We thank the reviewer for these useful comments which will certainly improve the manuscript. The reviewers' comments are reproduced in black, and our replies are provided in blue. When necessary, we have also included the modified section of the revised manuscript below our response.

Review RC3 (12 April 2021)

Green et al., propose some interesting insights related to seasonal changes in sea-ice cover during the LGM using PMIP3 and LOVECLIM simulations, in particular in relation to wind stress and surface ocean temperatures. While simulations are generally coherent with paleo reconstructions for LGM winter sea-ice cover, simulated glacial summer sea-ice cover differs widely between models and between models and (arguably limited) proxy-based reconstructions. While study is certainly relevant, it lacks some context, I feel. To me, the main outcome of the present study relates to the conclusion that the seasonal contrast in sea-ice cover is reduced today compared to the LGM. While clearly interesting, this finding should be placed into a broader context and outline how increased sea-ice dynamics would affect ocean circulation and more generally carbon and nutrient biogeochemistry during the LGM. Furthermore, it remains unclear why reconstructing summer sea-ice extent is relevant, in particular for air-sea gas exchange and deep water production, which to a large degree occur in winter. I certainly support publication of the present study in Climate of the Past, provided some additional contextualization can be provided.

We thank the reviewer for these comments and will include more information regarding the motivation of our work in addition to highlighting the broader contexts of our results. To clarify, through providing a spatial and seasonal assessment of LGM Southern Ocean sea-ice extent in PMIP3 models (and now also PMIP4 models), and then comparing that output to available sea-ice and SST records, we believe the main outcome of this manuscript is providing a better constraint on summer sea-ice extent, which is a slightly larger estimate than what has previously been published (Lhardy et al. 2020, Roche et al. 2012).

Our goals are now clarified in the Introduction and shown in the first response in the General Comment section below.

Additionally, our main outcome is clarified in the first paragraph of the discussion:

"We suggest that during the LGM, the likely austral winter sea-ice edge was between 50.5˚S and 51.5˚ S and during austral summer the sea-edge was likely between 61˚ and 62˚ S, with a mean sea-ice extent of 14-15 x 10^6 km^2, similar to the sea ice characteristics simulated by AWI-ESM-1 and FGOALS-G2. This is an improved constraint on LGM summer sea-ice extent as we use modeled sea ice in conjunction with paleo proxy SST and sea ice data to calculate our estimate. Our LGM summer sea-ice extent estimate is slightly larger than previous estimates of ~10.2 x 10^6 km^2 (Lhardy et al., 2021) and ~11.1 x 10^6 km^2 (Roche et al., 2012), which only use paleo proxy data to calculate their estimates."

It is important we reconstruct summer sea ice extent due to the impact of seasonal sea ice changes on Southern Ocean dynamics. We have included a sentence within our introduction highlighting this:

Introduction:
"Specifically, seasonal changes in sea ice have large implications on Southern Ocean dynamics through buoyancy (Marzocchi and Jansen, 2017) and carbon cycle changes (Haumann et al., 2016). Understanding these past changes in sea ice and their natural drivers, at different timescales and under different boundary conditions, will therefore allow us to better project future sea ice changes."

General comment

I'm certainly not a modeling expert, but the reason underlying the poor representation of the glacial summer sea-ice extent should be clarified. In particular, I don't quite understand why the distribution of mean summer SST during the LGM is generally coherent between models while summer sea-ice extent is not. Maybe this aspect could be clarified further at least for non-specialized readers.

Our study tries to provide answers to the questions raised by the reviewer, namely: is the LGM seasonal sea-ice extent coherent across models? Why are there such large differences? Can we provide constraints on the actual LGM seasonal sea-ice extent?
However, contrary to the reviewer's comment and as shown in Figure 2, the distribution of mean summer SST is not coherent across the models, with a ~3˚ C spread at 75˚ S and almost 6˚ C spread at 65˚ S. The fact that models display different ocean temperatures in the Southern Ocean will be clarified in the revised manuscript. Similarly, the suggested relationship between summer sea-ice extent and seawater temperature will also be clarified.

We are now more clearly defining the goals of the study in the Introduction:
"Here, we assess the minimum and maximum Southern Ocean sea-ice covers as simulated in LGM PMIP3 and PMIP4 experiments. To better assess intra- versus inter-model variability, LGM sensitivity experiments performed with LOVECLIM are also included. The PMIP3, PMIP4 and LOVECLIM experiments are compared to available LGM sea-ice and SST paleo-proxy data, allowing us to determine the best performing models. Combining models and proxy data, we can provide an updated estimate of seasonal Southern Ocean sea-ice cover during the LGM. Furthermore, we analyze the processes that lead to the inter-model differences in summer sea-ice extent at the LGM."

We are also more clearly mentioning the spread of simulated summer SSTs between the models when discussing Figure 2:

"Among the models, the distribution of zonally averaged SSTs are not consistent over the Southern Ocean. For example, at 75˚ S both PMIP3 and PMIP4 models simulate a SST spread of ~3˚ C while at 65˚ S both model groups simulate a SST spread of ~6˚ C (Figure 2c,d)."

Detailed comments

l. 15-27. Since the MS is focusing on seasonal contrasts in sea-ice extent, it may be relevant to briefly explain how seasonality affects the main processes outlined in this section today. For example, does a positive SAM phase affect both the winter and summer sea-ice extent linearly?

The reviewer makes a good point here. We are now describing the impact of SAM on seasonal sea-ice extent in the introduction. Since 1970 there has been a positive trend in the SAM, particularly in austral summer. Doddridge and Marshall (2017) found that a positive SAM led to a high latitude SST decrease and sea-ice increase with a damping timescale of ~3 months, except around the Antarctic Peninsula where the response of sea ice to positive SAM is toward a decrease. However, Ferreira et al. (2015) suggested that the short-term and long-term response to changes in the Southern Hemispheric westerlies are different, with positive SAM trends leading to a short-term cooling but a long-term warming due to the upwelling of relatively warm circumpolar deep waters. Geological data embed several tens of years of sedimentation. We are here looking at the LGM mean state and therefore also the mean response to the average position of the Southern Hemispheric westerlies over centuries to millennia.

Introduction:
"Doddridge and Marshall (2017) have shown that, on a seasonal timescale, Southern Ocean sea-ice was responding to changes in the southern annual mode (SAM), with a positive phase of the SAM leading to lower Southern Ocean sea surface temperatures (SST) and a larger sea-ice extent. However, on longer timescales, a positive phase of the SAM can lead to a Southern Ocean warming due to the enhanced upwelling of relatively warm circumpolar deep waters (Ferreira et al. 2015). "

l. 27-30. The statement is misleading. I believe the Southern Ocean has accounted for about 40% of the global OCEANIC uptake of anthropogenic CO2.

The reviewer is correct here and this will be fixed. The updated sentence is below:

Introduction:
"Given that the Southern Ocean has accounted for ~40% of the oceanic anthropogenic CO2 uptake between 1870 and 1995 (Sabine et al., 2004; Frölicher et al., 2015; Mikaloff-Fletcher et al., 2006; Landschützer et al., 2015, Watson et al., 2020), it is crucial to better understand the processes that impact Antarctic sea-ice cover."

l. 44. Could you briefly explain why records of summer sea-ice extent are generally more poorly constrained?

We decided to cut this sentence from our introduction, and the updated paragraph is below. However, for your information, most of the sediment cores from the Southern Ocean are from "topographic highs" such as the mid-oceanic ridges and Antarctic coast and slope. In between, the abyssal plains reach down to 5000m deep, where sedimentation rates are extremely low, microfossils are rare, dissolution is important and chronological issues are predominant. Though WSI reached the mid-oceanic ridges (several cores show it), SSI probably laid over the abyssal plains (so very difficult to get records of).

Introduction:
"Antarctic sea ice at the LGM was reconstructed using proxy data for the first time in 1981 (CLIMAP-Project-Members,1981). The LGM sea-ice compilation covering the Southern Ocean of Gersonde et al. (2005) is routinely used to provide estimates of LGM sea-ice cover. New Southern Ocean sea-ice data, reconstructed using statistical methods and diatom assemblages, has however been published since then (Allen et al., 2011; Benz et al., 2016; Ferry et al., 2015; Xiao et al., 2016; Ghadi et al., 2020; Nair et al., 2019) thus highlighting the need for an updated compilation. Here, we use this improved compilation, containing sea-ice records as well as summer SST estimates when present, to better constrain the minimum and maximum LGM sea-ice cover."

l. 110 – incomplete sentence

This has been fixed.

l. 161-163 & 168-169 – how does the relationship between SST and sea-ice cover equate for the winter months as a comparison?

There are similar relationships between ocean temperatures (SST and average temperatures across the entire water column) and sea-ice cover for both austral winter and summer. We have now included two new figures to our supplement showing both relationships and adjusted the Results section in the manuscript.

Results section 3.3:
"We first assess the relationship between zonally averaged austral summer SSTs in the Southern Ocean (50˚ S and 75˚ S) and sea-ice edge and extent (Figure 2a,b). The relationship between simulated summer SO SST and sea-ice edge or extent can be approximated by a linear fit, with R2 values of 0.90 and 0.81, respectively (Figure 2a, b, S2). Similarly, this relationship is also seen during austral winter. Using a linear fit to approximate this SST vs sea-ice edge and extent relationship we find R2 values of 0.80 and 0.88 (Figure S3)."

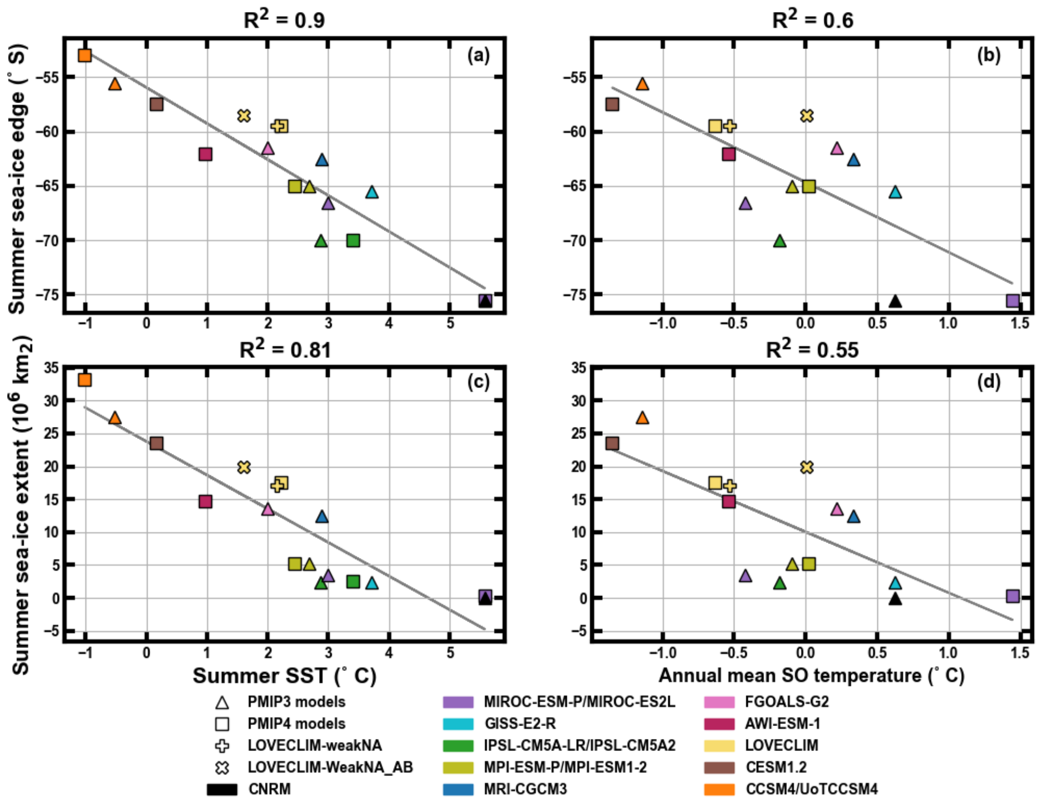

Figure R1 (referred to in the text as S2). The left column shows the relationship between austral summer SO (75˚S - 50˚S) SST and austral summer sea-ice edge (a) and sea-ice extent (c). The right column shows the relationship between annual mean SO temperatures averaged over the entire water column and austral summer sea-ice edge (b) and sea-ice extent (d). Using a linear fit approximation, the correlation for each relationship is found above each individual panel.

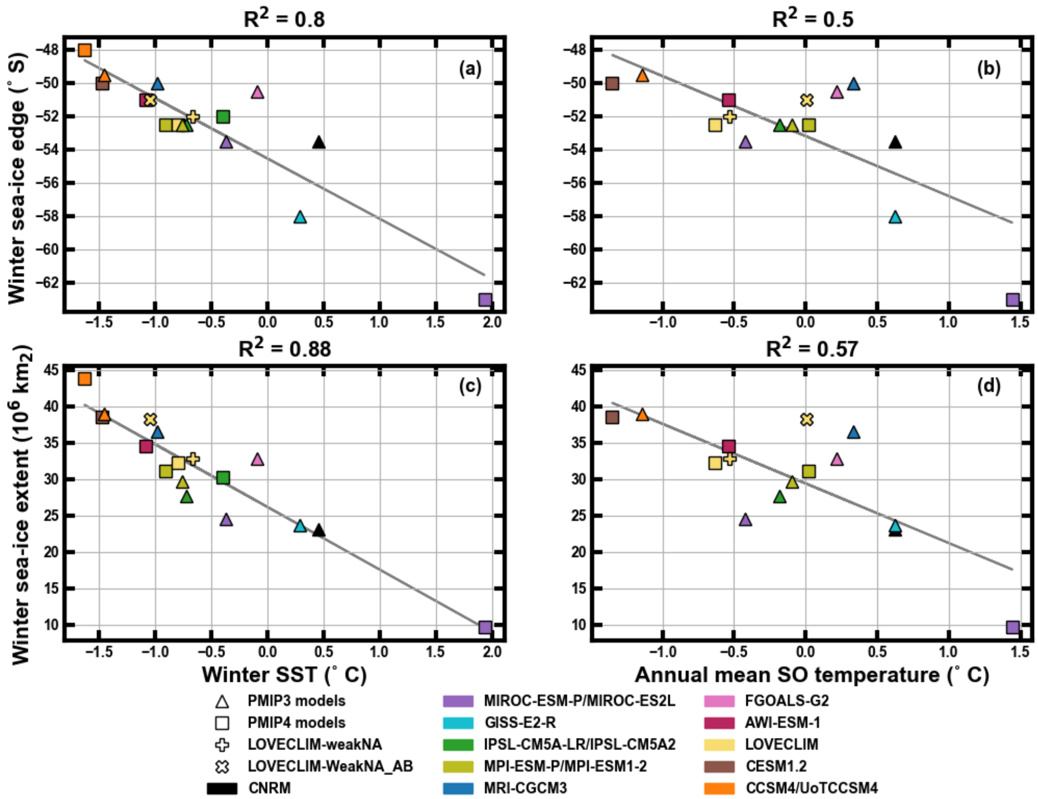

Figure R2 (referred to in the text as S3). The left column shows the relationship between austral winter SST (75˚S - 50˚S) and austral summer sea-ice edge (a) and sea-ice extent (c). The right column shows the relationship between annual mean SO temperatures averaged over the entire water column and austral summer sea-ice edge (b) and sea-ice extent (d). Using a linear fit approximation, the correlation for each relationship is found above each individual panel.

l. 203 – how does this value compare with modern SSI extent?

The modern average SSI extent for 1981-2010 is $3.1 x 10^6$ km^2 (Eayrs et al., 2019). We now include a comparison with modern values in the first paragraph of our discussion:

Discussion:
" This can be compared to the average modern austral winter sea-ice extent of 18.5×10^6 km^2 and the average modern austral summer sea-ice extent of 3.1×10^6 km^2 (Eayrs et al., 2019)."

l. 321-323 – assuming that most of the mixing occurs during the winter, I'm not too sure to understand how increased sea-ice melt during the spring-summer could enhance nutrient utilization (and by inference carbon drawdown)?

Increased sea-ice melt leads to increased surface stratification (Galbraith and de Lavergne, 2019). Increased surface stratification reduces nutrient supply to the surface waters in which the phytoplankton thrives. It also allows for more time for nutrient uptake. Both processes lead to increased nutrient utilization at high latitudes (François et al., 1997; Sigman and Boyle 2000, Abelmann et al 2015), where much of the current nutrient supply goes unused (Sigman et al., 1999). This enhanced nutrient utilization leads to higher rates of carbon drawdown (Sigman et al., 2021).