

Sun et al. investigate ice-climate interactions during the Late Ordovician using an asynchronous ice sheet and Earth system model approach. The Late Ordovician glaciation is particularly interesting due to the inferred coexistence of relatively high atmospheric CO₂ and expansive ice sheets in the Southern Hemisphere. While previous studies have investigated climate impacts on Late Ordovician ice sheet growth, most studies are limited by one-way coupling and limited representation of climate-ice sheet interactions. Sun et al. make a great advancement by incorporating asynchronous coupling of an Earth system model and ice sheet model and expand upon a similar study (Pohl et al., 2016) by investigating mechanisms of climate-ice sheet interactions in more depth. The authors reveal a key positive feedback loop where ice sheet growth initiates katabatic winds, which further expand ice sheets, providing a physical explanation for the coexistence of widespread ice sheets in a relatively warm climate. Overall, the authors provide a very interesting paper with detailed analysis of the ocean-atmosphere dynamics associated with ice sheet expansion, which is a valuable contribution to the field. However, I do have some concerns/questions that I detail below. In particular, I would like to better understand how the potential cold bias associated with the treatment of vegetation in the CESM simulations may be influencing the simulated expansion of Late Ordovician ice.

We sincerely thank you for your thorough and insightful review of our manuscript. Your review is very helpful in improving our manuscript. We address your comments point by point below.

- **Line 78:** “systematically analyze” and “, which is a gap”
Corrected.

- **Line 81:** CESM is an “earth system model” not a “general circulation model”
Sorry for the mistake; it has been corrected.

- **Lines 9-19:** I think you should incorporate the coexistence of widespread ice sheets and high CO₂ in this climate; it is a very interesting aspect of this time that you are attempting to explain.

We agree that the coexistence of high atmospheric CO₂ and widespread Gondwanan ice is an important context for the study. We avoid presenting this as an unresolved “mystery”, because the ~3.5% lower Ordovician solar luminosity is an important part of the explanation as the other reviewer pointed out. This article may focus more on describing the impact of ice sheets on the climate. However, we appreciate your suggestion and agree that it is important to clearly state that this was a period of high greenhouse gas levels.

We have revised the background introduction sentence to highlight the coexistence of high CO₂ and widespread ice sheets. The revised sentence now reads: “The Late Ordovician marks the first major continental ice sheet event in the Phanerozoic Eon, despite high CO₂ levels, coinciding with a dramatic global temperature drop and one of the largest mass extinctions.”

- **Lines 90-99:** I would highlight other deep-time paleoclimate studies that have used CESM1.2, demonstrating that it is a reliable model to use for this purpose.

We fully agree with you. We will add the following paragraph:

“CESM1.2 is derived from the CESM1 model generation, whose configurations contributed

numerous simulations to CMIP5 and have been widely evaluated by the climate-science community (Hurrell et al., 2013). Subsequent applications of this model framework in palaeoclimate studies have demonstrated its capability across a broad range of climate states (Zhu et al., 2019; Zhu et al., 2020; Li et al., 2022; Zhang et al., 2022; Yun et al., 2023; Sun et al., 2024).”

- **Lines 98:** The CNDV model in CLM4 traditionally has issues growing vegetation in paleoclimates. In Li et al. (2022), they mention a cold bias introduced by the used of CNDV because the vegetation is underpredicted thus much of the land has a very high surface albedo. Can you show a plot of the simulation’s vegetation distribution and leaf area index? Could this cold bias from unrealistic vegetation be allowing more land ice to grow under high CO₂?

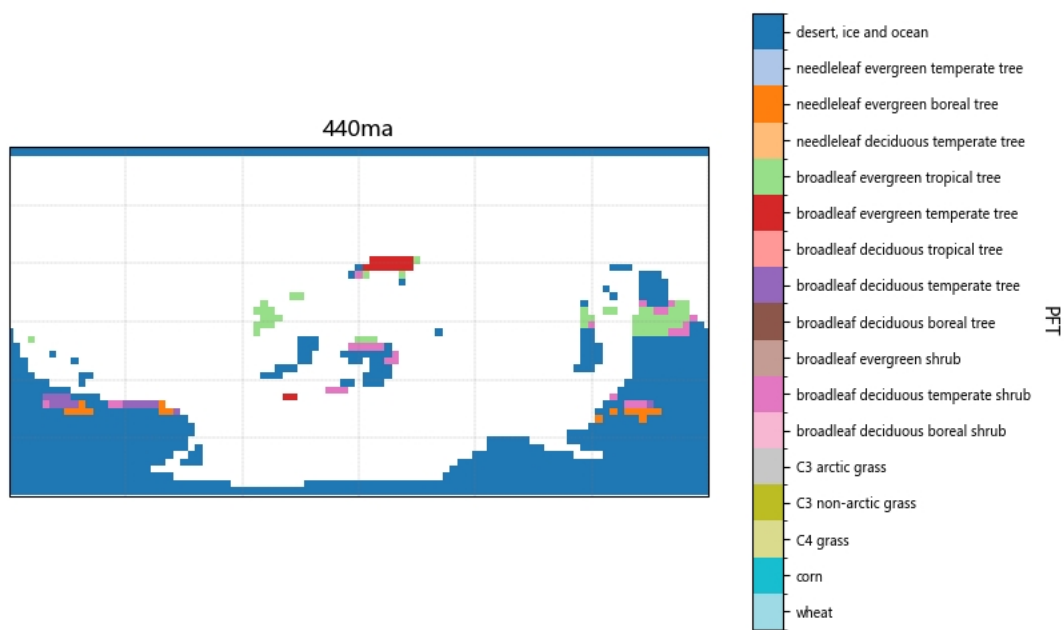


Figure R1. Global vegetation distribution at 440 Ma based on our CNDV simulations. Colors indicate plant functional types (PFTs), including forests (needleleaf and broadleaf, evergreen and deciduous), shrubs, grasses (C3 and C4), and crops (corn, wheat), as well as desert, ice, and ocean areas. This figure illustrates the baseline paleovegetation used in our climate-ice sheet coupled experiments.

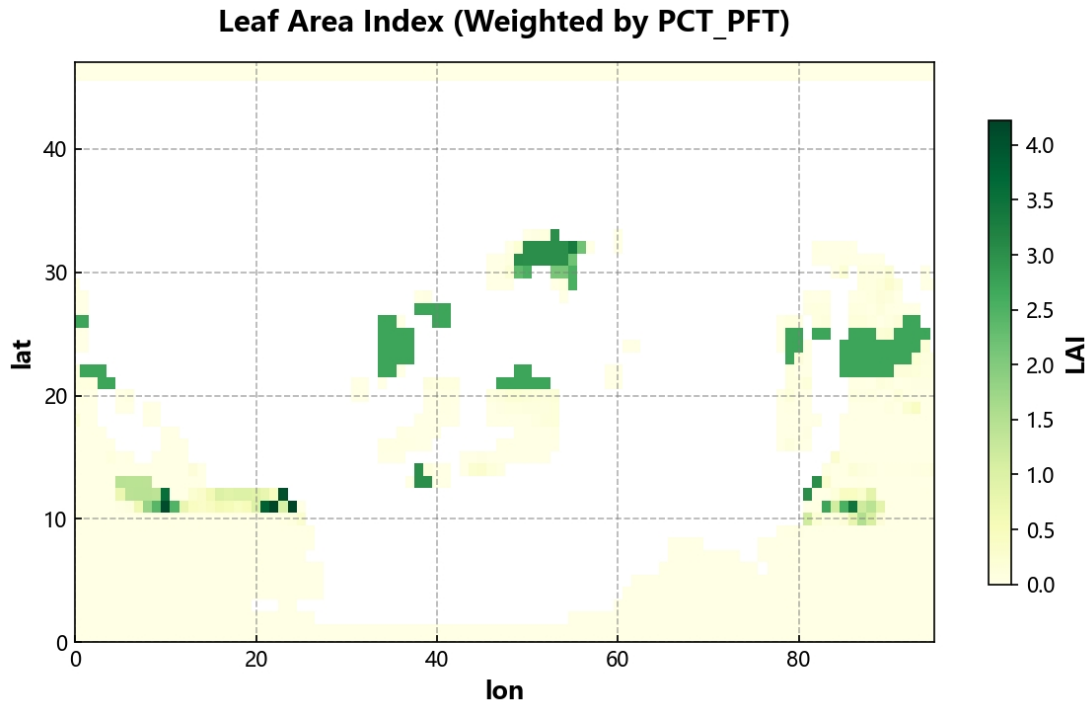


Figure R2. Global vegetation leaf area index at 440 Ma based on our CNDV simulations.

The CNDV model in CLM4 is indeed known to have some difficulties in simulating vegetation under paleoclimate conditions. As noted in Li et al. (2022), a cold bias can arise from the use of CNDV because vegetation tends to be underpredicted in the preindustrial (PI) simulations.

In fact, in our own tests, we compared simulations with CNDV turned on and off for the 440 Ma period with 6X pCO₂. Interestingly, we found that the global mean surface temperature (GMST) is actually higher when CNDV is active than when it is turned off (18.5 °C, 17.7°C, respectively). We think the explanation lies in the very different vegetation context of the 440 Ma period. At that time, large-scale terrestrial vegetation had not yet established. Therefore, turning on CNDV inadvertently introduces some "vegetation" into the land surface, which lowers the surface albedo and raises the temperature. This is the opposite of what is typically seen in the preindustrial (PI) simulations, where CNDV produces a cold bias due to insufficient vegetation cover.

Given this, our simulations do not overestimate CO₂ levels. If anything, the required CO₂ concentration might even be somewhat underestimated. Because our control experiment introduced excessive vegetation cover (albeit only a small amount), this still raised the temperature; in theory, we need to lower the temperature again by reducing pCO₂ levels. This, in turn, supports the plausibility of high greenhouse gas levels coexisting with extensive ice sheets during this period.

For the sake of comparison with the control experiment and to maintain consistency across our Phanerozoic simulations, we follow the approach of Li et al. (2022) and use their work as our benchmark. That said, we are aware of the limitations of the vegetation module, and related investigations are already underway. We aim to update and improve this component in future

work.

- **Lines 108-110:** Are any ice sheets prescribed in the Li et al. 440 control simulation? What does the polar surface cover look like?

No ice sheets are prescribed in the Li et al. simulation. The land types are shown in the figure below:

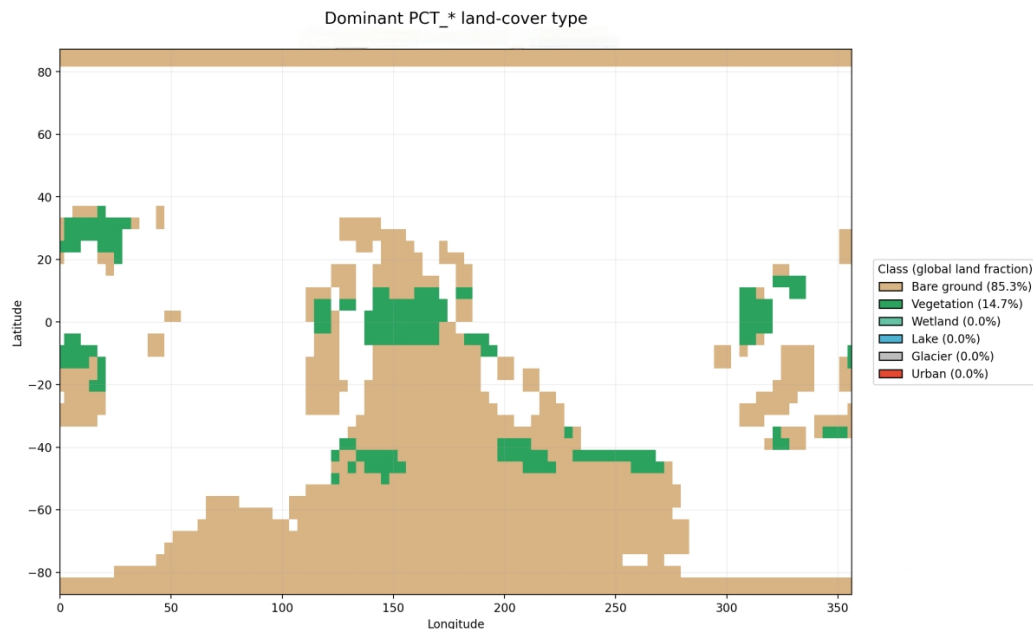


Figure R3. Global land types at 440 Ma.

- **Line 127-128:** You say “Despite its simplicity, this scheme has been demonstrated to reproduce large-scale ice sheet behaviour effectively and efficiently”, do you have a citation for this?

We've included some references: Reeh 1991; Hanna et al., 2011; Wake and Marshall, 2015.

- **Lines 172-173** You say “Lowering $p\text{CO}_2$ might reproduce an ice sheet extent in the offline simulations that is consistent with the geological records (Pohl et al., 2016).” The choice of 6 PAL CO_2 based on the approach of Li et al. (2022) and Scotese et al. (2026) is likely overestimated, as Li et al. state in their paper: “CNDV indeed causes cold biases and leads to an overestimation of the CO_2 concentrations by about 1.8 times as the ECS of 2.9 °C per doubling atmospheric CO_2 is considered.” How do you think that lowering CO_2 and prescribing vegetation (greening the surface) may impact the results?

We believe the impact would be limited, for two main reasons. First, during the 440 Ma period, large-scale terrestrial vegetation had not yet established, which fundamentally limits the extent to which vegetation can influence the climate in these simulations. Second, as we have shown earlier, turning CNDV on or off does not lead to a large difference in global mean surface temperature for this period. Moreover, our results suggest that the CO_2 levels may actually be somewhat underestimated rather than overestimated. Taken together, we consider our analysis and conclusions to be robust.

- **Figure 2:** Where are the glacial deposits from? Please provide citations here.

We've included the reference: Cocks and Torsvik, 2021.

- **Figure 5:** It is difficult to read the vectors in these plots, I would suggest thinning the vectors and/or increasing the size of the vector heads. The lat/lon labels should be simplified to prevent overlap. Also, the "cplSM" label for the coupled simulation should be defined in the figure caption and used consistently in the text (when do you use "cplSM" vs "150ka" vs "50ka" for coupled simulation).

We sincerely apologize for the confusion caused by the inconsistent and unclear naming of our experiments in the original manuscript. We fully agree with you that the terminology should be clearly defined and used consistently throughout the text and figures.

To address this issue, we have now standardized the naming of the three experiments across the entire manuscript, including all figure captions and the main text. The revised nomenclature is as follows:

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

CP: the coupled climate–ice sheet simulation conducted in this study. When referring to specific time slices within this coupled experiment (e.g., "150ka" or "50ka"), we now explicitly state that these refer to time points under the CP configuration.

OFFLINE: the offline ice-sheet simulation forced by the CESM output of CTRL.

Regarding Figure 5 specifically, we have also made the following improvements: the vector head sizes have been enlarged for better readability; the latitude/longitude labels have been reduced to prevent overlap; and the "cplSM" label has been replaced with the standardized "CP" nomenclature and is now clearly defined in the figure caption.

Because the data is highly uneven—with some arrows being very long and others very short—we have tried to strike a balance between conveying the information and maintaining image quality. Another reason is that the image quality has been severely compressed here. I'll export a high-resolution version when I submit the revision paper. And the revisions have been made as requested in Fig. 5. (The images modified here and below are attached at the end.)

- **Figure 6:** Similar suggestions to Figure 5.

Thank you. The revisions have been made as requested.

- **Figures B5 and B6** are almost impossible to understand due to resolution of the graphics and small plot sizes. I would suggest remaking these figures with improved image resolution and/or without lat/lon labels so that panels can be enlarged.

The revisions have been made as requested. Since we determined that the information in Figure B6 and Figure 6 was largely repeatative, we removed Figure B6 from the revised manuscript.

Figure 5:

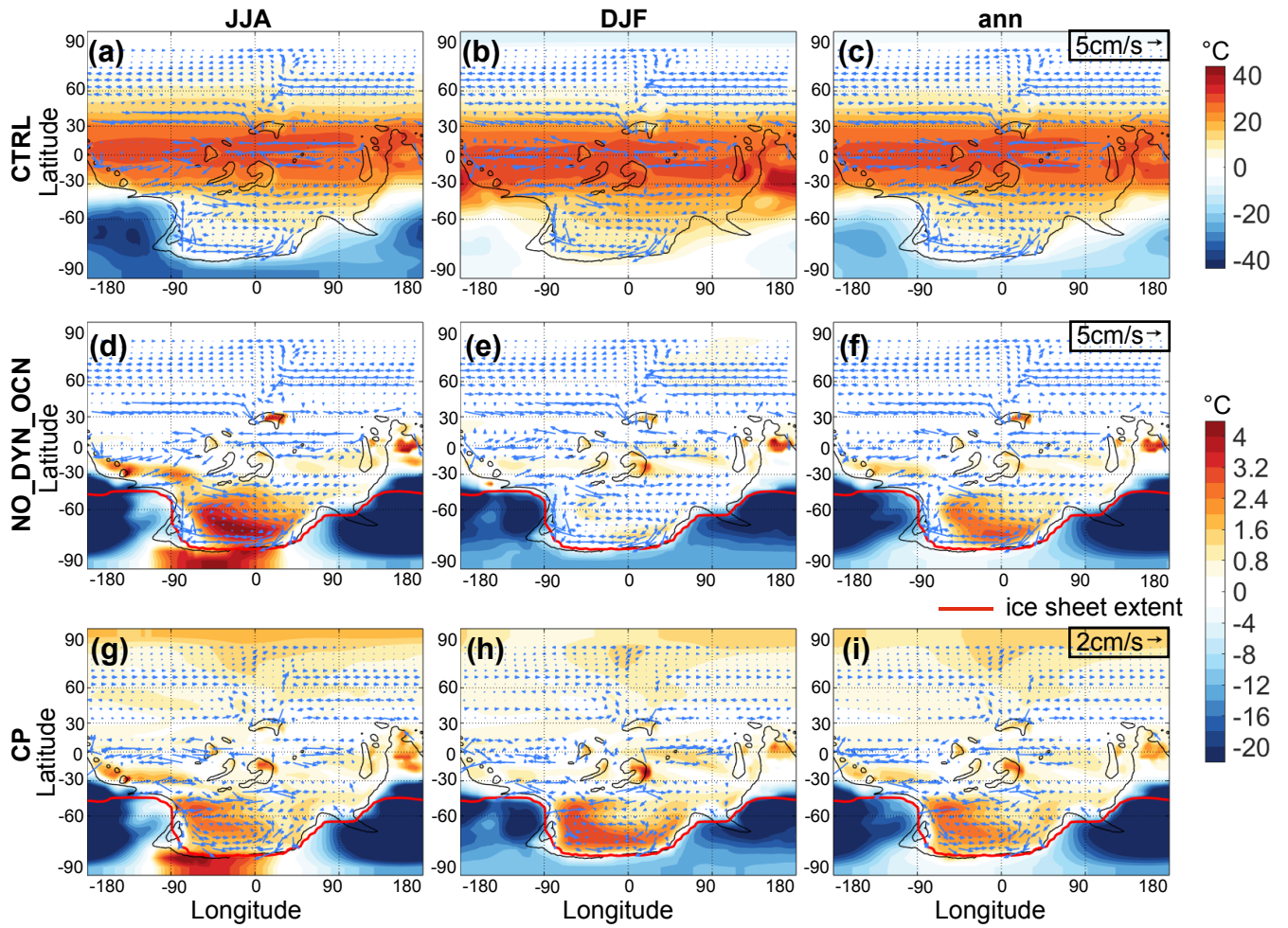


Figure 6:

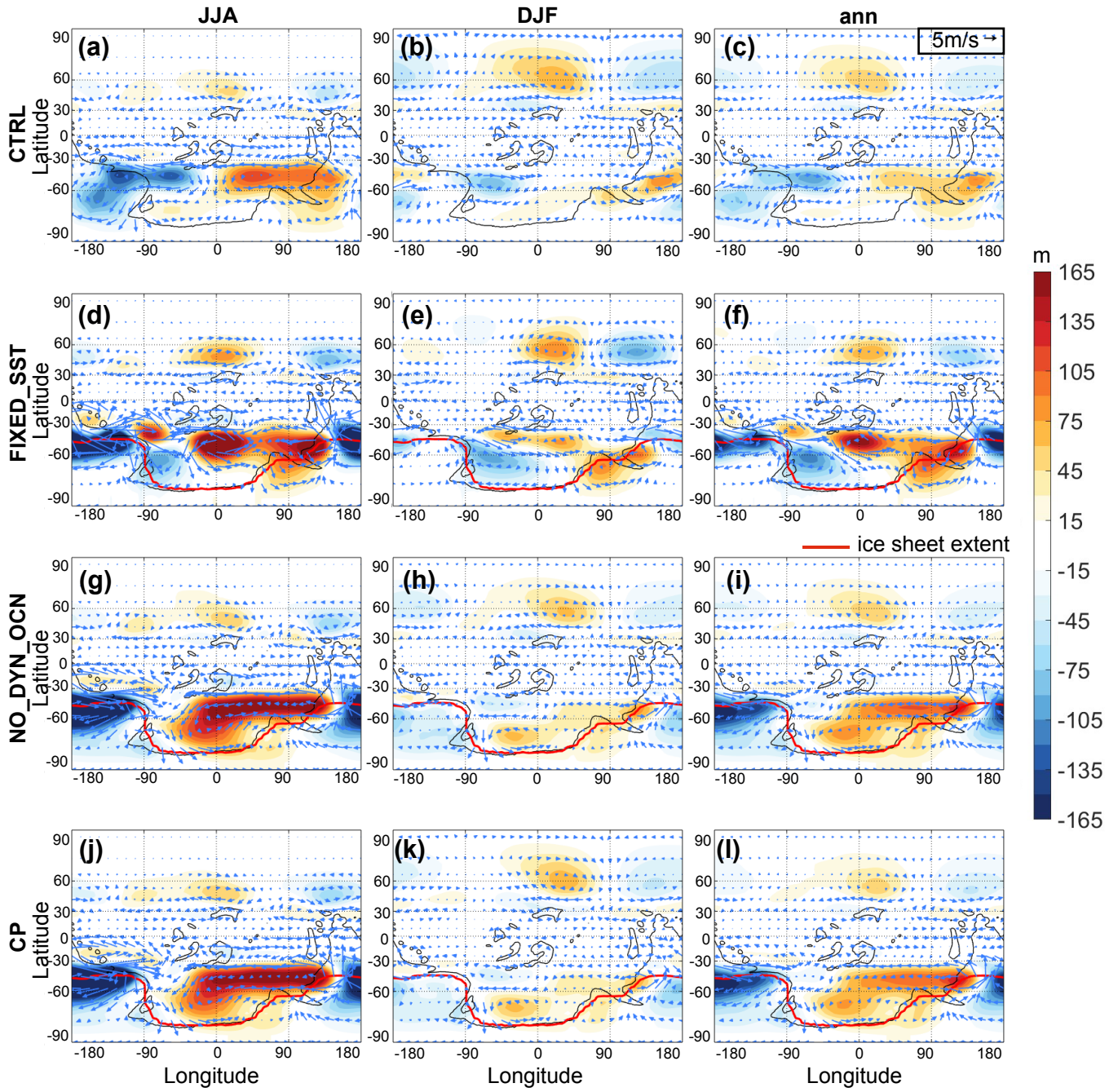


Figure B5:

