We thank the reviewers for their careful reading and comments which helpfully contribute to the clarification and overall improvement of the manuscript.
We are addressing the comments below (in blue), as well as keeping track of the corrections to the text (in green). It should be noted that all mentions of line and figure numbers are made according to the numbering of the original manuscript.

Reviewer #1:

This paper considers a series of simulations using the iLOVECLIM model to analyze the effect of different choices of LGM boundary conditions, parameterizations, and ad-hoc modifications (to wind stress and freshwater forcing) on the LGM solution, focussing on the surface climate as well as the deep ocean overturning. Although the results are generally interesting and worthy of discussion, I think the comparison between these experiments and conclusions about which "choices" are better or more important than others need to be drawn a bit more carefully, as these various modifications aren't really comparable and some are certainly more physical than others. The paper specifically highlights the use of a parameterization to represent “sinking brines” as key to obtaining a realistic simulation of the LGM overturning circulation. However, I believe that the discussion of these results needs improvement, as elaborated below. Most importantly, I think that a PI simulations with this parameterization needs to be presented for comparison. Since the physics of the ocean have not changed between the present and LGM, the model needs to be able to reproduce the PI ocean and LGM ocean circulation with the same parameterization.

We propose here corrections on the conclusions and elements of discussion according to the reviewer's suggestions. In particular, we show the results obtained for a PI simulation with the parameterization of the sinking brines.
While we understand the reviewer's legitimate concern about the fact that our simulations are relying on modifications which are more or less physical, we would like to stress that these simulations are only sensitivity tests and do not accurately reproduce the physics of the ocean. Still, they give us the opportunity to draw conclusions about key processes, (here quoted from reviewer #2) in particular “that the sensitivity tests with winds, brines, and freshwater have more potential to influence the simulated surface properties, and particularly the ocean overturning circulation and distribution of water masses, compared to the choice of boundary conditions. This highlights the importance of informed choices in model parameterizations of processes. In particular, it further clarifies the effect of deep-water formation and convection processes for achieving a realistic representation of the glacial deep ocean and its water masses.”
Our intention is certainly not to prescribe any modelling choice as key. When observing that the simulation ‘P4-I brines’ is the “best” one (with quotation marks, L330), we meant that it is the one that is in best agreement with geological data, given the variables analyzed in this study. We additionally qualified this simulation to be “quite crude” (L340) and we underlined it only as “one way of tackling this issue [of a simulated deep ocean circulation in disagreement with paleotracer data]” (L354). We hope that the proposed corrections will clarify this intention to the reader.

Specific comments:

-R1.1 : l. 15/16 in abstract. It would be good to clarify that you are referring to "different choices for LGM boundary conditions", or better yet "different choices for the LGM ice sheet topography" (see also comment below). After all, differences in boundary conditions between the PI and LGM are ultimately what has to explain the different circulation in the two climates.

Indeed. We have clarified this sentence following this comment and also the third comment of reviewer #2. This sentence now reads:

We investigate here the impact of a range of surface conditions in the Southern Ocean in the iLOVECLIM model, using nine simulations obtained with different LGM boundary conditions associated with the ice sheet reconstruction (e.g. changes of elevation, bathymetry, and land-sea mask), and/or modelling choices related to sea-ice export, formation of salty brines, and freshwater input.
Although the term “boundary conditions” might not be clear to a non-modeller reader, the change of boundary conditions due to the choice of different ice sheet reconstructions encapsulates changes of elevation, albedo, bathymetry, and land-sea mask. We prefer to use the term “ice sheet reconstruction” rather than “topography”, because we are concerned that the latter might be understood essentially as a change of elevation.
Note that we have noticed a few typos along the manuscript concerning the use of a hyphen in the expression “ice sheet reconstruction”, so we corrected them as well.

-R1.2 : In various places (e.g. l. 36-38) the issue of open ocean convection versus sinking along the AA slope seems to be used almost synonymously to the role of brine rejection in deep water formation, but these are rather different processes. Notably, the CCSM3 LGM simulation shows very salty AABW, clearly as a result of strong brine rejection, yet I assume AABW is still formed by open ocean convection (e.g. Shin et al. 2003, https://doi.org/10.1029/2002GL015513 - indeed this paper should be discussed).

In order to avoid confusion between the two processes, we removed the mention to brine rejection at L. 36-38.
As reviewer #2 also asked to develop this part, we included the following in the new version of the manuscript:
Moreover, Heuzé et al. (2013) showed that, even in present-day conditions, models generally simulate inaccurate bottom water temperatures, salinities and densities. Even when they do simulate relatively accurate modern bottom water properties, they still tend to form AABW via the wrong process (namely open ocean deep convection) whereas the largest proportion of AABW currently results from formation of dense shelf waters, overflowing in the deep ocean (Orsi et al., 1999; Williams et al., 2010). While some high resolution CMIP6 models now simulate dense shelf waters, Heuzé (in review, 2020) observed no obvious export of these waters, and open ocean deep convection remains a much too widespread and frequently occurring process.
We also thank the reviewer for pointing out that the Shin et al. (2003) paper is relevant for the present study. We think a mention to this reference would fit in this part of the introduction well:
And indeed, PMIP models struggle to reproduce the glacial sea-ice extent suggested by sea-ice proxy data, and especially its seasonality (Roche et al., 2012; Goosse et al., 2013; Marzocchi and Jansen, 2017). While Ferrari et al. (2014) have shown a dynamical link between the deep ocean circulation and Antarctic sea ice, Shin et al. (2003) have highlighted the major role played by Antarctic sea ice on the glacial AMOC by quantifying the haline density flux increase at the LGM in the CCSM model. Moreover, Marzocchi and Jansen (2017) have quantitatively attributed part of the observed discrepancies of the AMOC simulated by PMIP3 models to insufficient sea-ice formation and export. Therefore, targeting sea-ice biases in models may be necessary to improve the simulated water mass distribution.

-R1.3 : Relatedly, the parameterization of sinking brines needs to be described a little more– both in terms of the formulation and its physical interpretation. I understand that this method has been published previously, but since it is key to the presented conclusion I think the reader needs to be able to interpret the results from these simulations without first reading Bouttes et al. (2010). In l. 125 it is argued that "its objective is to account for the sinking of dense water along the Antarctic continental slope", and similarly in l. 301 it is referred to as "the parameterization of the sinking of dense water along the continental slope". This gives the impression that it may be a parameterization of downslopes gravity currents, which, however, seems quite misleading. Indeed, if I understand correctly, the parameterization simply transfers salt from brine rejection directly and locally to the bottom of the ocean (without any mixing along the way), and it is not limited to the Antarctic slope. Personally, I'll have to admit that this parameterization seems rather unphysical to me (even gravity currents are associated with lots of entrainment and detrainment as they proceed down the slope, and of course they only exist on the slope). The readers can form their own opinion, but to do so, the parameterization needs to be discussed clearly.

As the expressions "along the continental slope" may indeed induce confusion with the downslope currents, we have removed them at L.125 and L.301. Also, for the reader to understand better both the formulation of this parameterization and its physical interpretation without having to refer to Bouttes et al. (2010), we expanded the following sentences as follow:
We ran 'P4-I brines' using the parameterization of the sinking of brines described by Bouttes et al. (2010). The objective of this parameterization is to account for the sinking of dense water rejected during sea-ice formation. Indeed, this process is often limited by the horizontal resolution of models, as the rejected salt tends to get diluted in the surface grid cells where sea ice is forming. This parameterization allows for a fraction of the salt content of the surface grid cell to be transferred to the deepest grid cell underneath the location of sea-ice formation. As a result, the salinity and density of the bottom cells increase while the salinity and density of the surface grid cells decrease, without congruent motion of water masses. The modification of the salinity depends on the rate of sea-ice formation, as well as the chosen fraction parameter. Here the fraction was chosen at 0.8 to allow for a large effect of this sensitivity test, but the gradual effect of this parameter choice on the streamfunction is shown in Fig. S5, as well as the impact of this parameterization on the PI streamfunction (and deep water mass properties, see Fig. S6). This simple parameterization is relatively different than a downsloping current one as it is not confined to the continental slope and does not create mixing along the way of the sinking brines. While "this brine mechanism is idealized, it reflects the impact of intense Antarctic sea-ice formation during the LGM" (Bouttes et al. (2010)) on the AABW density.

-R1.4 : As discussed in the general comments above, the "P4-I brines" simulation needs to be compared to a corresponding PI simulation with the same parameterization. Ultimately the changes in the ocean circulation between the PI and LGM climates have to be attributable to differences in the boundary conditions, not different physics. It needs to be verified that the model is able to reproduce a reasonable solution for both the LGM and PI ocean with the same parameterization. (One aspect that should be paid attention to here are the T and S properties of NADW and AABW. Importantly, AABW is fresher than NADW in the modern climate, which needs to be reproduced by any model that adequately represents water mass transformation processes in the SO.)

We agree with the reviewer. We have run a 'PI brines' simulation with the same parameter. The streamfunction obtained is presented in Fig. 1 below. We have also added it in SI for interested readers (see Fig. S5), alongside the streamfunctions of 'PI', 'P4-I' and 'P4-I brines' to enable an easier comparison, as well as other simulations that the reviewer #2 mentioned (a 'New P2 brines' and two 'P4-I brines' with a different parameter). We observe that despite the large parameter (0.8) used in 'PI brines', the differences with 'PI' remain relatively small. There is a change of the Southern Ocean overturning cell (which is expected given that the parameterization is transferring salt to the deep ocean without explicitly advecting water masses) and also a small strengthening of the bottom overturning cell in the Atlantic, but the cell limits remain similar. Therefore, we expect no significant change in the water mass distribution. As a result, we think that adding the results from 'PI brines' as a 10th simulation in all parts of the manuscript is not critical.
As for the T and S properties of deep water masses, they are now shown in Figure S6: please refer to our response to your twelfth comment for more detail.

It can also be noted that the chosen parameter for a ‘PI brines’ simulation (and more generally the brine parameterization) has been discussed in the reviews of Bouttes et al. (2010), which can be found at: https://cp.copernicus.org/articles/6/575/2010/cp-6-575-2010-discussion.html.

‘PI’ ‘PI brines’

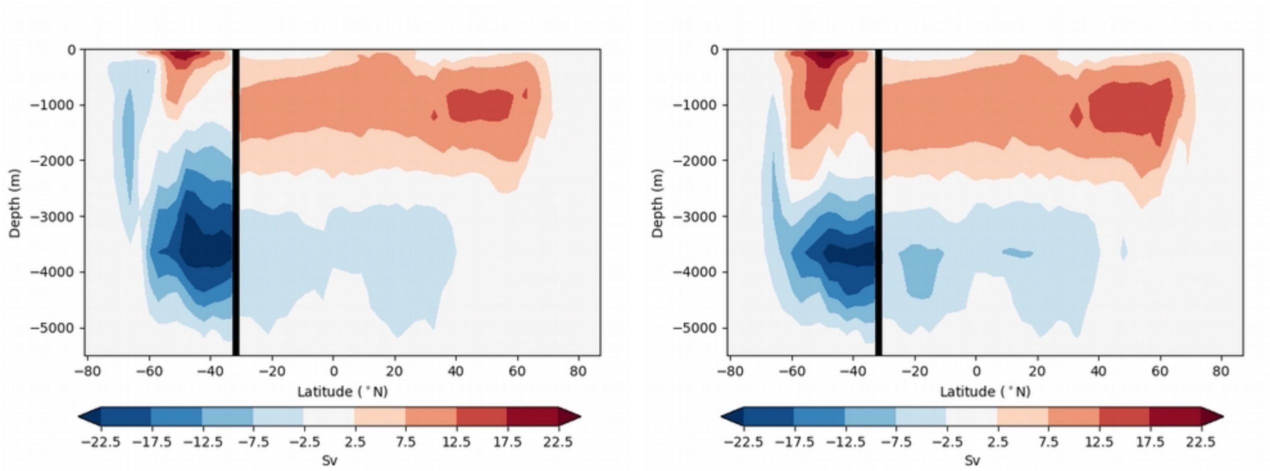


Figure 1: Streamfunctions (Sv) (as in Fig. 7) of ‘PI’ and ‘PI brines’ simulations

-R1.5 : in l. 131/132 it is argued that a quasi-equilibrium state is ensured. How is this evaluated?

We calculated the drift in time series of the global deep ocean temperature to assess when the equilibrium state is achieved – which is usually the case after 1000 years of run, though it may be a bit longer for simulations such as ‘P4-I brines’. We propose clarifying this point like this:
Each simulation has been run either 3000 or 5000 years to ensure a quasi-equilibrium state. The drift for any individual simulation is less that 2.10^{-4} °C per century for the deep ocean temperature (global mean of all oceans below 2,000 meters depth).

-R1.6 : l.161: does "surface extent" here refer to sea ice extent or still the surface of the continent? I assume the former, but please clarify.

Indeed. We have added the term “sea-ice” to avoid confusion.

-R1.7 : The error bars of 10% and 20% for winter and summer sea ice extent seem to be mostly accounting for the uncertainty in the continental margins, which is probably relatively small compared to the large uncertainty in the sea ice line. As a result, these error estimates seem very optimistic to me. Indeed this seems to be confirmed by the fact that the previous estimates of Gersonde at al. (2005) and Roche et al. (2012) fall significantly outside of this error bar. I’m not arguing that either estimate is better or worse, but simply that a larger uncertainty has to be acknowledged. I think the uncertainty range should at least encapsulate the best estimates of these major previous studies.

We here stress that both Gersonde et al. (2005) and Roche et al. (2012) used a different projection system (South Pole stereographic projection that increases distance with decreasing latitude) and subtracted the modern Antarctic ice-sheet surface to calculate the LGM winter and summer sea-ice extent instead of the LGM one. Consequently, the winter sea-ice extent of 39×10^6 km^2 and 43.5×10^6 km^2 presented in these studies was overestimated. We here used a discretization of the sea-ice line approximated on a grid with a fixed latitudinal and longitudinal spacing on a sphere and subtracted the LGM Antarctic ice sheet. We also added new control points from Benz et al. (2016)

refining the winter sea-ice extent in the Pacific sector. The recalculated area of 32.9 × 10^6 km^2 is therefore much more robust. Applying a similar approach to the winter sea-ice extent in Gersonde et al. (2005) and Roche et al. (2012) would provide very similar values as the one presented here. For this reason, our error bars do not need to encapsulate previous (overestimated) sea-ice extent estimates.
We however agree that error bars of 10% and 20% seem optimistic, especially as the summer sea-ice edge is poorly constrained from the data point of view. There is a clear lack of control points and the estimation of the sea-ice line is partly done by default (we know it is South of the marine cores with no indication of sea-ice presence, but where exactly?). We could easily double these values, though 20% seems a little pessimistic for the winter sea-ice edge which is relatively well-constrained. To find a middle ground, we have chosen to change the error bar values to 15% and 30% in Fig. 5 and S3, and corrected the text accordingly.
However, it should remain clear for the reader that these values are only indicative. In fact, it is impossible to compute error bars in the usual sense, given the uncertainty of the reconstructed sea-ice edge drawn based on point data. We still wish to provide the reader with some sense of the magnitude of the error, which is why we quantified the order of magnitude of the error linked with the discretization of both this reconstructed sea-ice contour and the Antarctic continent contour at the LGM (L161-173), which adds a further element of uncertainty to the model-data comparison of the sea-ice extent. We assumed that the error associated with the sea-ice line is of the same order of magnitude as the error linked with the discretization, given the relatively coarse resolution of the CLIO model. Still, there is no statistical test which could help use quantify the error bars accurately, so the chosen values will remain questionable in any case. This is what we meant by the use of the adjective “indicative” (L161). Therefore, it would not be right to interpret how well the simulations are doing in terms of sea-ice extent based on whether they “fall inside or outside these error bars” (which is also an argument why these errors bars should not necessarily encapsulate estimates from previous studies). Note that this is an expression that we haven’t used in Section 3.2, we are simply saying which simulation “falls close” to the reconstructed sea-ice extent or tend to “underestimate”/“overestimate” the sea-ice extent compared to the reconstructed one.
To stress this element further and warn the reader that these estimated error bars should not be taken at face value, we have added the adjective “indicative” in the legend of Fig. 5 as well, and modified the following sentence (L174):
Considering the order of magnitude of these alternative estimates, error bars of 15% and 30% seem reasonable. Still, these estimates are only indicative of the order of magnitude of the error.
An alternative option is, obviously, to remove all error bars. This would, however, give a false impression of certainty to the reconstructions provided.

-R1.8 : l. 220: It is argued that "the transfer of brines leads to a cooling of the Southern Ocean". Notably, however, the cooling does not occur in the regions of AABW formation but further north. There also is pronounced warming (relative to P4-I) in the North Atlantic. Do you have an explanation for these results? And does the warmer North Atlantic play a role in explaining the relatively weak and shallow AMOC in this simulation? The focus here seems to be almost entirely on the Southern Ocean, but what’s the effect of the brine parameterization in the North Atlantic?

No cooling can be simulated in the regions of AABW formation due to the presence of sea ice, as the SST is at the freezing point value. The cooling is happening further north, notably in regions of upwelling and is probably due to the enhanced stratification (and decreased convection in the SO cell). We propose adding a sentence here:
We note that the transfer of salt to the bottom of the ocean leads to a cooling of the Southern Ocean (‘P4-I brines’, Fig. 2f), while the opposite occurs with the addition of a freshwater flux around Antarctica (‘P4-I hosing’, Fig. 2h). Observed in ice-free regions (i.e. where the SSTs are not necessarily at the freezing point value), this cooling is probably a consequence of the enhanced

stratification, since a well-mixed water column in upwelling regions would tend to dampen the effect of low winter surface temperatures on the SSTs.
As for the warming of the North Atlantic, it is difficult to pinpoint the exact cause of it. We only used the brine parameterization in the Southern Ocean, so it should be a consequence of the effect of this localized parameterization on the global stratification. We observe a shallower but not weaker NADW cell in ‘P4-I brines’, a denser AABW and fresher surface salinities. These effects should have consequences on ocean heat transport: we observe for example a slightly stronger North Atlantic drift. However, we have not looked deeper into it as this is not the bulk of our study.
Indeed, we focused here essentially on the Southern Ocean. We have only used the brine parameterization in the Southern Hemisphere in ‘P4-I brines’, arguably because the different bathymetry affects the convection processes, but also simply to isolate the effect of a denser AABW. Though not shown in this study, we did run a simulation with the brine parameterization implemented everywhere (with the same frac=0.8) and have observed a similar structure of the AMOC, but with a weaker NADW cell and a slightly weaker bottom cell as well (compared to ‘P4-I brines’), which slightly improves the model-data agreement with $\delta^{13}C$ proxy data and the atmospheric CO_2 concentration (also not shown here). We think including the results from this simulation is not really telling in the context of our study.

-R1.9 : l. 214: what is the statement that "’Cold P2’ is not the simulation with the best overall agreement" based on? From what is shown in the paper, it seems to at least show among the best agreement in terms of SSTs. (And believing the Tierney et al. (2020) estimate it would also be the best in terms of global mean temperature.)

Believing the estimate from Tierney et al. (2020), ‘Cold P2’ is indeed best in terms of global mean surface temperature. However, considering the regional patterns of SSTs, we learn a few things. We observe in Fig. 3 (see triangles) that the simulation ‘Cold P2’ achieves a smaller RMSE for the Southern Ocean (and especially in the Atlantic and Indian sectors of the Southern Ocean, the region with the poorest model-data agreement) due to its lower SSTs. This is not surprising given the systematic warm bias we observe in summer around 40–50°S (Fig. 4). However, looking at the mean RMSE in winter (see crosses in Fig. 3b), we see that the RMSE for ‘Cold P2’ is higher than ‘P4-I brines’ for example: despite the lower RMSE for the Southern Ocean (Atlantic and Indian sectors, see triangles), this simulation also presents a deteriorated agreement for the Atlantic Ocean (see diamonds) in winter. This suggests that a cooling of the Southern Ocean (especially the latitudes 40–50°S of the Atlantic and Indian sectors, not so much the latitudes ~60°S of the Pacific sector) improves the model-data agreement but it is not necessarily true if this is associated with too strong a winter cooling in the North Atlantic and Arctic Ocean (see ‘Cold P2’ compared to ‘P4-I brines’ in Fig. 2). In these regions, the difference between the simulated SSTs and the SST data from MARGO Project Members (2009) can be examined in plots similar to Fig. 4 but for the Northern Hemisphere latitudes (not shown here as the focus is on the Southern Ocean).
Basically, we observe from this model-data comparison that a simulation in relatively good agreement with regional data is not necessarily the “best” simulations with respect to global estimates – and the reverse is also true. This fact is actually a limitation of the Tierney et al. (2020) data assimilation method, as their global estimate is based on the simulation with the best multi-regional agreement to data, and is not freed of potential model biases in less well-constrained regions.
Without going into too much detail, we have clarified the sentence L.214 like this:
The simulations with a colder Southern Ocean (‘Cold P2’, ‘P4-I brines’) show a better agreement with the SST data, as indicated by a smaller RMSEs computed for the Southern Ocean (see triangles in Fig. 3). However, ‘Cold P2’ is not the simulation with the lowest mean RMSE (see crosses in Fig. 3b), as it notably shows a higher RMSE in the Atlantic basin in winter (see diamonds).

-R1.10 : Fig. 7: What exactly is plotted here? Is it only the resolved Eulerian mean overturning or does this include the parameterized eddy transport associated with the GM parameterization? What matters for the transport of physical and geochemical tracers is really the isopycnal overturning (which probably does not have two counter-clockwise cells in SO). Computing the latter is admittedly more challenging and not commonly done in studies like this, but at least the GM contribution should be included.

We thank the reviewer for making us aware of this relevant issue. We checked how the streamfunction output of the model is computed: the contribution from the GM parameterization is indeed added to the Eulerian velocities. As for the isopycnal overturning, it has never been computed in the iLOVECLIM model and would be relatively difficult to do in a reasonable time considering our current workforce.

-R1.11 : From Fig. 7, it also seems that the AMOC in the PI simulation is too weak and too shallow, which should be discussed.

The AMOC in the PI simulation is indeed relatively weak and shallow, though it is not an outlier in the PMIP3/PMIP4 ensemble (see Fig. S1 and S2 of Kageyama et al. (in review, 2020)): the pre-industrial AMOC simulated by iLOVECLIM is fairly comparable to the pre-industrial AMOC of HadCM3, AWIESM2, MIROC-ESM and CNRM-CM5, and actually stronger and deeper than that of IPSL-CM5A2 (and IPSL-CM5A-LR).
This text has been included in the new version of the manuscript as follow:
The AMOC in our PI simulation is within the PMIP3/PMIP4 ensemble (see Fig. S1 and S2 of Kageyama et al. (in review, 2020)). In more details, it is fairly comparable to the pre-industrial AMOC of HadCM3, AWIESM2, MIROC-ESM and CNRM-CM5, and actually stronger and deeper than that of IPSL-CM5A2 (and IPSL-CM5A-LR).

-R1.12 : For the evaluation of deep ocean water mass properties it would be very useful to show T and S (as a function of latitude and depth).

Following this suggestion from the reviewer, we added plots of T and S distribution in the Atlantic ocean in Figure S6. These deep water mass properties were previously evaluated in the iLOVECLIM model under PI conditions in Bouttes et al. (2015) (Figures 6 and 7), using data from the World Ocean Atlas 2009. We reproduced the same type of plots for our 'PI' and 'PI brines' simulations, using the same data for comparison. We observe that using the brines parameterization (with the fairly high parameter choice of 0.8) warms the deep ocean interior by a few degrees, which deteriorates the agreement with WOA09 data. Moreover, while this parameterization has no significant effect on the temperature patterns at the subsurface, it causes a decrease of the surface salinity. At depth, although it lessens the salinity difference between the NADW and the fresher AABW, it also improves the salinity patterns in the North Atlantic mid-depths with respect to WOA09 data.

-R1.13 : l. 303-305: I don't follow the argument here about why 'P4-I wind' has a stronger Southern Ocean cell. My guess would be that the stronger wind stress over ice leads to enhanced ice export, which in turn leads to more new sea ice formation and thus brine rejection (c.f. Shin et al 2003).

The multiplication of the wind tension over ice indeed leads to enhanced sea-ice export and as a result increases the sea-ice area (Fig. 5), sea-ice formation and brine rejection at high latitudes. It also leads to sea ice piling up (increased sea-ice thickness). This was not clearly stated in the manuscript, which is why we propose the following modification:
On the other hand, the Southern Ocean cell is enhanced for 'P4-I wind', but moderately ('P4-I hosing') or strongly ('P4-I brines') suppressed for the other sensitivity tests. These results could be

due to the fact that the experimental setting of ‘P4-I wind’ – with the multiplication of the meridional wind stress on ice – enhances sea-ice export, which leads to an increased sea-ice formation and its consequent brine rejection (Shin et al., 2003).

-R1.14 : In Fig. 8 and throughout much of the manuscript "convection" seems to be used synonymously to the large-scale overturning circulation. However, convection can occur without a large-scale overturning and vice versa. I suggest to replace all references to convection cells with overturning cells.

We agree that such a terminology is more appropriate. We have changed it accordingly in Section 3.4 and in the captions of Fig. 8 and S5.

-R1.15 : In section 4.1 the various simulations are separated into those that amount to different choices for "boundary conditions" and "experimental setting", a separation that makes its way also into the abstract and conclusions. This separation, and the term "experimental setting" seems very vague. E.g. the assumed glacial temperature profile affects the simulation results via heat flux in or out of the glacier surface, and thus effectively also amounts to a difference in boundary conditions. In general it seems that "boundary conditions" is only used for cases with different choices for ice sheet topography, so I suggest to simply be explicit about that. As for the various other experiments, I don’t see how they can be lumped into one category.

We also thought that the term “experimental setting” may be too vague, so thank you for the confirmation. After discussing the terminology, we find that this term is too general as it encapsulates both changes of boundary conditions (which are the changes of elevation, albedo, bathymetry and land-sea mask associated with the choice of the ice-sheet topography, such as GLAC-1D, ICE-6G-C or ICE-5G), and the modelling choices made in sensitivity tests, which concern either forcings (such as in ‘Cold P2’, ‘P4-I hosing’, ‘P4-I wind’), or model parameter choices (‘P4-I brines’, as ‘P4-I’ would be with a chosen fraction of 0). This inadequate use of terminology is probably why the distinction of these different types of modelling choices seems vague. It should be clearer with the following specifications and corrections or the term “experimental setting”:
- L. 72: Since the ice sheet reconstructions are still associated with large uncertainties, Kageyama et al. (2017) describe the common experimental design for LGM experiments in the current phase 4 of the project but let modelling groups choose from three different ice sheet reconstructions: GLAC-1D (Tarasov et al., 2012), ICE-6G-C (Peltier et al., 2015; Argus et al., 2014), or PMIP3 (Abe-Ouchi et al., 2015). To see the impact of such a choice, we have implemented in this study the boundary conditions (e.g. elevation, bathymetry, land-sea mask) associated with the first two options since these reconstructions are the most recent.
- L.54: “boundary conditions and other experimental settings”
- L.204: “the choice of boundary conditions and of the sensitivity tests”
- L. 295: “using different boundary conditions and/or forcing or model parameter choices (in the sensitivity tests)”
- L.286: “modelling choices”
- L. 299: “choice of forcings and model parameters”
- L.317: “relative impact of boundary conditions and other modelling choices (related to forcings or model parameter choices)”
- L.323: “the modelling choices made in sensitivity tests”
- L. 394: “sensitivity tests”

-R1.16 : Section 4.3.: Given the high uncertainty, particularly in the reconstructions of summer sea ice cover, I think it would be useful to provide some estimate of uncertainty for the sea ice seasonality from proxy data.

If we consider (as we first did) indicative error bars of 10% and 20% for the winter and summer sea-ice extent respectively, we get a seasonality estimate of 22.7×10^6 km^2 +/- 5.3×10^6 km^2. Considering higher indicative error bars of 15% and 30%, we get an estimate of 22.7×10^6 km^2 +/- 8.0×10^6 km^2, though this high uncertainty is mostly induced by the chosen error bar of 15% since the winter sea-ice extent is much larger (yet more well-constrained) than the summer one. If it was a strict estimate of the uncertainty, we would need to be more cautious with statements such as L.256-257 ("This suggests that the enhanced seasonality of the LGM Southern Ocean sea ice (22.7×10^6 km^2 according to our proxy reconstructions, compared to the modern seasonal range of 15.4×10^6 km^2) is not entirely simulated by the model [...]"). However, as mentioned above, these estimates are only meant to give the reader a sense of the magnitude of the error, which is why we propose the following cautious addition:
First of all, the simulated seasonal amplitude of sea ice is too small with respect to the proxy data estimates, which suggest a sea-ice seasonality of 22.7×10^6 km^2 (+/- 8.0×10^6 km^2 based on 15% and 30% error bars on winter and summer sea-ice extent, respectively).

-R1.17 : I find the last paragraph of section 4.3 and specifically the attempt to reconcile the conflicting results between this study and Heuze et al. (2013) hard to follow and it seems very speculative. I don't think this discussion is necessary either, so I suggest removing this paragraph.

Having reflected on the previous text of the paragraph, we indeed found it difficult to follow in relation with the previous paragraphs. We therefore propose to modify it as follow, in the hope that it will be much clearer:
Identifying the origin of a bias is always a challenge. It might be an especially hard task to identify the origin of biases in the simulated sea-ice cover, considering the sheer number of feedbacks involved (Goosse et al., 2018). What can be noticed is that the simulated sea-ice seasonal cycle is affected by some of our modelling choices (increased in 'P4-I brines', reduced in 'P4-I wind'). Alongside, the Southern Ocean convection is suppressed in the first sensitivity test, and enhanced in the second. In a climatological mean in our model there seems to be a link between reduced Southern Ocean convection and increased sea-ice seasonal cycle. In opposition to this observation, Heuzé et al. (2013) have underlined the fact that CMIP5 models with a large sea-ice seasonality are also the ones simulating open ocean convection over extensive areas at modern times, arguing that strong sea-ice formation could precondition the ocean for open ocean deep convection. This questions the relative importance of the different simulated mechanisms at play linking the ocean convection and the sea-ice seasonal cycle, an aspect that is present in several studies (e.g. Marshall and Speer, 2012, Behrens et al., 2016; Ma et al., 2020).

-R1.18 : Based on the issues pointed out above, I'm not sure the last sentence of the conclusion can be justified. At the least, "boundary conditions, such as the ice sheet reconstruction" should be reduced to just "the ice sheet reconstruction".

We removed the term "boundary conditions" and added "for the variables analyzed in this study" to be more accurate. Still, we would like to point out that thanks to our set of simulations, we tested the impact of different types of LGM boundary conditions: ICE-5G, ICE-6G-C and GLAC-1D differ in terms of elevation (mostly), but also albedo, land-sea mask and bathymetry, whereas it is only the ocean boundary conditions which are different in the simulations 'Warm P2' and 'New P2'. As mentioned before, we are concerned that the term "ice sheet reconstruction" might be automatically associated with a change of atmosphere boundary conditions in the reader's mind, which is why we propose the following clarification:
For the variables analyzed in this study, it would therefore seem that the correct simulation of convection processes is paramount, and far more important than the choice of ice sheet reconstruction used to implement the orography and bathymetry.

We are not implying here that the convection processes simulated (or rather, parametrized) in ‘P4-I brines’ are “correct”. This simulation is only useful to show that the intensity of the open ocean convection which is simulated in the Southern Ocean by iLOVECLIM and the large majority of models (also see Section 4.2) might be detrimental to a realistic representation of both the water mass distribution and the sea-ice seasonality. This could be of importance for other modelling groups (especially those also working on EMICs) since targeting the representation of convection processes in models may be more critical to improve the simulated glacial deep ocean circulation than spending time to implement the boundary conditions associated with different ice-sheet reconstructions in order to account for the uncertainties in the reconstructions (as suggested by Kageyama et al., 2017).
We also note that the simulation ‘New P2 brines’ (added on the second reviewer’s suggestion in Fig. S5) yields a result similar to ‘P4-I brines’ (which is also the case of a simulation ‘P4-G brines’ not shown here), which strengthens this conclusion on the secondary impact of the choice of boundary conditions at the LGM (at least for the model resolution and variables examined in this study).

References

Abe-Ouchi, A., Saito, F., Kageyama, M., Braconnot, P., Harrison, S. P., Lambeck, K., Otto-Bliesner, B. L., Peltier, W. R., Tarasov, L., Peterschmitt, J.-Y., and Takahashi, K.: Ice-sheet configuration in the CMIP5/PMIP3 Last Glacial Maximum experiments, Geosci. Model Dev., 8, 3621–3637, https://doi.org/10.5194/gmd-8-3621-2015, 2015.

Annan, J. D. and Hargreaves, J. C.: A new global reconstruction of temperature changes at the Last Glacial Maximum, Clim. Past, 9, 367–376, https://doi.org/10.5194/cp-9-367-2013, 2013.

Antonov, J. I., Seidov, D., Boyer, T. P., Locarnini, R. A., Mishonov, A. V., Garcia, H. E., Baranova, O. K., Zweng, M. M., and Johnson, D. R.: World Ocean Atlas 2009, Volume 2: Salinity, Levitus, S., NOAA Atlas NESDIS 69, US Government Printing Office, Washington, D.C., 2010.

Argus, D. F., Peltier, W. R., Drummond, R., and Moore, A. W.: The Antarctica component of postglacial rebound model ICE-6G-C (VM5a) based on GPS positioning, exposure age dating of ice thicknesses, and relative sea level histories, Geophys. J. Int., 198, 537–563, https://doi.org/10.1093/gji/ggu140, 2014.

Benz, V., Esper, O., Gersonde, R., Lamy, F., and Tiedemann, R.: Last Glacial Maximum sea surface temperature and sea-ice extent in the Pacific sector of the Southern Ocean, Quat. Sci. Rev., 146, 216–237, https://doi.org/10.1016/j.quascirev.2016.06.006, 2016.

Bé, A. W. H. and Hutson, W. H.: Ecology of planktonic foraminifera and biogeographic patterns of life and fossil assemblages in the Indian Ocean, Micropaleontology, 23, 369–414, https://doi.org/10.2307/1485406, 1977.

Böhm, E., Lippold, J., Gutjahr, M., Frank, M., Blaser, P., Antz, B., Fohlmeister, J., Frank, N., Andersen, M. B., and Deininger, M.: Strong and deep Atlantic meridional overturning circulation during the last glacial cycle, Nature, 517, 73–76, **https://doi.org/10.1038/nature14059**, 2015.

Bouttes, N., Paillard, D., and Roche, D. M.: Impact of brine-induced stratification on the glacial carbon cycle, Clim. Past, 6, 575–589, https://doi.org/10.5194/cp-6-575-2010, 2010.

Bouttes, N., Roche, D. M., Mariotti, V., and Bopp, L.: Including an ocean carbon cycle model into iLOVECLIM (v1.0), Geosci. Model Dev., 8, 1563–1576, https://doi.org/10.5194/gmd-8-1563-2015, 2015.

Cortese, G. and Prebble, J.: A radiolarian-based modern analogue dataset for palaeoenvironmental reconstructions in the southwest Pacific, Marine Micropaleontology, 118, 34–49, https://doi.org/10.1016/j.marmicro.2015.05.002, 2015.

Crosta, X., Sturm, A., Armand, L., and Pichon, J.-J.: Late Quaternary sea ice history in the Indian sector of the Southern Ocean as recorded by diatom assemblages, Mar. Micropaleontol., 50, 209–223, https://doi.org/10.1016/S0377-8398(03)00072-0, 2004.

Esper, O. and Gersonde, R.: New tools for the reconstruction of Pleistocene Antarctic sea ice, Palaeogeography, Palaeoclimatology, Palaeoecology, 399, 260–283, https://doi.org/10.1016/j.palaeo.2014.01.019, 2014.

Fretwell, P., Pritchard, H. D., Vaughan, D. G., Bamber, J. L., Barrand, N. E., Bell, R., Bianchi, C., Bingham, R. G., Blankenship, D. D., Casassa, G., Catania, G., Callens, D., Conway, H., Cook, A. J., Corr, H. F. J., Damaske, D., Damm, V., Ferraccioli, F., Forsberg, R., Fujita, S., Gim, Y., Gogineni, P., Griggs, J. A., Hindmarsh, R. C. A., Holmlund, P., Holt, J. W., Jacobel, R. W., Jenkins, A., Jokat, W., Jordan, T., King, E. C., Kohler, J., Krabill, W., Riger-Kusk, M., Langley, K. A., Leitchenkov, G., Leuschen, C., Luyendyk, B. P., Matsuoka, K., Mouginot, J., Nitsche, F. O., Nogi, Y., Nost, O. A., Popov, S. V., Rignot, E., Rippin, D. M., Rivera, A., Roberts, J., Ross, N., Siegert, M. J., Smith, A. M., Steinhage, D., Studinger, M., Sun, B., Tinto, B. K., Welch, B. C., Wilson, D., Young, D. A., Xiangbin, C., and Zirizzotti, A.: Bedmap2: improved ice bed, surface and thickness datasets for Antarctica, Cryosphere, 7, 375–393, https://doi.org/10.5194/tc-7-375-2013, 2013.

Galbraith, E. and de Lavergne, C.: Response of a comprehensive climate model to a broad range of external forcings: relevance for deep ocean ventilation and the development of late Cenozoic ice ages, Clim. Dynam., 52, 653–679, https://doi.org/10.1007/s00382-018-4157-8, 2019.

Gersonde, R. and Zielinski, U.: The reconstruction of late Quaternary Antarctic sea-ice distribution —the use of diatoms as a proxy for sea-ice, Palaeogeography, Palaeoclimatology, Palaeoecology, 162, 263–286, https://doi.org/10.1016/S0031-0182(00)00131-0, 2000.

Gersonde, R., Crosta, X., Abelmann, A., and Armand, L.: Sea-surface temperature and sea ice distribution of the Southern Ocean at the EPILOG Last Glacial Maximum — a circum-Antarctic view based on siliceous microfossil records, Quat. Sci. Rev., 24, 869–896, https://doi.org/10.1016/j.quascirev.2004.07.015, 2005.

Goosse, H., Brovkin, V., Fichefet, T., Haarsma, R., Huybrechts, P., Jongma, J., Mouchet, A., Selten, F., Barriat, P. Y., Campin, J. M., Deleersnijder, E., Driesschaert, E., Goelzer, H., Janssens, I., Loutre, M. F., Morales Maqueda, M. A., Opsteegh, T., Mathieu, P. P., Munhoven, G., Pettersson, E. J., Renssen, H., Roche, D. M., Schaeffer, M., Tartinville, B., Timmermann, A., and Weber, S. L.: Description of the Earth system model of intermediate complexity LOVECLIM version 1.2, Geosci. Model Dev., 3, 603–633, https://doi.org/10.5194/gmd-3-603-2010, 2010.

Goosse, H., Roche, D. M., Mairesse, A., and Berger, M.: Modelling past sea ice changes, Quat. Sci. Rev., 79, 191–206, https://doi.org/10.1016/j.quascirev.2013.03.011, 2013.

Heuzé, C., Heywood, K. J., Stevens, D. P., and Ridley, J. K.: Southern Ocean bottom water characteristics in CMIP5 models, Geophys. Res. Lett., 40, 1409–1414, https://doi.org/10.1002/grl.50287, 2013.

Heuzé, C.: Antarctic Bottom Water and North Atlantic Deep Water in CMIP6 models, Ocean Sci., https://doi.org/10.5194/os-2020-66, in review, 2020.

Howard, W. R. and Prell, W. L.: Late Quaternary surface circulation of the Southern Indian Ocean and its relations to orbital variations, Paleoceanography, 7, 79–117, https://doi.org/10.1029/91PA02994, 1992.

Jackson, E. K., Roberts, W., Nelsen, B., Williams, G. P., Nelson, E. J., and Ames, D. P.: Introductory overview: Error metrics for hydrologic modelling – A review of common practices and an open source library to facilitate use and adoption, Environmental Modelling and Software, 119, 32–48, https://doi.org/10.1016/j.envsoft.2019.05.001, 2019.

Kageyama, M., Albani, S., Braconnot, P., Harrison, S. P., Hopcroft, P. O., Ivanovic, R. F., Lambert, F., Marti, O., Peltier, W. R., Peterschmitt, J.-Y., Roche, D. M., Tarasov, L., Zhang, X., Brady, E. C., Haywood, A. M., LeGrande, A. N., Lunt, D. J., Mahowald, N. M., Mikolajewicz, U., Nisancioglu, K. H., Otto-Bliesner, B. L., Renssen, H., Tomas, R. A., Zhang, Q., Abe-Ouchi, A., Bartlein, P. J., Cao, J., Li, Q., Lohmann, G., Ohgaito, R., Shi, X., Volodin, E., Yoshida, K., Zhang, X., and Zheng, W.: The PMIP4 contribution to CMIP6 – Part 4: Scientific objectives and experimental design of the PMIP4-CMIP6 Last Glacial Maximum experiments and PMIP4 sensitivity experiments, Geosci. Model Dev., 10, 4035–4055, https://doi.org/10.5194/gmd-10-4035-2017, 2017.

Kageyama, M., Harrison, S. P., Kapsch, M.-L., Löfverström, M., Lora, J. M., Mikolajewicz, U., Sherriff-Tadano, S., Vadsaria, T., Abe-Ouchi, A., Bouttes, N., Chandan, D., LeGrande, A. N., Lhardy, F., Lohmann, G., Morozova, P. A., Ohgaito, R., Peltier, W. R., Quiquet, A., Roche, D. M., Shi, X., Schmittner, A., Tierney, J. E., and Volodin, E.: The PMIP4-CMIP6 Last Glacial Maximum experiments: preliminary results and comparison with the PMIP3-CMIP5 simulations, Clim. Past, https://doi.org/10.5194/cp-2019-169, in review, 2020.

Locarnini, R. A., Mishonov, A. V., Antonov, J. I., Boyer, T. P., Garcia, H. E., Baranova, O. K., Zweng, M. M., and Johnson, D. R.: World Ocean Atlas 2009, Volume 1: Temperature, Levitus, S., NOAA Atlas NESDIS 68, US Government Printing Office, Washington, D.C., 2010.

Lynch-Stieglitz, J., Adkins, J. F., Curry, W. B., Dokken, T., Hall, I. R., Herguera, J. C., Hirschi, J. J.-M., Ivanova, E. V., Kissel, C., Marchal, O., Marchitto, T. M., McCave, I. N., McManus, J. F., Mulitza, S., Ninnemann, U., Peeters, F., Yu, E.-F., and Zahn, R.: Atlantic Meridional Overturning Circulation During the Last Glacial Maximum, Science, 316, 66–69, https://doi.org/10.1126/science.1137127, 2007.

MARGO Project Members: Constraints on the magnitude and patterns of ocean cooling at the Last Glacial Maximum, Nat. Geosci., 2, 127–132, https://doi.org/10.1038/NGEO411, 2009.

Orsi, A. H., Johnson, G. C., and Bullister, J. L.: Circulation, mixing, and production of Antarctic Bottom Water, Prog. Oceanogr., 43, 55–109, https://doi.org/10.1016/S0079-6611(99)00004-X, 1999.

Peltier, W. R.: Global glacial isostasy and the surface of the ice-age Earth: the ICE-5G (VM2) model and GRACE, Annu. Rev. Earth Pl. Sc., 32, 111–149, https://doi.org/10.1146/annurev.earth.32.082503.144359, 2004.

Peltier, W. R., Argus, D. F., and Drummond, R.: Space geodesy constrains ice age terminal deglaciation: The global ICE-6G-C (VM5a) model, J. Geophys. Res.-Sol. Ea., 120, 450–487, https://doi.org/10.1002/2014JB011176, 2015.

Prahl, F., Herbert, T. D., Brassell, S., Ohkouchi, N., Pagani, M., Rosell-Melé, A., Repeta, D., and Sikes, E.: Status of alkenone paleothermometer calibration: Report from Working Group 3, Geochem. Geophys. Geosyst., 1, https://doi.org/10.1029/2000GC000058, 2000.

Roche, D. M., Dokken, T. M., Goosse, H., Renssen, H., and Weber, S. L.: Climate of the Last Glacial Maximum: sensitivity studies and model-data comparison with the LOVECLIM coupled model, Clim. Past, 3, 205–224, https://doi.org/10.5194/cpd-2-1105-2006, 2007.

Roche, D. M., Crosta, X., and Renssen, H.: Evaluating Southern Ocean sea-ice for the Last Glacial Maximum and pre-industrial climates: PMIP-2 models and data evidence, Quat. Sci. Rev., 56, 99–106, https://doi.org/10.1016/j.quascirev.2012.09.020, 2012.

Rousset, C., Vancoppenolle, M., Madec, G., Fichefet, T., Flavoni, S., Barthélemy, A., Benshila, R., Chanut, J., Levy, C., Masson, S., and Vivier, F.: The Louvain-La-Neuve sea ice model LIM3.6: global and regional capabilities, Geosci. Model Dev., 8, 2991–3005, https://doi.org/10.5194/gmd-8-2991-2015, 2015.

Shin, S.-I., Liu, Z., Otto-Bliesner, B. L., Kutzbach, J. E., and Vavrus, S. J.: Southern Ocean sea-ice control of the glacial North Atlantic thermohaline circulation, Geophys. Res. Lett., 30, https://doi.org/10.1029/2002GL015513, 2003.

Sikes, E. L., Volkman, J. K., Robertson, L. G., and Pichon, J.-J.: Alkenones and alkenes in surface waters and sediments of the Southern Ocean: Implications for paleotemperature estimation in polar regions, Geochimica et Cosmochimica Acta, 61, 1495–1505, https://doi.org/10.1016/S0016-7037(97)00017-3, 1997.

Tarasov, L., Dyke, A. S., Neal, R. M., and Peltier, W. R.: A data-calibrated distribution of deglacial chronologies for the North American ice complex from glaciological modeling, Earth Planet. Sc. Lett., 315-316, 30–40, https://doi.org/10.1016/j.epsl.2011.09.010, 2012.

Tierney, J. E., Zhu, J., King, J., Malevich, S. B., Hakim, G. J., and Poulsen, C. J.: Glacial cooling and climate sensitivity revisited, Nature, 584, 569–573, https://doi.org/10.1038/s41586-020-2617-x, 2020.

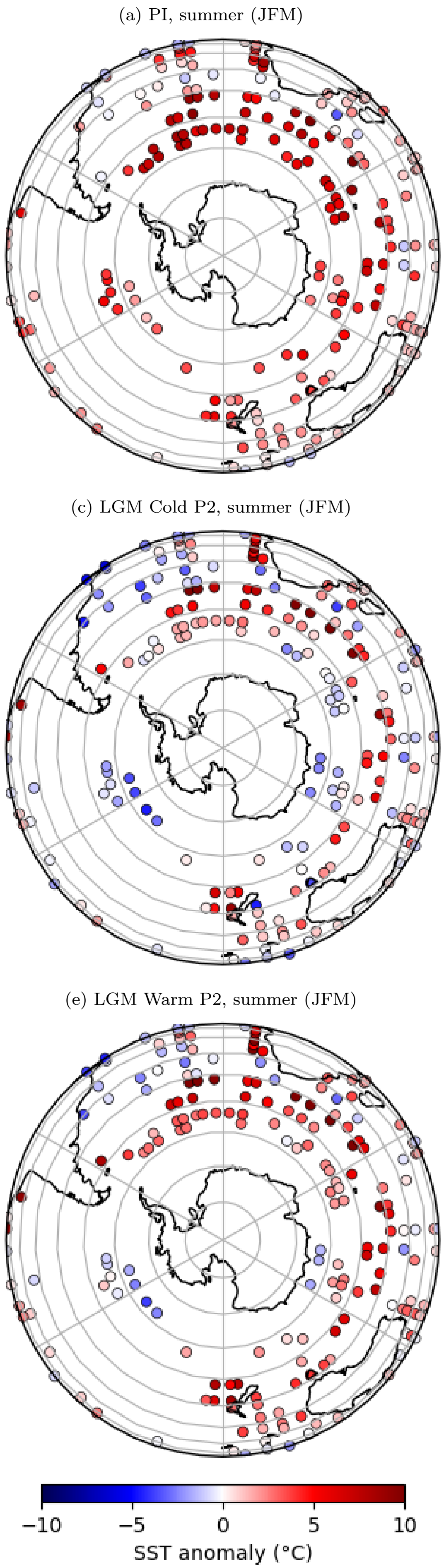
US National Snow and Ice Data Center: NSIDC, https://nsidc.org/.

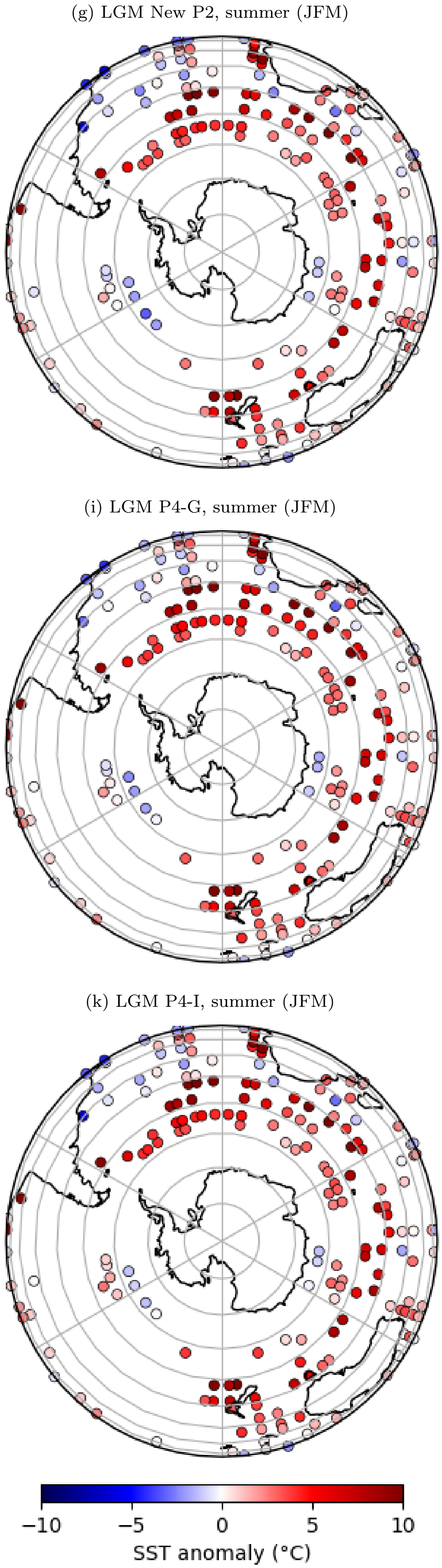
Watterson, I. G.: Non-dimensional measures of climate model performance, International Journal of Climatology: A Journal of the Royal Meteorological Society, 16, 37–391, https://doi.org/10.1002/(SICI)1097-0088(199604)16:4<379::AID-JOC18>3.0.CO;2-U, 1996.

Williams, G. D., Aoki, S., Jacobs, S. S., Rintoul, S. R., Tamura, T., and Bindoff, N. L.: Antarctic Bottom Water from the Adélie and George V Land coast, East Antarctica (140–149E), J. Geophys. Res., 115, https://doi.org/10.1029/2009JC005812, 2010.

World Ocean Atlas: http://ingrid.ldeo.columbia.edu/SOURCES/.NOAA/.NODC/.WOA98/, 1998.

Supplementary information




(g) LGM New P2, summer (JFM)
(h) LGM New P2, winter (JAS)
(i) LGM P4-G, summer (JFM)
(j) LGM P4-G, winter (JAS)
(k) LGM P4-I, summer (JFM)
(l) LGM P4-I, winter (JAS)
−10
−5
0
5
10
SST anomaly (°C)
−10
−5
0
5
10
SST anomaly (°C)

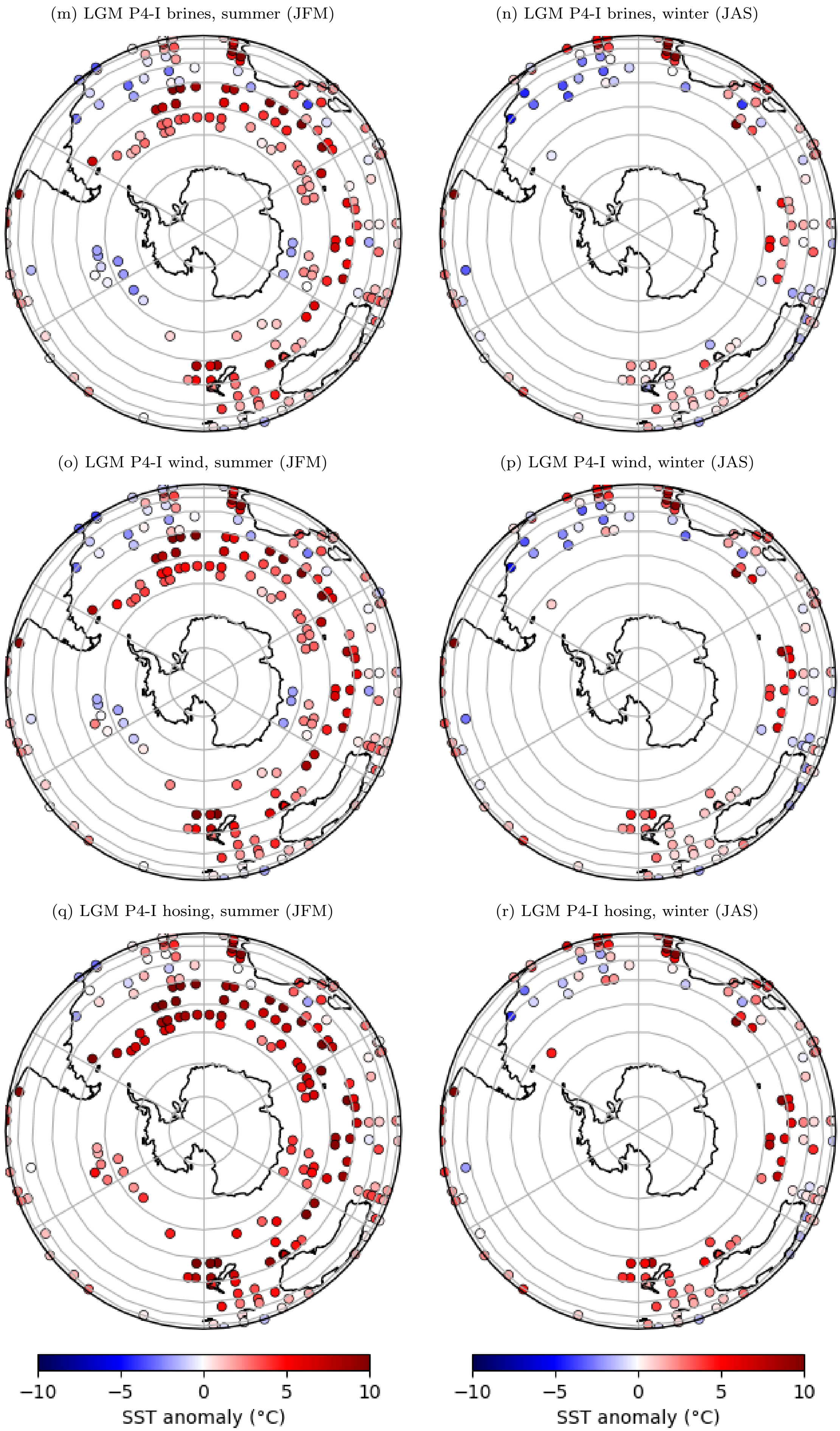
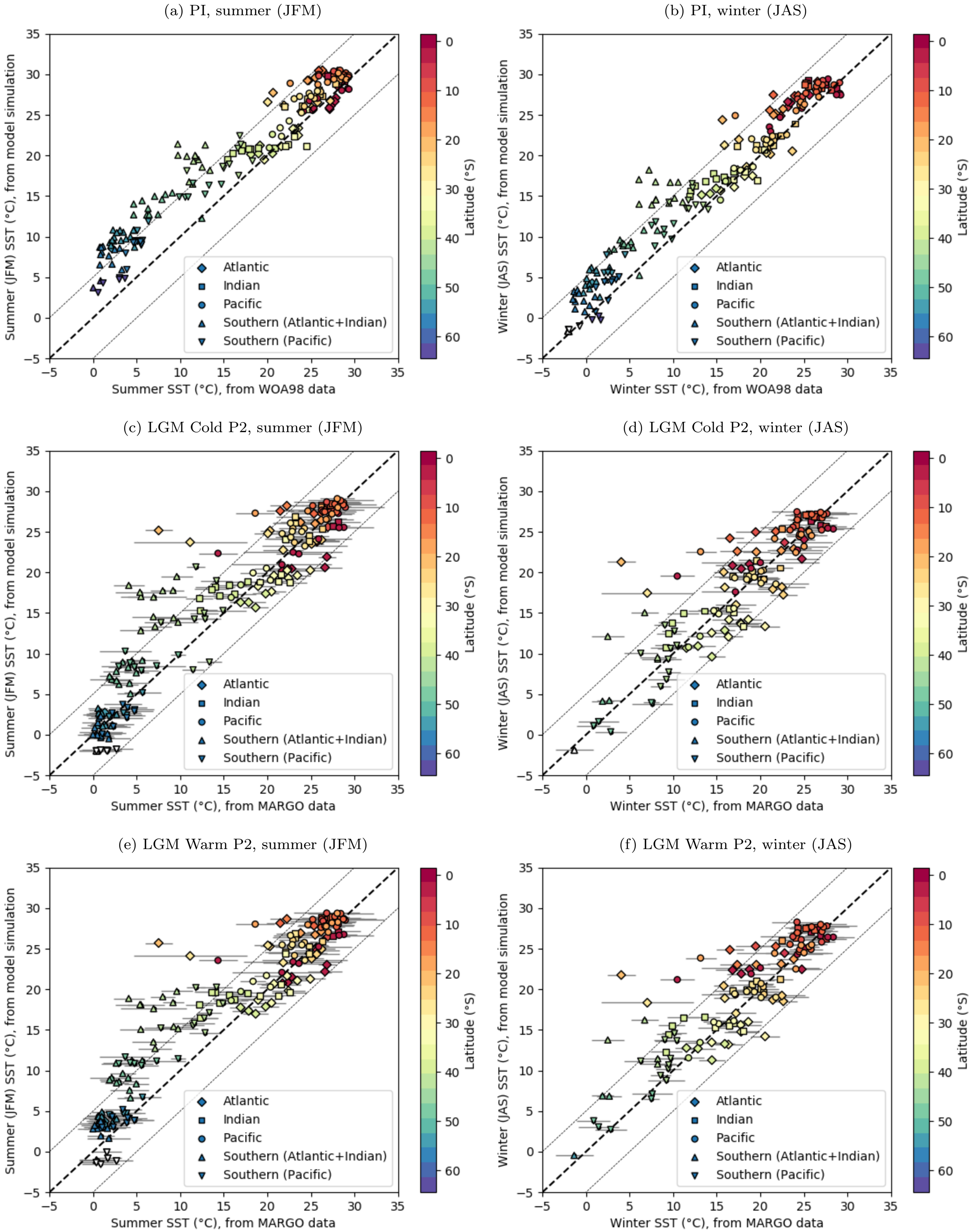
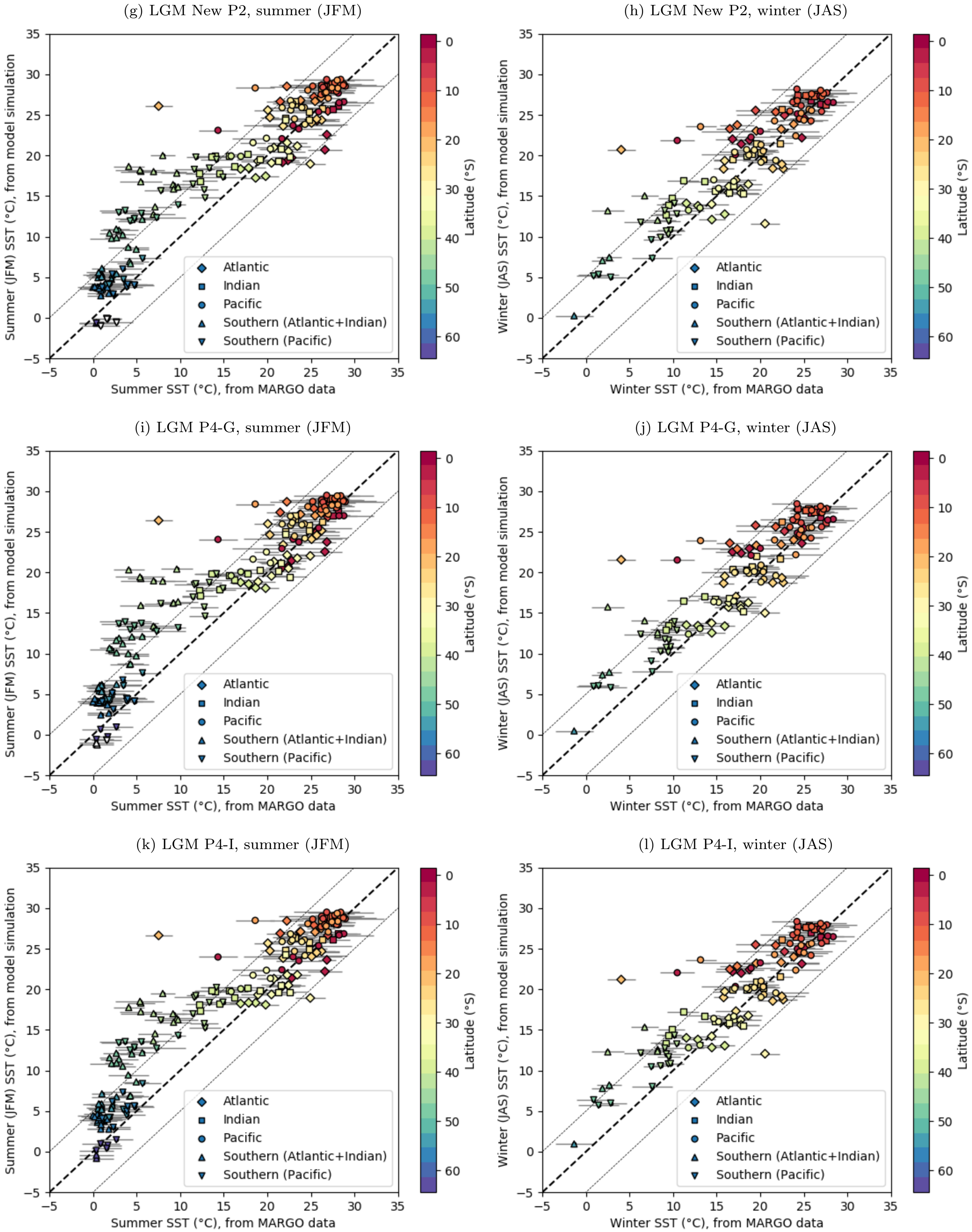


FIGURE S1 – Austral summer (JFM) and winter (JAS) SST anomalies relative to proxy data from the regridded product of MARGO Project Members (2009) (or World Ocean Atlas (1998) for the PI simulation).


(a) PI, summer (JFM)
(b) PI, winter (JAS)
(c) LGM Cold P2, summer (JFM)
(d) LGM Cold P2, winter (JAS)
(e) LGM Warm P2, summer (JFM)
(f) LGM Warm P2, winter (JAS)
Summer (JFM) SST (°C), from model simulation
Winter (JAS) SST (°C), from model simulation
Summer SST (°C), from WOA98 data
Winter SST (°C), from WOA98 data
Summer SST (°C), from MARGO data
Winter SST (°C), from MARGO data
Latitude (°S)
Atlantic
Indian
Pacific
Southern (Atlantic+Indian)
Southern (Pacific)


(g) LGM New P2, summer (JFM)
(h) LGM New P2, winter (JAS)
(i) LGM P4-G, summer (JFM)
(j) LGM P4-G, winter (JAS)
(k) LGM P4-I, summer (JFM)
(l) LGM P4-I, winter (JAS)
Summer (JFM) SST (°C), from model simulation
Summer SST (°C), from MARGO data
Winter (JAS) SST (°C), from model simulation
Winter SST (°C), from MARGO data
Latitude (°S)
Atlantic
Indian
Pacific
Southern (Atlantic+Indian)
Southern (Pacific)

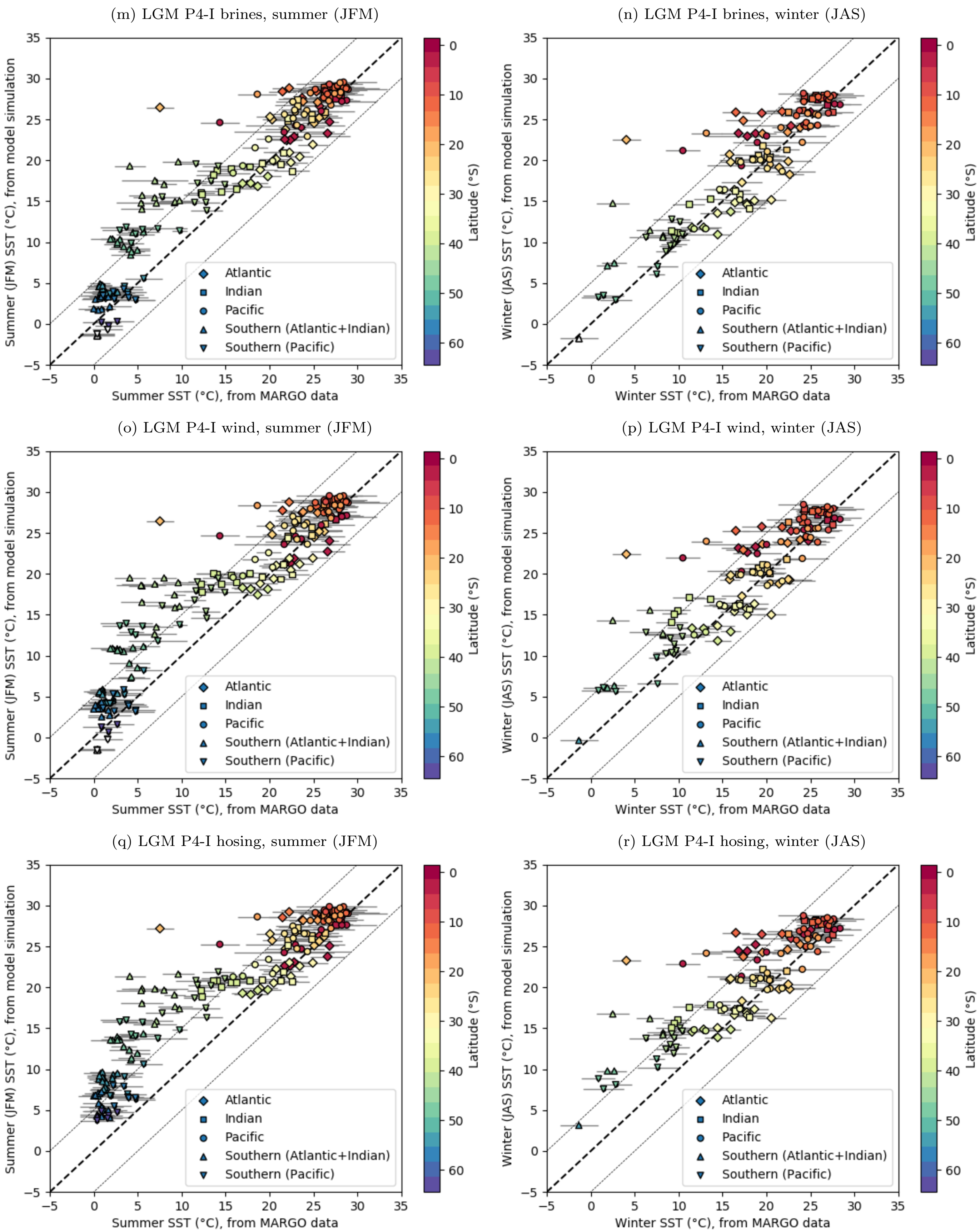


Figure S2 – Austral summer (JFM) and winter (JAS) sea-surface temperatures of the Southern Hemisphere in a model versus data diagram, for all simulations. The simulated SSTs are plotted against the SST data from the regridded product (MARGO Project Members (2009) or World Ocean Atlas (1998)) thanks to the aggregation of the coordinates on the nearest ocean grid cell. The 1 :1 line features a perfect model-data agreement (black dashed line), while the grey dotted lines features a 5°C departure from it. The marker style indicates the ocean basin of each core. The marker color shows the latitude of the core, except it is white where the model simulates sea ice in the Southern Ocean. The uncertainties associated with the SST data are plotted by the grey horizontal bars.

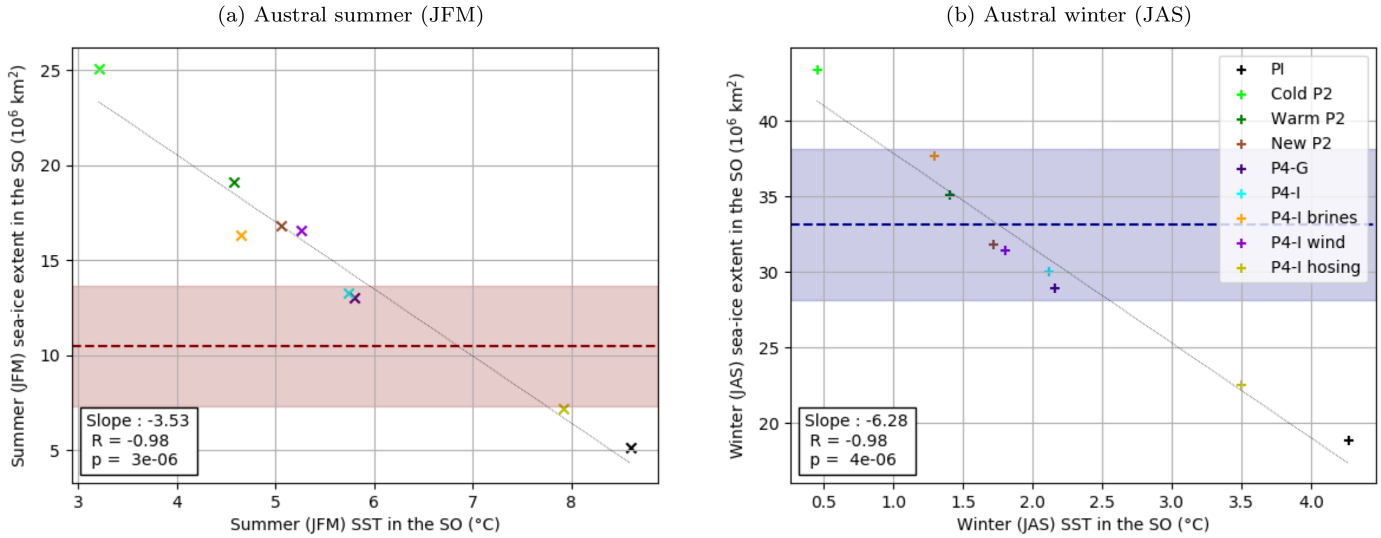
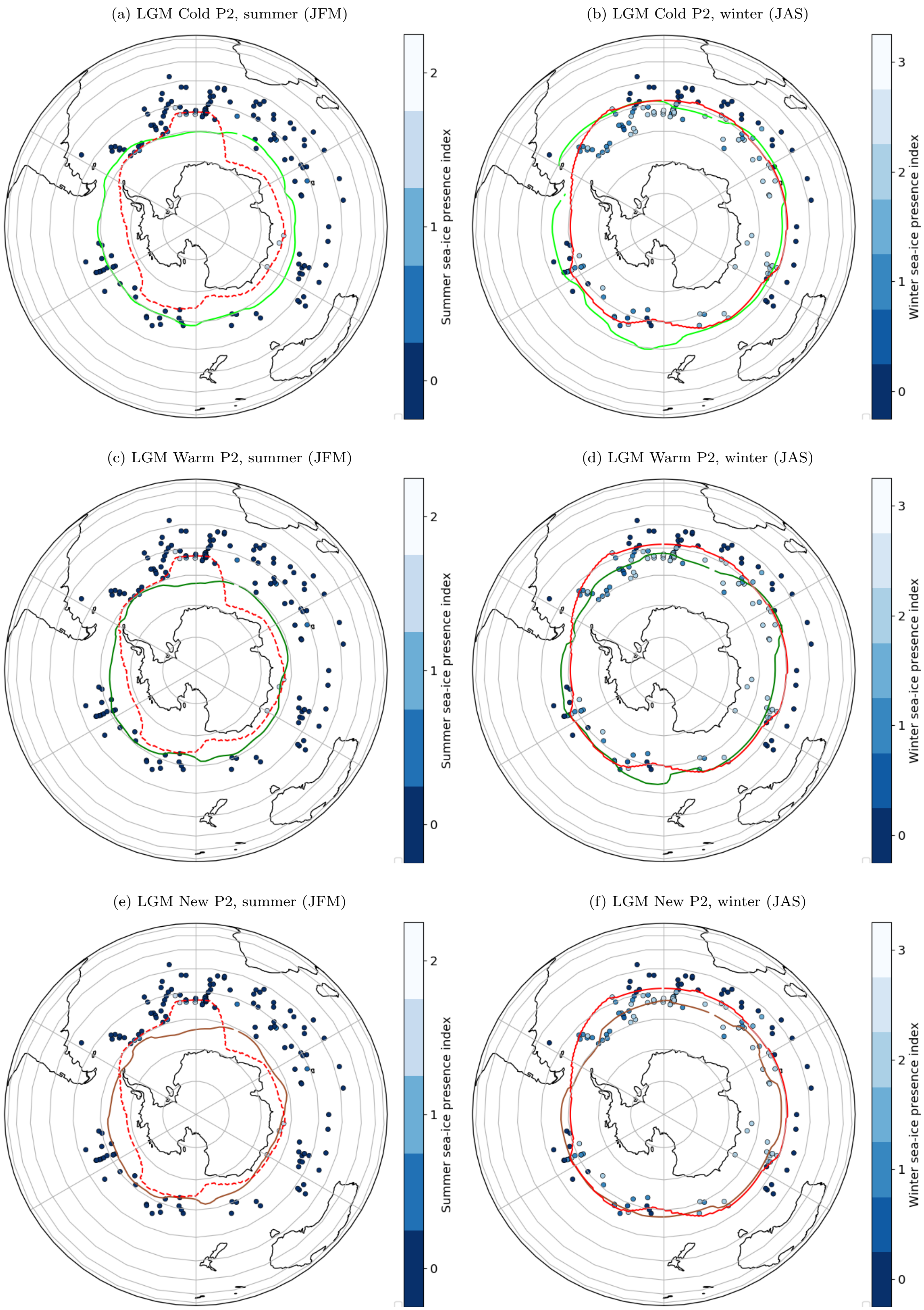
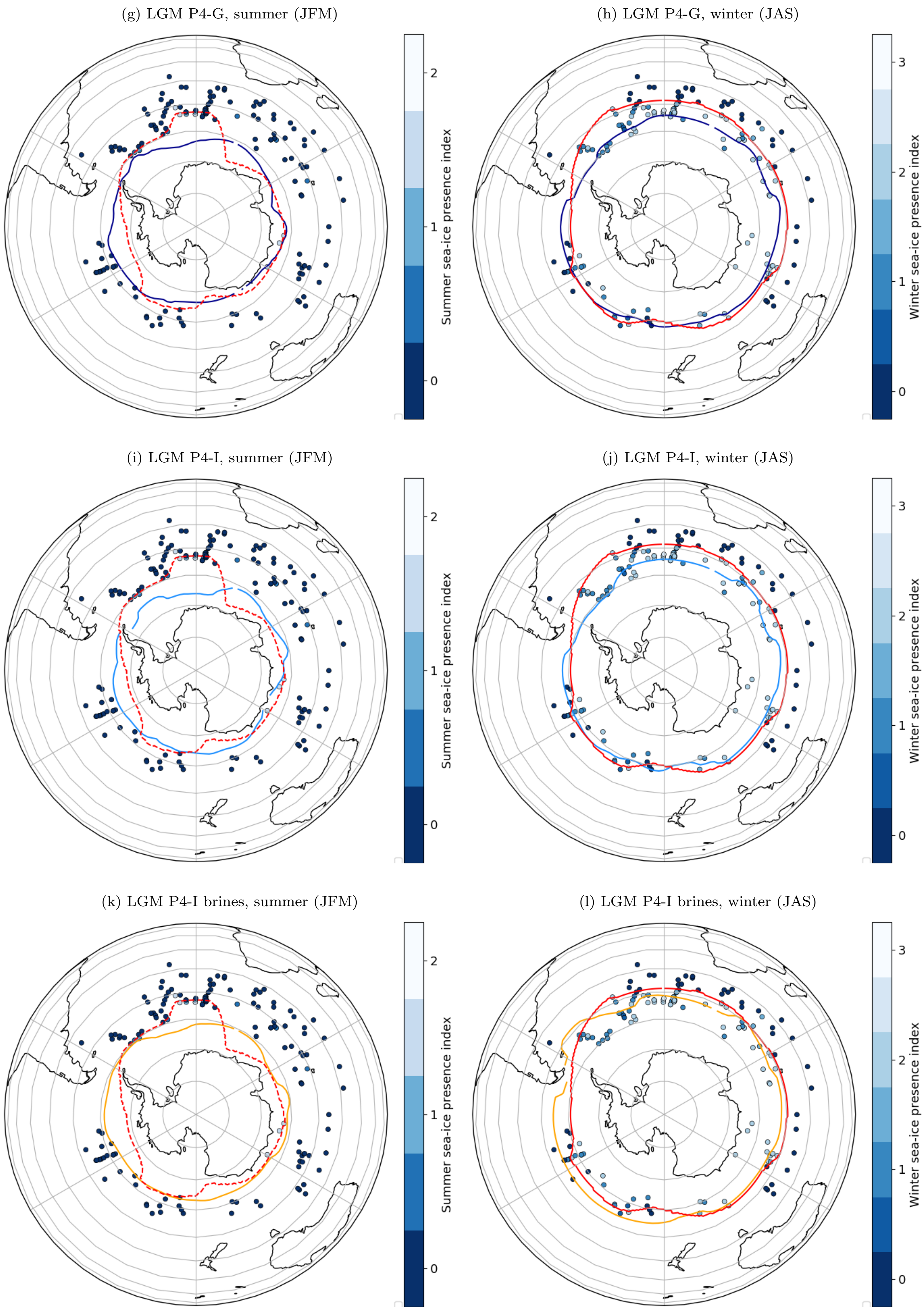


FIGURE S3 – Relationship between the mean SST (averaged up to 36°S) and the sea-ice extent in the Southern Ocean. he LGM sea-ice extent estimated using the proxy data compilation is represented by the red (summer) and the blue (winter) dashed lines (with an indicative error bar of 30% and 15% respectively).



(a) LGM Cold P2, summer (JFM)
Summer sea-ice presence index
0
1
2
(b) LGM Cold P2, winter (JAS)
Winter sea-ice presence index
0
1
2
3
(c) LGM Warm P2, summer (JFM)
Summer sea-ice presence index
0
1
2
(d) LGM Warm P2, winter (JAS)
Winter sea-ice presence index
0
1
2
3
(e) LGM New P2, summer (JFM)
Summer sea-ice presence index
0
1
2
(f) LGM New P2, winter (JAS)
Winter sea-ice presence index
0
1
2
3


(g) LGM P4-G, summer (JFM)
Summer sea-ice presence index
0
1
2
(h) LGM P4-G, winter (JAS)
Winter sea-ice presence index
0
1
2
3
(i) LGM P4-I, summer (JFM)
Summer sea-ice presence index
0
1
2
(j) LGM P4-I, winter (JAS)
Winter sea-ice presence index
0
1
2
3
(k) LGM P4-I brines, summer (JFM)
Summer sea-ice presence index
0
1
2
(l) LGM P4-I brines, winter (JAS)
Winter sea-ice presence index
0
1
2
3

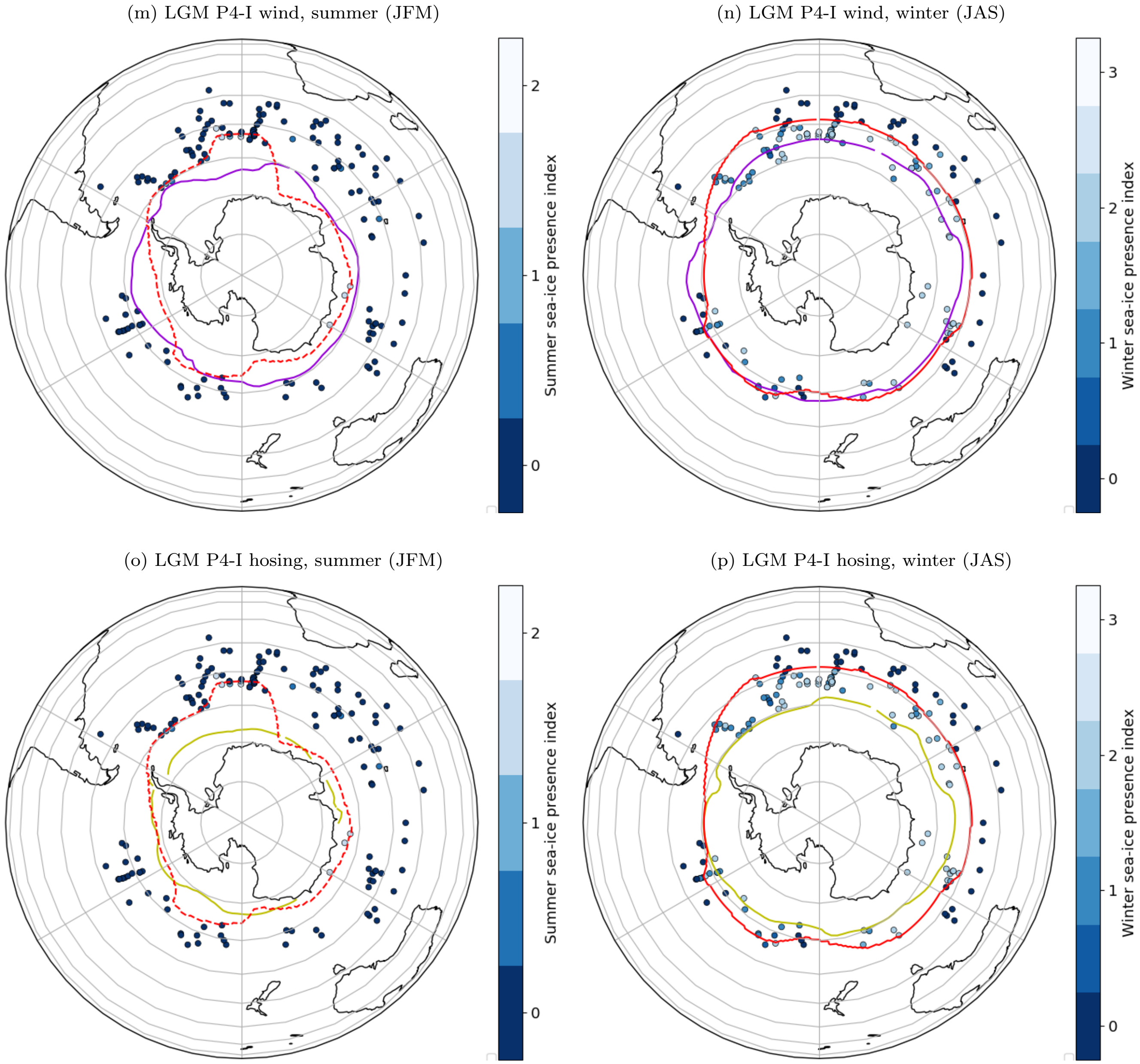


FIGURE S4 – Austral summer (JFM) and winter (JAS) sea-ice edges (at 15% of sea-ice concentration) in the Southern Ocean. The sea-ice presence suggested by marine cores data is represented as an arbitrary index on a blue to white scale, where blue denotes no indication of sea ice in proxies, and white denotes agreement of several proxies on the presence of sea ice. The red lines mark the likely delimitation of the sea-ice presence according to the proxy data (compilation of data from Gersonde et al. (2005), Allen et al. (2011), Ferry et al. (2015), Benz et al. (2016), Xiao et al. (2016), Nair et al. (2019), and Ghadi et al. (2020)). We used a solid red line for the winter months but a dashed line for the summer months as the summer contour is not well-constrained (see Sect. 2.4).

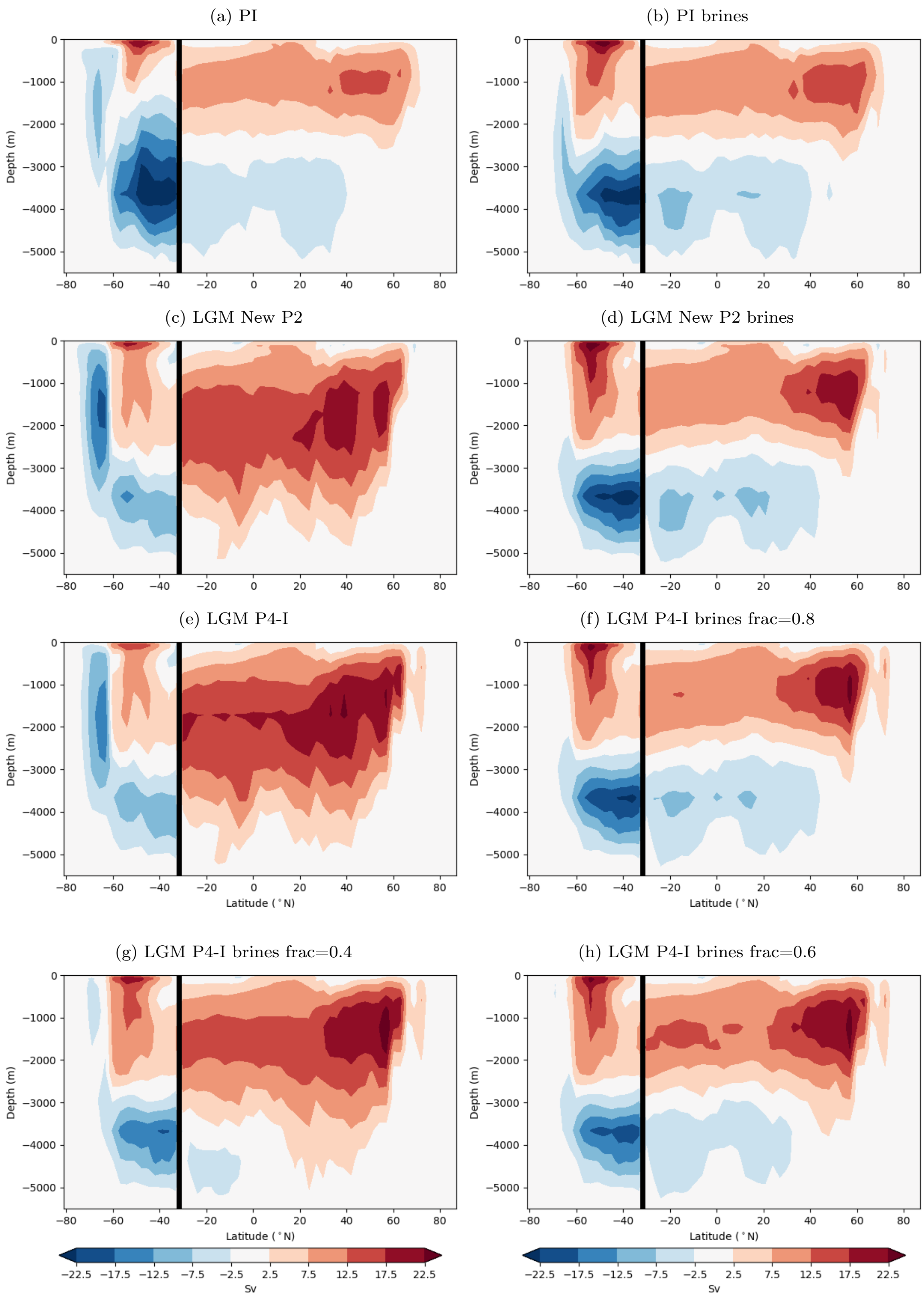


FIGURE S5 – Streamfunctions (Sv) in the Atlantic (North of 32°S) and Southern Ocean basins (South of 32°S). The black vertical line represents the limit between these two basins, chosen at 32°S. This figure shows similar plots as in Figure 7. The streamfunctions of additional simulations using the parameterization of the sinking of brines are displayed to show the effect of the chosen boundary conditions (those of 'PI', 'New P2', or 'P4-I') and of the parameter choice (fraction at 0.4, 0.6 or 0.8) on the streamfunction. For more information, note that the parameter choice and the brine parameterization in general has been discussed in the reviews of Bouttes et al. (2010), which can be found at : https ://cp.copernicus.org/articles/6/575/2010/cp-6-575-2010-discussion.html.

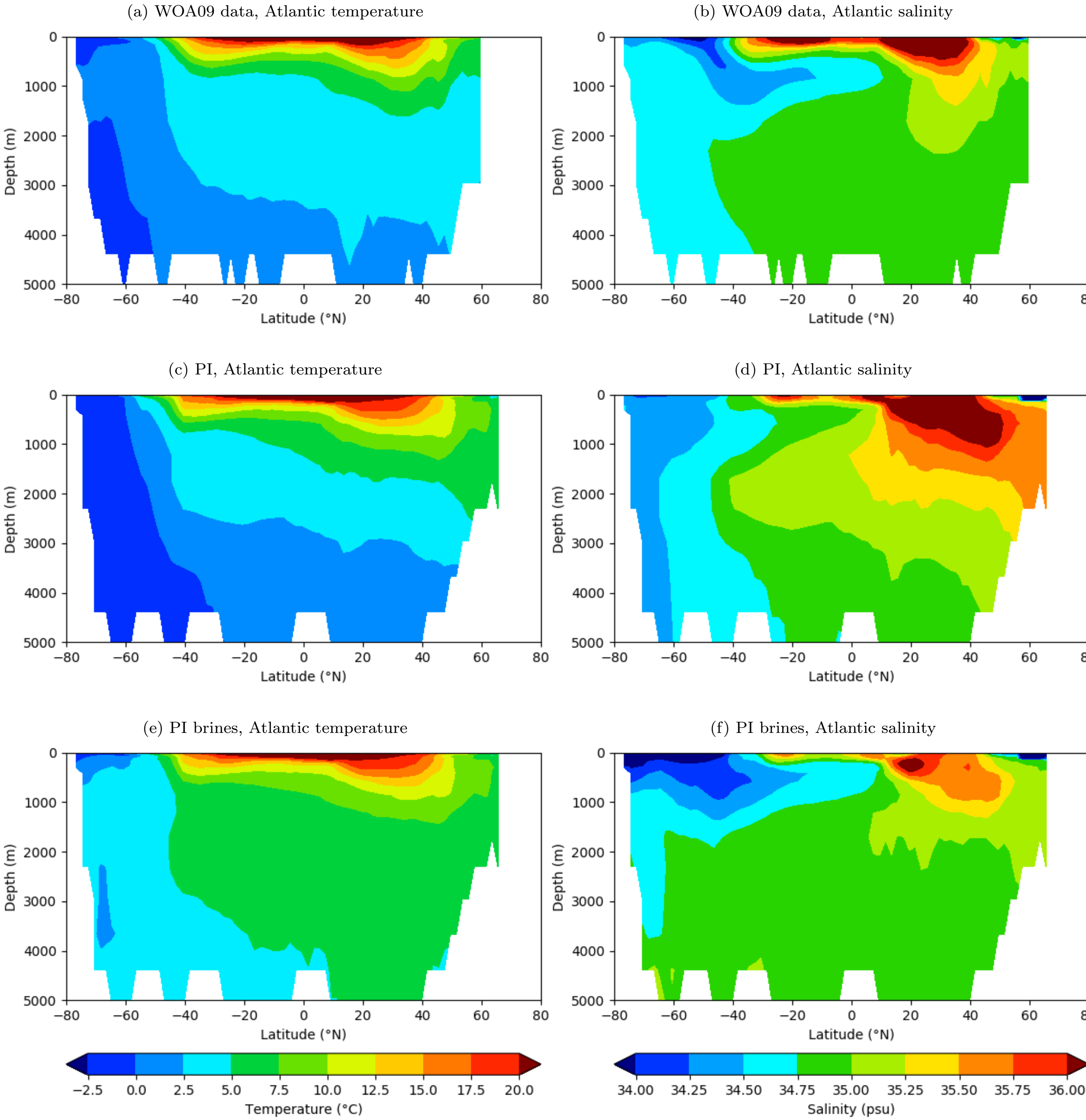


FIGURE S6 – Zonal average of the temperature (a, c, e) and salinity (b, d, f) distribution in the Atlantic ocean. The temperature and salinity distribution simulated at the PI with (e, f) or without (c, d) the parameterization of the sinking of brines is compared to data from the World Ocean Atlas 2009 (Locarnini et al., 2010 ; Antonov et al. 2010).

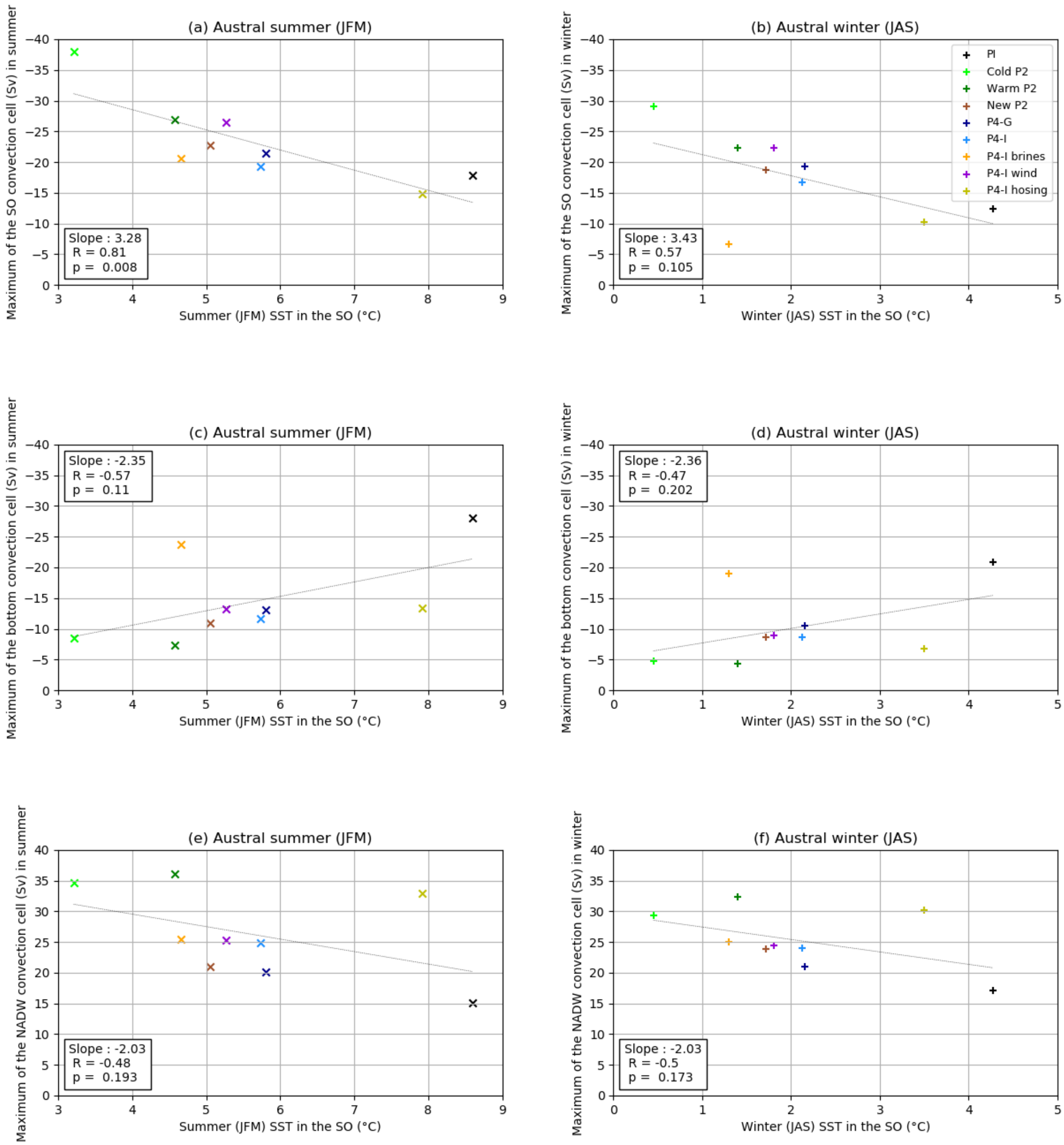


FIGURE S7 – Relationships between the mean SST in the Southern Ocean (averaged up to 36°S) and the Southern Ocean (a, b), bottom (c, d) or NADW (e, f) overturning cell maximum for all simulations. The y-axis is inverted for the two anticlockwise cells (a, b, c, d).