ simulation. For me, ‘control’ would be a land-ice-free run.

We confirm that CTRL is indeed a land-ice-free run. To improve clarity and facilitate reader indexing, we have now standardized the naming of the three experiments, and all figure captions and the main text have been updated accordingly to avoid confusion throughout as follows:

CTRL: the land-ice-free control simulation. These settings follow the Phanerozoic palaeoclimate simulations of Li et al. (2022)

CP: the coupled climate–ice sheet simulation in this study
OFFLINE: the offline ice-sheet simulation forced by the CESM output of CTRL

- **Fig. 5.** I think that averaging upper-ocean currents over 200 m rather than 50 m would be more instructive (since it would better account for Ekman deviation).

We fully agree with this suggestion and have updated Fig. 5 to show upper-ocean currents averaged over the top 200 m rather than 50 m, to better account for Ekman deviation. This change does not affect the current conclusions, but we agree to make it.

- **Line 296.** What is a 'wavenumber-1 structure'? See also line 391.

A "wavenumber-1 structure" refers to a planetary-scale spatial pattern in which a given field (e.g., sea-surface temperature, geopotential height, precipitation) exhibits a single maximum and a single minimum along a full circle of latitude (i.e., around the globe).

- **Caption of Fig. 8.** 'The differences in (a-c) net surface *shortwave* radiation'?

Thank you for pointing out this error. The variable shown in panels (a-c) is indeed net surface shortwave radiation. We have corrected this in the revised manuscript accordingly.

- **Line 335.** I am not totally sure that air coming from the ocean would warm low-latitude continental masses. Isn't land warming rather driven by changes in the hydrological regime (precipitation minus evaporation)?

We examined the net precipitation and latent heat flux in this region, and indeed confirmed that changes in the hydrological regime (precipitation minus evaporation) are the dominant contributors to this warming, rather than direct thermal advection from the adjacent ocean. We will show the net precipitation and latent heat flux in the supplementary materials.
Accordingly, we have revised the original sentence in the manuscript: "While for the tail of the supercontinent extruding into the tropical region, the warming is caused by the changes in the hydrological regime, as confirmed by the net precipitation and latent heat flux anomalies in this region (not shown)."

- **Fig. 9.** A very short comparison of the global pattern of the global ocean circulation in light of previous modeling results would be a good addition. I also suggest to add contours and contour labels for clarity. I am also surprised to see that waters seem to sink at the middle latitudes in the southern hemisphere – please show mixed-layer depth maps in the supplement, this would be instructive (and make sure to update all .nc files in the repository to reflect the data plotted in the manuscript for easy re-use by the community later, in line with FAIR principles; from this point of view, the README file would deserve being revised for typos notably). The authors may also want to stress that the simulated decrease in deepwater formation in the SH provide no explanation to regional ocean warming (which would require an increase) - further pointing towards a driven role of atmospheric processes in the coupled model - hence further supporting their analysis.

✧ We will add contours and contour labels as suggested. We've updated the repository with all data plotted in the manuscript and rewritten the README. We also plan to add the following text to the manuscript to compare the most significant differences between the MOC from previous modeling results.

"It is worth noting that our ice-sheet-coupled simulation shows weak influence on the MOC, with no northern-sourced deep water formation before or after ice-sheet inception. In contrast, previous studies have demonstrated that changes in pCO_2 and solar constant exert a far stronger impact on ocean circulation. (Torsvik et al., 2012; Pohl et al., 2017)"

Since our article does not intend to focus on the deep-ocean circulation, we will not delve too deeply into this topic; research on the deep-ocean circulation during this period may be explored more in future work.

✧ We agree that the apparent mid-latitude sinking in the Southern Hemisphere is surprising, and we thank you for pointing this out. Following this suggestion, we have added maps of annual-mean mixed-layer depth for both the CTRL and CP cases to the supplementary materials. These maps show that the deepest mixed layers occur mainly in the southern high-latitude oceans, while the spatial pattern remains broadly similar between the two experiments. However, diagnosing the detailed causes of this feature would require a more comprehensive analysis. We acknowledge that, given our current understanding, it is difficult to immediately explain why the meridional circulation appears to consist of two branches: one that sinks at high latitudes and another that sinks at mid-latitudes and appears to be stronger at first glance. This structure is very similar to that observed in the modern Pacific (PMOC), and may offer clues to the answer. But now, because the MOC response to ice-sheet inception is relatively small in the present experiments, and the coupled ice-sheet simulation produces only modest changes in mixed-layer depth, a full mechanistic investigation of the deep circulation is somewhat beyond the scope of this study and would constitute a substantial topic for future work. But we would also be very happy to discuss this issue further with you, as it is an interesting and surprising aspect of the simulated ocean circulation.

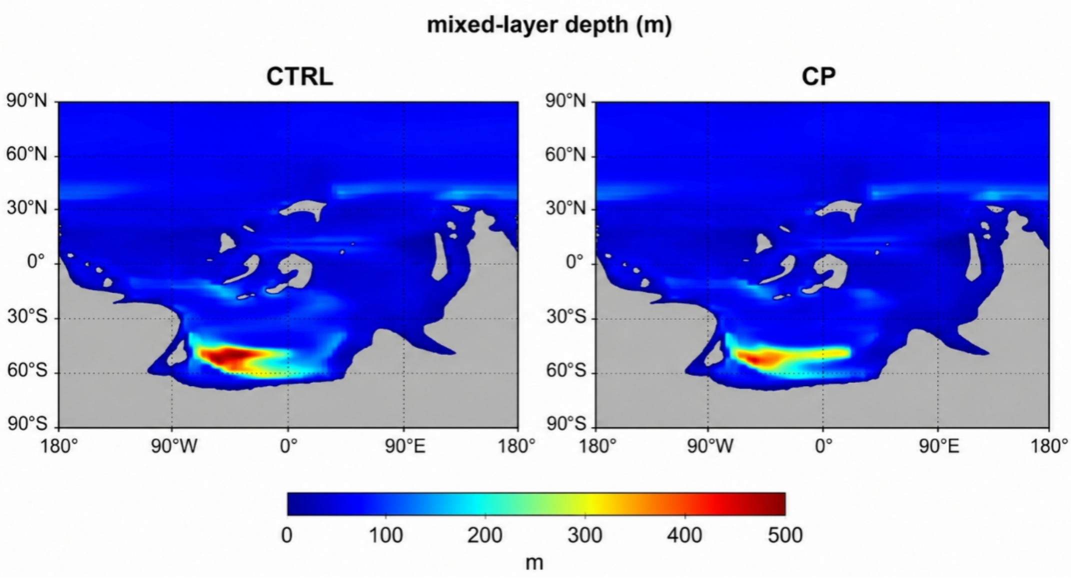

Figure R7 (Fig. S* in the supplementary materials). Comparison of mixed-layer depth between the CTRL and CP experiments. Shading indicates mixed-layer depth (m).

✧ As suggested by the reviewer, we have supplemented one relevant sentence in the revised manuscript to clarifies that weakened Southern Hemisphere deep-water formation consolidates the key conclusion that atmospheric processes dominate the warming in our coupled simulation: “Meanwhile, the decrease in SH deep-water formation provides no explanation for the regional ocean warming — which would require an increase in deep-water formation — further pointing towards a driving role of atmospheric processes in the coupled model.”

✧ We have revised the README file, correcting typos and improving clarity to better guide users of the repository. When we submit the revised manuscript, we will update it with the latest data and include the results from the additional experiments.

- **Lines 366-367.** There is also geological data supporting a Darriwilian onset of the glaciation (see references cited in our 2016 paper, and maybe more recent ones). I suggest rapidly stressing this point for completeness.

We have revised the text to include geological evidence supporting a Darriwilian onset of glaciation, in addition to the modeling results of Pohl et al. (2016). The revised sentence now reads: "Meanwhile, Middle to Upper Ordovician sedimentary successions document repeated glacioeustatic fluctuations (Dabard et al., 2015; Rasmussen et al., 2016). These eustatic cycles point to the existence of a continental ice sheet as early as the Darriwilian (467 Ma), rather than a sudden, Hirnantian-restricted glaciation (445-444 Ma). Furthermore, Pohl et al. (2016) provided support from coupled ice-sheet modelling simulations for a prolonged glaciation that may have begun as early as the Middle Ordovician."

- **Lines 368–370.** Although I overall get the authors’point, I think the current phrasing looks contradictory – suggesting a limited impact and then a stabilization role. Please revise to better convey the message.

We have revised Lines 368–370 to explicitly distinguish the ice sheet’s disparate influences on tropical versus Southern Hemisphere high-latitude oceans. The revised text is as follows:

“Our simulations show that the initial formation and early expansion of the ice sheet have minimal impact on tropical SSTs, suggesting that the ice sheet activity may not be accompanied by global-scale cooling. On the contrary, combined with our foregoing results that the continental ice-sheet induces ocean warming over SH high latitudes, it plays a crucial role in maintaining SH high-latitude ocean temperature stability, delaying its sharp cooling.”

- **Lines 370–372.** Again, I get the point but the phrasing is misleading – the curve reflects tropical SST. Please revise. See also lines 398–399.

The revisions have been made.

- **Line 379.** Please stay consistent with the terms ‘control’, ‘offline’ or ‘uncoupled’. I suggest to use offline throughout, see previous comment.

Please see our response to the earlier comment. All instances in the text and figure captions have been updated accordingly.

- **Line 380.** How is ‘realism’ evaluated here? This is usually bold to state that deep-time simulations are realistic.

We agree that "realism" is a strong term in the context of deep-time simulations. We have revised the sentence to use more cautious wording, and the revised sentence now reads: "The results indicate that the inclusion of bidirectional feedback between the ice sheet and the climate system is a key factor in improving the agreement between simulated outcomes and geological reconstructions."

- **Line 382.** Please define the geological record. Please note that the Hirnantian sedimentological record cannot be used to document the Middle Ordovician land-ice state.

We have added the relevant references (Scotese et al., 2021; Trotter et al., 2008). Our study primarily relies on Scotese's temperature reconstruction curve, with Trotter's tropical temperature records serving as a supplementary reference.

- **Lines 403-409.** Another limitation is the use of the simple PDD scheme for ablation.

We have added a sentence in the discussion, acknowledging the limitations of the simple PDD scheme. The added text reads: "A further limitation is the use of a simple PDD scheme for ablation, which may not adequately capture insolation-driven melt processes critical to ice-sheet retreat (Ganopolski et al., 2010; Robinson and Goelzer, 2014)."

- **Lines 444-445.** Please provide a reference to support this statement. This is very important.

Added (Man et al., 2023).

- **Fig. B3.** What are the 3 columns?

Sorry, we forgot to include the image captions. We've added them now: from left to right: austral winter (JJA), summer (DJF), and annual mean.

- **Line 63**: 'and warmer the subpolar'. Please revise.

warmer⟶ warms

- **Caption of Fig. 2.** 'ice sheet surface' > add 'elevation' for clarity? I also suggest to clearly label the 60°S and 30°S parallels.

The revisions have been made as requested.

- **Lines 276–277.** Please revise to properly match Fig. 5 content.

We have revised the text, and the revised sentence now reads: "Figure 5 shows the surface temperature and ocean surface currents from CTRL, the temperature differences between NO_DYN_OCN and CTRL, and the differences in surface temperature and ocean surface currents between CP_ISM and CTRL."

- **Line 277.** 'mostly bare'. Please revise/clarify the meaning.

Since this has little impact on the analysis, we have removed this statement.

- **Line 280.** 'The majority landmass'. Please revise.

Change to: the majority of the continent

- **Line 310.** ‘shifts’.

Corrected.

- **Line 345.** Exponent formatting missing.

The revisions have been made.

- **Line 396.** ‘Response’

Corrected.

- **Fig. B4.** ‘triangle’ (singular)

Corrected.