Response to the comments of Martina Zapponini

The study discusses the influence of the Antarctic Circumpolar Current (ACC) on the position and dynamics of the winter sea ice edge in the Southern Ocean, highlighting the role of the Polar Front (PF) among various oceanic fronts and different heat transport mechanisms. The definitions of ACC fronts are based on both oceanographic observations and satellite data, which are used to analyze their relationship with the mean location of the sea ice edge. The PF is identified as the best indicator of the ACC's influence on sea ice, due to the lower uncertainty in its position derived from observations and its greater independence from sea ice processes. It influences sea ice advance and the position of the winter ice edge by modulating heat transport toward high latitudes, both through oceanic processes (via eddy-induced transport) and atmospheric processes (via meridional wind transport). Through regression models predicting the winter ice edge position using the latitude of the PF, eddy kinetic energy (EKE), and wind velocity, the authors find that PF latitude is the most reliable predictor. Including EKE or winds leads to little or no improvement in predictive skill.

The manuscript is overall well written and clear. The methodology and results are presented in a clear and sufficiently detailed manner.

We would like to thank the reviewer for the positive evaluation and the suggestions that will contribute to improve the quality of our manuscript. Our responses below are in blue and the suggested modifications in the text in green.

My only main comment concerns the use of mean wind speed at 60°S, which is often not co-located with the PF or the sea ice edge. This could result in only a partial assessment of the impact of winds on the atmospheric heat transport from the PF to the sea ice.

We selected the mean wind speed at 60°S as it is representative of the winds at high latitudes in the Southern Ocean, close to the ice edge. Compared to the winds at the latitude of the PF or of the sea ice edge, this choice has the advantage that it does not require any information on the location of the PF or of the ice edge and is thus independent of those locations. As suggested by the reviewer, we have repeated the analyses using the wind speed at the location of the PF and of the ice edge. This has some influence on the values obtained but without major changes in our conclusions. This is discussed in more details below in the response to the specific comments on this point.

Minor comments

Line 37. “the sea ice seasonal cycle of sea ice cover” - there is a repetition

This will be removed in the revised version.

Figure 1,3,4. Blue and purple are not an ideal combination for color-blind safe figures. I suggest using a different color combination

Before submission, we have checked the figures using the site https://www.color-blindness.com/coblis-color-blindness-simulator/ to choose the colors. There is no ideal solution but we find that the selected colors were a good compromise, as they have different lightness values. We also tested the option to have dashed or dotted lines but the front positions display rapid fluctuations and this breaks in some region the continuity of the curve. We are of course open to all the suggestions to improve the quality and readability of our figures and happy to change them at any stage, including at the production stage, if a better option is found.

Line 71. variability and noise are weaker than at surface

Thanks, this will be corrected in the revised version.

Line 70-81. It is not clear whether the two identifications methods are linked or represent two distinct approaches. The paragraph could be rephrased to clarify this point.

The two identifications methods are based on different observations (satellite versus in situ) and criteria. However, they are linked as the criteria selected to define the front from satellite observations are selected to match the position of the front inferred from in situ observation in key locations, where the fronts are well defined and observed.

After a few rounds of discussion among co-authors, we reached a consensus to reduce the technical/ methodological information inside the introduction section and focus on that in the methods section. So, we will direct the readers to section 2a and include in section 2a the following.

In the introduction :
The correspondence between the sea surface height (SSH) gradients linked to those jets and specific SSH values have led to another method for identifying frontal positions using a judicious choice of circumpolar SSH contours. See section 2a for more details on frontal definitions.

In section 2a:
These two definitions are thus linked but they are based on independent data sets (i.e. in situ measurements of ocean properties for Orsi et al., 1995, and satellite observations of SSH for Park et al., 2019).

Line 210. The PF's position relative to the ice edge is more consistent between regions. However without further evidence, you cannot conclude yet that PF's influence is more robust.

We will suppress the word 'robust' as we agree that we cannot conclude without additional evidence.

Line 211. The sACCF and the SBdy are close to the winter ice edge in several regions

Thanks, this will be corrected in the revised version.

Line 229-230. "which is systematically located…"- this phrasing is somewhat repetitive

We propose to replace 'systematically' by 'always' but we consider that the part of the sentence after 'which' is necessary to have an explicit mention of the conditions for both the sACCF and the SBdy (close to the ice edge) and the PF (north of the ice edge). We could keep part of it implicit but we fear that it may be less clear for some readers, although we agree that for some other readers it may imply a repetition of the information.

Figure 2. Square brackets denote "units of" in scientific notation: [Depth] m, so it would be more correct to use (m) instead of [m]

As suggested, we will use (m) instead of [m] on Figure 2.

Line 251-254. This sentence is not clear, please consider rephrasing for clarity

The goal of this sentence was to insist that, while the presence of warm water at depth is not a strong criterion to determine the position of the winter sea ice edge, it can still play a large role for other elements of the system, such as the melting of ice shelves. We propose to rephrase it to make this clearer:

Besides, the presence of warm water at depth and its southward transport can have a large impact on other elements of the Southern Ocean system. For instance, a recent southward shift of the Circumpolar Deep Water, the sACCF and the SBdy has been observed off East Antarctica, potentially leading to additional melting of the ice shelves in this region (Yamazaki et al., 2021; Herraiz-Borreguero and Naveira Garabato, 2022).

Line 263-266. The statement may not be fully supported unless the correlation with the distance from the coast or with other factors are also not reported.

We agree with the Referee that this statement is not supported by our results. We propose thus to remove this sentence in the revised version. The alterative option to compute the correlation between the ice edge and other factors (such as the distance to the coast but potentially many others) could distract the reader from the flow of the discussion which is on the role of the ACC, not on other potential factors.

Line 291-293. I think the fact that the distance between the front position and the sea ice edge shows a high correlation with latitude better explains the high correlate on between front position and sea ice edge latitude, rather than the magnitude of this distance, as mentioned earlier (lines 286–288).

From our analyses, the correlation of the distance from the PF position to the sea ice edge with the latitude of the front reaches 0.82 and 0.83 for the two definitions of the front. The values are thus lower than for the correlation of the latitude of the front with the latitude of the ice edge (0.92 and 0.90). This will be specified in the revised version. However, those lines are mainly descriptive, discussing only the correlations, so we prefer not to go deeper in the potential interpretation at this stage. We will also change 'reason' to 'element that explains' to insist on this descriptive objective:

The main element that explains these changes in the distance between the winter ice edge and the fronts is the variation in the latitudes of the fronts and of the ice edge themselves: the further north the fronts are, the larger the distance between the fronts and the winter ice edge. The correlation between the distance from the fronts to the ice edge and the latitude of the fronts at the same longitude is higher than 0.80 (i.e. slightly less than the correlation between the latitude of the front and that of the ice edge), except for the SBdy following the definition of Orsi et al. (1995) (Table 2).

Line 315. It should probably be "stronger northerly winds." It may also be worth adding a clarification about the sign convention used for the wind direction.

We checked and the sentence seems correct to us with 'stronger southerly winds associated with a larger distance between the PF and the winter ice edge'. However, to avoid confusion we will add a definition of the convention in the first sentence of this paragraph:

It is also possible that where southerly winds (i.e. winds from the south, corresponding to positive values on Fig. 4) tend to favour sea ice cover expansion by pushing it northward toward the PF,…

Line 377. more zonal than the fronts

Thanks, this will be corrected in the revised version.

Line 388-390. It should be noted that there is also substantial heat loss in the Indian Ocean sector, despite the PF being located farther north.

As mentioned in the submitted version (lines 385-387), there are major losses in nearly all the regions close to the ice edge; including in the Indian Sector. Nevertheless, the region with stronger

oceanic heat loss than in any other sectors is in the Amundsen-Bellingshausen Sea. This will be specified more explicitly in the revised version :

Nevertheless, the oceanic heat loss is much larger and on a wider latitude band in the Amundsen-Bellingshausen Sea, where the PF is displaced further to the south than in other regions, consistent with the interpretation above.

The region in the Indian sector eastward of the Kerguelen Plateau is also characterized by large heat losses of a wide latitudinal range but on a narrower longitude band. We interpret this as consequence of the oceanic currents and strong eddy activity there. Consequently, we do not mention it in this section devoted to atmospheric processes to avoid confusion but discuss this point in the subsection devoted to oceanic transport.

Line 391-392. The phrase “the heat extracted from the ocean to the north of the PF, towards the south” is unclear, it should probably be “the heat extracted from the ocean north of the PF, towards the south”

Thanks, this will be corrected in the revised version.

Lines 393–395. Does the fact that in sectors where the PF is farther north it is close to 50°S—and thus the 60°S meridional winds may not be representative—affect the interpretation of the relationship with atmospheric heat transport?

We have repeated our analyses using the meridional winds at the locations of the PF and of the ice edge. The main message is that using the location of the ice edge instead of the value at 60°S does not change much our results. For instance, we have computed the correlation of the distance between the front and the ice edge with the meridional winds at the location of the ice edge and we obtained values of 0.68 for both the definitions of Orsi et al. (1995) and Park et al. (2019) (instead of 0.61 and 0.55, Table 2). This confirms our choice that using 60°S provides a good estimate of the value close to the ice edge, considering the consistency of climatological winds on scales of several hundreds of kms. By contrast, using values at lower latitudes gives lower correlations. For the correlation of the distance between the front and the ice edge with the meridional winds at either 50°S or the latitude of the PF, we obtain values that are always lower than 0.2. It suggests that the most important element is not the atmospheric heat transport at the PF itself but the conditions more southward that favor the transport of this heat to the region of the ice edge. For instance, we can imagine a case where the winds are southward at the PF but shift quickly to a northward direction between the PF and the ice edge. In that case, the southward atmospheric heat transport could be large at the PF but much lower close to the ice edge and thus have a smaller impact on it. We will add this additional information at two locations in the revised manuscript.

When we first use the latitude of 60°S, we will modify the text to

We have chosen 60°S here as it is close to the mean position of the winter ice edge (Fig. 3) but results are not sensitive to a change of this latitude by a few degrees, or to using instead the winds at the latitude of the winter sea ice edge.

Second, when we discuss the potential role of the atmospheric transport, we will add:

It should also be mentioned that the correlations decrease if we use a latitude of 50°S or that of the PF instead of 60°S. This suggests that the latitude of the ice edge is influenced more by the heat that reaches the highest latitudes than by the transport at the latitude of the PF itself.

Line 428. Similar to lines 393–395, it might be worth considering a latitude that varies with the PF's position, to better assess the impact of winds.

In the regression model, we selected variables that are as much independent of each other as possible. If we use the winds at the latitude of the PF, we will include information on both the winds and the position of the PF and disentangling the contributions of the winds from the one of the position of the PF would thus be more difficult. Furthermore, if we use the winds at the latitude of the PF, the correlations are much lower than for 60°S, and the RMS of the corresponding regression model higher.

Line 501-505. This sentence is too long, please split it to make it more clear.

We propose to remove in the revised version the parts of the sentence starting with 'which' that make the sentence longer without adding much information.

Line 511. it is also possible that the position

Thanks, this will be corrected in the revised version.

Line 513-516. This sentence is not clear, please consider rephrasing for clarity

To make this sentence clearer. We propose to split it in two sentences and to reformulate the second part:

Those questions are important to understand the variations of the sea ice cover, but more generally the global climate. For instance, carbon dynamics in the Southern Ocean, which are considered as a main driver of glacial-interglacial transitions, are also strongly influenced by the position of the fronts and the winter sea ice extent (e.g., Martinson, 2012; Skinner et al., 2010; Sigman et al., 2021; Ai et al., 2024).