Response to the comments of Dr. Kaihe Yamazaki

This manuscript investigates the influence of the ACC fronts on the climatological mean position of the Antarctic winter sea ice edge. Using established frontal definitions (Orsi et al., 1995; Park et al., 2019) and observational/reanalysis datasets for sea ice, atmospheric, and oceanic variables, the authors find strong correlations (> 0.85) between the latitudes of all major ACC fronts and the winter sea ice edge. The Polar Front (PF) is identified as the most consistent indicator. The study proposes two primary mechanisms for this control: 1) poleward heat transport by mesoscale eddies generated downstream of topographic barriers, and 2) atmospheric warming above warmer surface waters near the PF, with this heat subsequently transported poleward towards the ice, particularly with southward-directed winds. The authors conclude that bathymetry, by shaping the PF's path, strongly constrains the winter sea ice edge.

General Comments:

A very well-written, clearly structured, and valuable contribution to understanding the controls on Antarctic sea ice extent. The study addresses an important and under-explored link in a circumpolar manner. The use of multiple frontal definitions and a relatively simple yet effective methodology lends robustness to the main conclusions. The identified mechanisms are physically plausible and supported by the presented evidence and previous studies. The figures are generally clear and effectively support the text, with Figure 9 providing an excellent summary.

We would like to thank the reviewer for his positive evaluation of our manuscript and the constructive comments.

My concern is the relative lack of discussion on the role of subpolar gyres and the Antarctic Divergence. These features are intrinsically linked to the ACC, upwelling of CDW, and spread of WW, and thus might be highly relevant to SIE positioning. The central narrative that the "ACC/PF controls the winter sea ice edge," while supported by the presented correlations, might potentially be a trivialization or, at least, could benefit from a more nuanced discussion of these interconnected Southern Ocean dynamics.

We totally agree that the Southern Ocean dynamics includes many aspects that are interconnected and it is not easy to identify the contribution of individual mechanisms as they can be linked or driven by similar constraints, such as land topography or oceanic bathymetry. Specifically, we will extend in the revised version the discussion of the role of the subpolar gyres and more generally of the role of horizontal ocean currents. We hope this will bring a more nuanced interpretation of our results. We have also correlated the position of Antarctic Divergence with the one of the winter ice edge and found lower correlation than for the fronts. More details are given below following the related specific comments.

Specific Comments:

1. The manuscript does mention subpolar gyres (L338-340: "Consistent with the development of the subpolar gyres to the south of the ACC..."). However, their role feels somewhat secondary to the direct influence of the fronts. Subpolar gyres are major conduits for heat towards the Antarctic continent and potentially influence subsurface ocean heat content and sea ice formation/melt. I think the authors can

elaborate on how the ACC fronts interact with or shape these gyres, and how gyre dynamics themselves contribute to the SIE position. Is the gyre influence primarily a consequence of the ACC's path (as implied), or do they exert a more independent, synergistic control on the SIE alongside the fronts? Ultimately, the authors may want to present how the ACC is more important than gyres in locating the SIE. The discussion on EKE hotspots (L348-353) or somewhere around could be a place to better integrate gyre dynamics, as these are often associated with gyre boundaries or instabilities. As a consequence of such discussion, can we still say "the ACC is controlling the winter sea ice edge"?

We acknowledge that the discussion of the gyres and more generally of large-scale currents was brief in the submitted version. There were three main reasons for that.

- First, our outlook is that the path of the large-scale currents poleward of the ACC and the position of the gyres are all constrained by oceanic bathymetry. Therefore, the position of gyres and the position of the ACC, are directly connected by having the same constraint. In particular, the two of the main gyres (Weddell and Ross Gyres) form around the major embayments around the Antarctic continent and are shown to follow the major bathymetric features to the north. Because of those relationships, the position of the fronts (which we use as a central diagnostic in our study) brings some information on the ACC itself but also on the horizontal circulation and the location of the gyres. It is thus difficult to disentangle the direct contribution from the ACC from an indirect one coming for instance from the role of the gyres.
- Second, there are different views on the structure of the Subpolar gyres in the Southern Ocean with most studies mainly presenting only the two main gyres (Weddell and Ross Gyres) (e.g. Armitage et al. 2018; Dotto et al., 2018; Vernet et al., 2019), while some others present one supergyre from the Weddell Sea to the Ross Sea (e.g., Sonnewald et al., 2023), with also smaller subpolar gyres in the Indian Ocean sector (e.g., Yamazaki et al. 2020). In contrast to the other diagnostics presented in the submitted version, we did not find a good way to present a robust and circumpolar diagnostic allowing to study the link between the subpolar gyres and the position of the ice edge as for the other elements investigated here. Of course, this does not preclude the role of the gyres in some regions as we mentioned in the submitted version L338-340.
- Third, the Ross and the Weddell gyres are located south of the winter ice edge. Consequently, while they are essential elements of the heat balance at higher latitudes, they are not expected to contribute directly to the southward transport of heat to region of the winter ice edge. They can only influence it indirectly through their role on the advance of sea ice in fall when the ice edge is positioned southward of the northern limit of the gyre.

Nevertheless, we propose to expand the discussion of the potential role of the gyres replacing L338-340 of the submitted version by the following:

Being located south of the ACC, the development of the subpolar gyres is connected to the path of the ACC itself, with both the gyres and the ACC being controlled by the oceanic bathymetry (Armitage et al., 2018; Patmore et al., 2019; Wilson et al., 2022). The southward translation of the fronts and associated large-scale currents at 20°E and

220°E correspond to the traditional eastward limits of the Weddell and Ross gyres (e.g. Dotto et al., 2018; Vernet et al., 2019). In those regions, the circulation of each subpolar gyre is also southward, contributing to the oceanic heat transport towards the Antarctic continent. While this transport is essential for the heat balance at high latitudes, the Weddell and Ross gyres are located to the south of the winter ice edge. Consequently, the gyres do not directly transport heat to the region of the winter ice edge, but can play an indirect role through their impact at higher latitudes and on the sea ice advance in fall, when the ice edge is positioned to the south of the gyres' northern limit. Furthermore, the subpolar circulation cannot be reduced to the Weddell and Ross gyres (e.g., Sonnewald et al., 2023). In particular, it has been argued that smaller sub-gyres are present in other sectors of the Southern Ocean, as in the Indian Sector (Aoki et al., 2010; Yamazaki et al., 2020), where they could be closer to the ice edge and contribute to meridional exchanges there.

We will also ensure that the text is nuanced enough each time we discuss the role of the ocean in transporting heat southward, insisting that this transport is not limited to eddies but horizontal currents, in connection with the subpolar gyres, can also play a role.

We answer specifically the reviewer's point 'can we still say "the ACC is controlling the winter sea ice edge"?' in our answer to comment 3. below.

New references (compared to the submitted version)

Armitage, T. W. K., Kwok, R., Thompson, A. F., and Cunningham, G.: Dynamic topography and sea level anomalies of the Southern Ocean: Variability and teleconnections. J. Geophys. Res.:Oceans, 123, 613–630. https://doi.org/10.1002/2017JC013534, 2018

Aoki, S., Sasai, Y., Sasaki, H., Mitsudera, H., and Williams, G. D. (). The cyclonic circulation in the Australian–Antarctic basin simulated by an eddy-resolving general circulation model. Ocean Dynamics, 60(3), 743–757. https://doi.org/10.1007/s10236-009-0261-y, 2010

Patmore, R.D., Holland, P.R., Munday, D.R., Naveira Garabato, A.C., Stevens, D. P., and Meredith, M.P.: Topographic control of Southern Ocean gyres and the Antarctic Circumpolar Current: a barotropic perspective. J. Phys. Ocean. 49, 3221-3244. https://doi.org/10.1175/JPO-D-19-0083.1, 2019

Yamazaki, K., Aoki, S., Shimada, K., Kobayashi, T., and Kitade, Y. . Structure of the subpolar gyre in the Australian-Antarctic Basin derived from Argo floats. J. Geophys. Res.: Oceans, 125, e2019JC015406. https://doi.org/10.1029/2019JC015406, 2020

2. The Antarctic Divergence is a circumpolar feature characterized by the zero zonal wind and the associated surface Ekman upwelling. This potentially impacts mixed layer depth and temperature, which might be crucial for sea ice formation and the position of the SIE. I hope the manuscript should explicitly discuss the potential role of the Antarctic Divergence. How does its mean position relate to the ACC fronts and the SIE? Could variations in upwelling along the Divergence explain some of the regional variability in the SIE or the distance between the PF and the SIE? How is it

related to the surface meridional winds mentioned in the manuscript? The influence is not just about heat transported from the PF, but also about heat supplied from ocean closer to the ice edge via wind-driven divergence of ice floes.

The dynamics of the Southern Ocean and the characteristics of the water masses are strongly influenced by the Antarctic Divergence and the associated upwelling. However, the Antarctic Divergence is located southward of the winter ice edge at all longitudes (Figure R1). This means that the heat supplied to the surface at the Antarctic Divergence does not directly contribute to the balance at the ice edge but of course it can have an indirect effect, as discussed above for the gyres. Furthermore, the position of the Antarctic Divergence displays much less variation as a function of longitude than the winter ice edge or the Polar Front. The correlation between the Antarctic Divergence and the winter ice edge reaches 0.43 i.e. much less than between the position of the Polar Front and the one of the ice edge. This suggests that the constraint brought by the position of the Antarctic Divergence on the position of the winter ice edge is weaker than the one of the fronts. We have repeated the analysis with other diagnostics of the wind-driven divergence such as the latitude of the maximum wind stress curl or of the maximum of the derivative of the zonal wind stress as a function of latitude, arriving at similar conclusions. This is consistent with the broader picture that zonal winds (and atmospheric temperatures) display less zonal differences than oceanic variables such as the SST or the position of the fronts. This indicates that the differences in the latitudinal position of the ice edge between the different sectors is more controlled by oceanic processes (and the bathymetry) than by atmospheric ones such as the position of the zero zonal wind. This will be discussed in the revised version at the end of the new subsection 3d ‘d/ Atmospheric processes responsible for the link between the position of the ACC and the winter ice edge’:

By contrast, although westerly winds have a large impact on the oceanic upwelling and thus on the temperature at depth in the ocean, the correlation between the location of the Antarctic Divergence and that of the winter ice edge reaches only 0.43 i.e. much less than between the position of the fronts and that of the ice edge. The Antarctic Divergence is defined here as the latitude at which the climatological zonal mean wind velocity is equal to 1 m s^{-1} in September. We have chosen this value instead of the traditional definition, based on a zero mean zonal wind, as in some regions of the Ross Sea the value is positive at all the latitudes of the Southern Ocean in the ERA5 reanalysis. This avoids the occurrence of undefined values for some longitudes and induces only a very minor shift in the other regions.

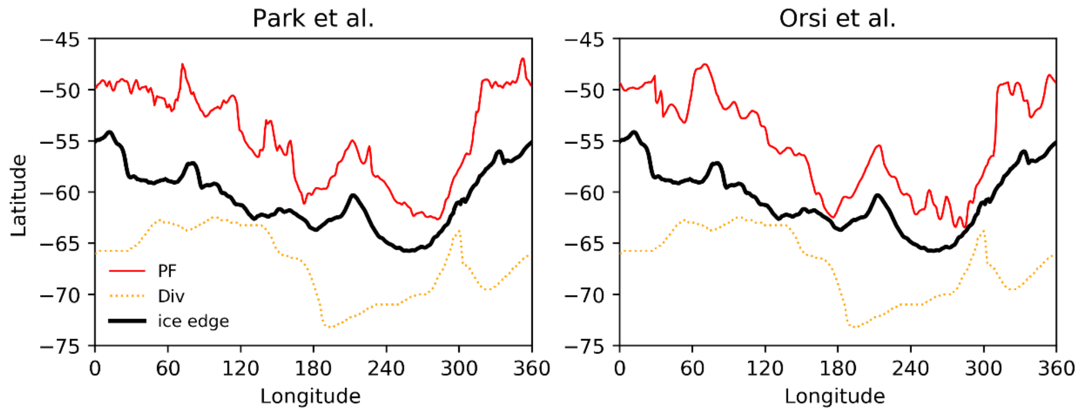

Figure R1. Latitudes of the climatological mean winter ice edge, of the Antarctic Divergence (Div) and of the Polar Front as a function of longitude, using definitions of Park et al. (2019) and Orsi et al. (1995). The Antarctic Divergence is defined here as the latitude at which the climatological zonal mean wind velocity is equal to 1 m s^{-1} in September. We have chosen this value instead of the traditional definition, based on a zero mean zonal wind, as in some regions of the Ross Sea the value is positive at all the latitudes of the Southern Ocean in the ERA5 reanalysis. This avoids the occurrence of undefined values for some longitudes and induces only a very minor shift in the other regions.

3. While the correlations are strong, the term "control" sounds like a very direct and dominant causal mechanism. The ACC fronts (and gyres) are themselves largely controlled by bathymetry. The paper argues the fronts are key mediators of this bathymetric influence on the SIE. This is plausible. While the authors do use "constrain" and "influence," consider if the overarching message of "control" is fully supported for all aspects, or if wording like "influence" or "constrain" could be more accurate in some contexts (especially when considering currently unaddressed roles of gyres and the Divergence).

   The word "control" may indeed seem too strong for some aspects. It is the reason why in many paragraphs of the text we used "constrain" and "influence". Our intention with the title 'On the control of the position of the winter sea ice edge by the Antarctic Circumpolar Current' was to state that the goal of the paper was to investigate this potential control, not to give the conclusion that such control is the only element setting the position of the ice edge. As this may give a wrong impression of our overarching message, we suggest removing the word 'control' to the title and to change it to 'Winter sea ice edge shaped by Antarctic Circumpolar Current pathways'.

   We consider that the word 'control' can still be used, for instance when we mention the influence of the bathymetry on the path of the ACC or the eddy hotspots, but we will check the whole manuscript for each occurrence of 'control' to ensure that it does not imply a dominant causal mechanism when this is not necessarily the case.

4. The two proposed mechanisms (eddy heat transport and atmospheric heat transport mediated by SSTs near the PF) are The link between southward-directed winds and atmospheric heat transport (L391-396) is interesting. However, the correlation between meridional winds and the PF-SIE distance is positive (Table 2, Fig 4), suggesting stronger southerlies are associated with a larger PF-SIE distance. The text

(L312-318) acknowledges this and argues against wind-driven sea ice transport being the primary factor for this correlation. The subsequent argument for winds influencing atmospheric heat transport (L391-396) needs to be carefully reconciled with this earlier point to avoid reader confusion. Perhaps the argument is that despite stronger southerlies pushing ice north (which would intuitively decrease the PF-SIE distance if the PF were a fixed barrier), the atmospheric heat transport effect in regions with southward winds (from PF to SIE) is more dominant in setting the SIE further south (thus increasing the PF-SIE distance if the PF is far north). I think this needs very clear articulation.

The Reviewer is totally right, and that is the message we wanted to convey in this paragraph. The discussion was too short in the submitted version and we will reformulate the argument in the revised version to make this clearer, adding also a more explicit reference to the subsection where we discuss first the potential impact of meridional winds on sea ice transport:

This leads to a positive correlation between the winds at 60°S and the distance between the ice edge and the PF (Table 2, Fig. 4). Stronger northward winds could push the sea ice to the north, closer to the fronts. This would lead to a negative correlation between the meridional winds and the distance between the ice edge and the PF (see section 3b). However, this effect is overcompensated by the influence of the meridional winds on the heat transport, which explains the positive correlation.

5. To better understand the spatial extent of the ACC front-SIE relationship, I hope the authors to consider estimating a characteristic horizontal length scale of the observed high correlations. Analyses like lagged spatial correlation or spectral methods could achieve this.

The correlation remains high on a large horizontal length scale (Figure R2), which is consistent with the latitude of the fronts and the ice edge that displays high auto-correlation on length scales of several tens of km. For instance, if we analyse the correlation between the latitude of the PF (definition of Orsi et al.,1995) and the position of the ice edge at different spatial lags, the correlation remains positive from lag of -100° of longitude (PF shifted westward) to a lag of 71° of longitude (PF shifted eastward). The correlation remains higher than 0.45 (half of the maximum value from a lag of -54° to 36°. The maximum correlation is found for a lag of -1° but the difference with the value at lag zero is very small (0.9005 compared to 0.8991). To highlight this point, we suggest adding in the revised version the following sentence when we discuss Fig.3:

The correlation remains high (with values larger than half of the peak correlation) for a spatial lag between the positions of the ice edge and of the front exceeding 30° of longitude, indicating that the observed high correlations have a large horizontal scale. The peak correlation is generally very close to a spatial lag of zero degrees of longitude.

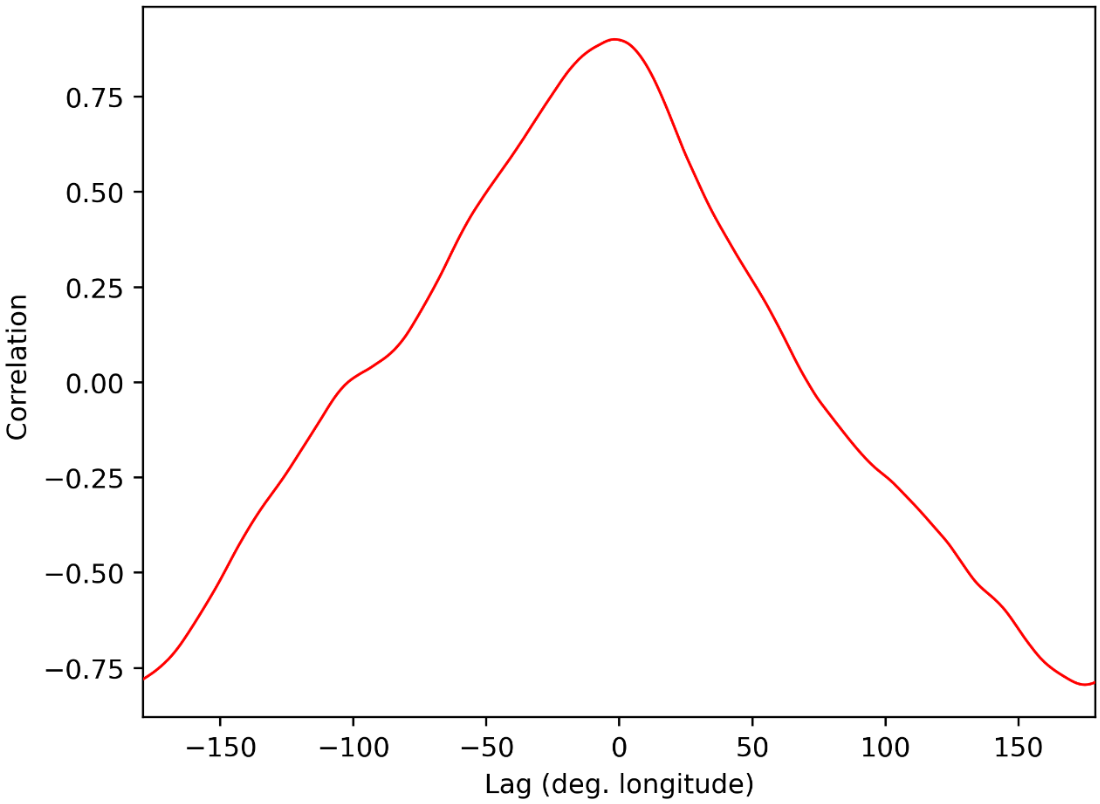

Figure R2. Lagged spatial correlation between the latitude of the ice edge and the latitude of the Polar Front (following the definition of Orsi et al. 1995) for lags between -180° of longitude (PF shifted westward) and +180° of longitude (PF shifted eastward).

6. Although the focus on the climatological mean is a valid simplification, it would be beneficial to briefly acknowledge in the discussion that interannual variability of winter sea ice edge, regarding the recent sea ice extremes, even if it's beyond the scope of this paper.

   As suggested we propose to add a short discussion of the interannual variability, as a perspective in the last paragraph of the revised version:

   In this framework, the interaction with the ACC could reduce the sea ice variability where the fronts are close to the ice edge, by limiting strongly the northward expansion of the pack. Concurrently, the variability of frontal positions could underpin changes in sea ice extent. It would be very instructive to investigate how these two potentially opposed ACC contributions to sea ice variability interact, and which one dominates as a function of location and timescale.

7. L290: "the further north the fronts are, the larger the distance between the fronts and the winter ice edge." – Intriguing. I wonder why this is the case, and the authors might also want to explain more about it (perhaps in terms of the meridional gradient of ocean temperature and/or EKE).

   In the submitted version, we discussed this positive correlation between the distance from the fronts to the ice edge and the latitude of the fronts in the paragraph following the sentence (the paragraph including this sentence is only descriptive). We will add the information explicitly to make this clearer in the revised version. Our argument is that a Polar Front located more northward has a weaker relative contribution to the position of the ice edge than a front located more southward, where the climate is on average colder and the role of the front more dominant. This leads to the larger distance between the ice edge and the fronts when the fronts are more northward. In other words, the oceanic and atmospheric heat transport from the PF latitude to the south must compensate for the heat losses at a particular latitude in order to prevent sea surface temperature to reach the freezing point and sea ice formation. If the front is located at a more southward position, the surface temperature is colder and the oceanic heat losses can be very large. The heat transported southward of the PF are thus sufficient to prevent ice formation over a few degrees of latitude south of the PF only. This leads to a smaller distance between the PF and the ice edge than where the PF is more northward and thus in regions where the climate is milder. This effect can be modulated by the wind direction (this part will be modified in the revised version to make the links stronger, see the response to point 4 above). We also discuss this contribution of the atmospheric and oceanic heat transport from the front in the Results section (labelled subsection 3d in the revised section). However, we were not able to find a clear link between the latitude of the front and SST gradients or with EKE, the latter having too large longitudinal variations to identify a systematic effect of latitude.

Additionally, we propose to add the following text in the paragraph in which we explain the origin of the positive correlation to make this clearer:

Specifically, the heat transport from the latitude of the PF to the ice edge must compensate at all longitudes for the cooling (i.e. heat loss) at the ice edge, to prevent sea ice freezing. When the ice edge is located further to the south, where atmospheric temperatures tend to be colder, the oceanic heat loss is typically larger, and the heat transported from the PF should also be larger to prevent ice formation. This can be attained only over relatively short distances, such that the ice edge remains closer to the PF. In contrast, where the ice edge is located further north in a milder climate (with a warmer atmosphere), the heat required to prevent sea ice freezing is considerably lower. The PF can then be more distant from the ice edge, with the ocean still providing sufficient heat to avoid ice formation.

8. The Results section is quite extensive. Please consider dividing it into thematic subsections for readability.

   As suggested, we will add in the revised version subsections in the Results section.

9. Fig 2: Adding the winter sea ice edge would be useful for interpretation. Please also clarify which definition is adopted for the frontal positions (perhaps Orsi or Park) in the caption.

   The position of the winter ice edge will be added in the revised version. The front follows the definition of Orsi. This will be specified in the revised version.

10. Fig 4: Please unify the y-axis ticks for the wind velocity.

As suggested, we will unify the y-axis ticks for the wind velocity in the revised version.

11. Is Fig 8 supposed to be referred in somewhere around L409-420?

    Sorry to have missed this reference. We will add in the revised version a reference to Fig. 8 when presenting the regression model.

12. Fig 9: Might be more effective and easier to interpret if presented in a normal plan view (top-down map perspective) rather than the current tilted view.

    We agree that a normal plan view can be more effective but the advantage of the tilted view is to show clearly that this figure is a sketch, in contrast to the other figures in normal plan view. Nevertheless, we will reevaluate this point for the revised version and check which option is the most adequate.

I believe that addressing these points will strengthen the manuscript and offer a more balanced perspective on the complex oceanographic controls influencing the Antarctic winter sea ice edge. This work is otherwise of high quality and is well-suited for publication in The Cryosphere. I sincerely thank the authors for their valuable contribution and look forward to their response.

Thanks again for the constructive suggestions that will improve the quality of our manuscript and strengthen our conclusions.