Goosse et al. is a well-written, engaging paper that offers evidence that the role of the ocean in controlling sea ice edge variability is not limited to long timescales, adding an interesting alternative to the classical view of the differing roles of the atmosphere and ocean for controlling interannual sea ice edge variability. This paper explores the pattern of local interannual winter sea ice edge variability, showing how it is represented in observations and in a few high resolution model simulations. The pattern of sea ice variability in observations has prominent sharp peaks that are shown to be controlled mainly by oceanic processes shaped by bathymetry. This pattern of sea ice edge variability has been stable over the past few decades, despite observed changes in sea ice. The two high-resolution model simulations both do a relatively good job reproducing the pattern of interannual variability. This indicates that the pattern of interannual variability is not dependent on the specific atmospheric conditions. Then they look at the specific mechanisms that may be controlling this pattern of variability, highlighting the role of mesoscale eddy activity, ocean heat transport, and the relative location of the Polar Front.

Overall, I think these results are novel and would be of interest to the geophysical community. The methods are sound, and the mixture of observations and model output provides a useful comparison of results and highlights specific model biases. I have a few comments and suggestions which are outlined below, but I recommend this paper for publication after minor revisions.

We would like first to thank the Reviewer for the positive evaluation of our work and the suggestions that helped to improve the quality of our manuscript. Our responses to the specific comments are in blue below. The proposed revised text is in orange.

General comments:

1. In general, I think it would be helpful to include more discussion of the model results, how they compare to the observational results and how they compare between each of the simulations. The results felt very skewed towards the observational results, and considering how well the models reproduced the observed pattern of ice edge standard deviation, I was surprised that more of the later results did not use the model output. Along a similar line, did you compute similar evaluations for the role of the meridional winds, the polar front, ocean currents, and sea ice velocity from model output? If so, it would be interesting to note that or include a supplementary figure showing these results.

We did not include these analyses for the models in the submitted version to avoid repetitions as they basically confirm the results deduced from observations. However, we agree that this could strengthen the discussion so we will include in the supplementary material of the revised version the evaluation of the role of ocean currents and sea ice velocity for NEMO-ERA5 (Fig. R1.1 below). No additional diagnostic is needed for the winds as the forcing comes directly from an observation-based product (see figure 4 of the submitted version) and EKE is already provided in the submitted version for the models (Fig. S3 of the submitted version). Unfortunately, the constraints for data storage for the high-resolution coupled simulations used here are very tight and the ice velocity and ocean currents are not among the variables that are available in the standard repositories. For NEMO-ERA5, the conclusion on the role of the ocean currents and sea ice velocity is similar to the one deduced from observations, with a potential role in some regions but modest correlation overall.

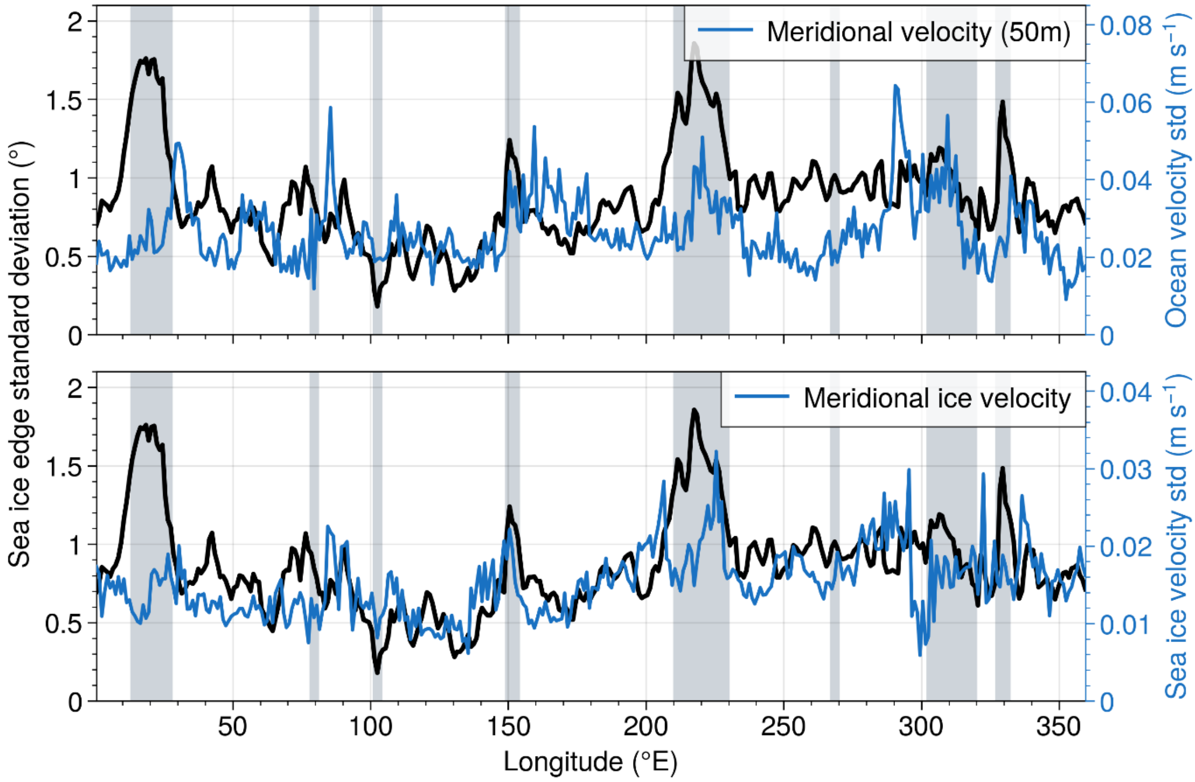


Figure R1.1 a) Standard deviation of the winter ice edge position (in °, black) and standard deviation of the mean meridional ocean velocity at 50m averaged over the region 5° northward and 5° southward of the mean ice edge (m $s^{-1}$ , in blue) in NEMO simulation (1/12°) forced by ERA5 over the period 1995-2024. The correlation between the two series is 0.16 b) Standard deviation of the winter ice edge position (in °, black) and the standard deviation of the meridional sea ice velocity averaged in a band located from 5° south to 5° north of the mean ice edge position (in m $s^{-1}$, blue). The correlation between the two series is 0.35.

2. Since so much of your argument is related to the representation of bathymetry, if possible, it could be worthwhile to try and show what the bathymetry of the models looks like, to see if there are obvious differences between the various models and with observations that results in the differences in the representation of ice edge variability.

The bathymetry of NEMO is based on GEBCO2019, with additional information from BedMachine (Morlinghem et al. 2020) (mainly on the continental shelf and for the iceshelf cavities). The other coupled models similarly base their bathymetry on high-resolution observation products. The bathymetry is interpolated from these sources on the model grid with a small additional smoothing where needed and a few ad hoc adjustments, for instance to remove oceanic points totally surrounded by land (i.e. without oceanic neighbor and thus no method to compute transport in the model). This means the model bathymetry is very close to observations. The details of the bathymetry can be important in some regions such as in narrow straits or on the continental Antarctic continental shelf where uncertainties of observations can be large and the presence of some narrow canyons have a large impact on the exchanges with the deep ocean (e.g. Ong et al. 2024). However, we document here the influence of the main large-scale features of the bathymetry such as the Kerguelen Plateau or the major ridges of the Southern Ocean that are well represented by the model bathymetry. By construction, a map of the model and observations at the same resolution shown in parallel would be nearly indistinguishable while a difference would highlight some-scale features that are not essential for our arguments. To specify this, we will include in the revised version a sentence mentioning the sources of the bathymetry for NEMO and insisting that the model representation of the bathymetry is consistent with observations at the model resolution:

The bathymetry of the model is based on GEBCO2019 with additional information from BedMachine (Morlinghem et al. 2020) close to Antarctica. The bathymetry is interpolated from these sources on the model grid with a small additional smoothing where needed and a few ad hoc adjustments, for instance to remove oceanic points totally surrounded by land. This ensures that the model bathymetry represents well the most important bathymetric features at a scale consistent with model resolution.

References

Morlighem, M., Rignot, E. , Binder, T., Blankenship, D., Drews, R., Eagles, G., Eisen, O., Ferraccioli, F., Forsberg, R., Fretwell, P., Goel, V., Greenbaum, J.S., Gudmundsson, H., Guo, J., Helm, V., Hofstede, C., Howat, I., Humbert, A., Jokat, W., Karlsson, N.B., Lee, W.S., Matsuoka, K., Millan, R., Mouginot, J. , Paden, J., Pattyn, F., Roberts, J., Rosier, S., Ruppel, A., Seroussi, H., Smith, E. C., Steinhage, D., Sun, B., van den Broeke, M. R., D. van Ommen, T., van Wessem, M. and Young D. A. : Deep glacial troughs and stabilizing ridges unveiled beneath the margins of the Antarctic ice sheet, Nat. Geosci., 13, 132–137 https://doi.org/10.1038/s41561-019-0510-8, 2020

Ong E. Q. Y., E. Doddridge, N. C. Constantinou, A. McC. Hogg, and M. H. England, 2024. Intrinsically Episodic Antarctic Shelf Intrusions of Circumpolar Deep Water via Canyons. J. Phys. Ocean. 54, 1195–1210 https://doi.org/10.1175/JPO-D-23-0067.1

GEBCO Bathymetric Compilation Group 2019 (2019). The GEBCO_2019 Grid - a continuous terrain model of the global oceans and land. British Oceanographic Data Centre, National Oceanography Centre, NERC, UK. doi:10.5285/836f016a-33be-6ddc-e053-6c86abc0788e

Specific comments:

L56-57: This sentence is a bit confusing, do you mean the variability of the ice edge within a sector of longitudes only covering a few hundred kms or do you mean the variability of ice edge moving latitudinally a few hundred kms?

We mean 'within a sector of longitudes only covering a few hundred kms'. This will be specified explicitly in the revised version.

In contrast to these large-scale changes, the variability of the ice edge position within sectors only covering a few hundred kilometers has received less attention.

L80: Do you have any thoughts on whether these mechanisms to apply to other months, especially months where the variability is higher?

In this paper, as in the previous paper cited L80, we focus only on the winter ice edge. As explained lines 82-85, the argument is that the ocean and in particular the ACC should play a larger role in winter as the ice edge is most northward (and closer to the fronts and the zone of high eddy kinetic energy). It is also the period with the deepest mixed layer and thus the strongest interactions between the ice and the ocean. We thus expect that the processes analyzed in our manuscript have a smaller contribution in summer but we have not investigated specifically this point.

To insist on the fact that we only address the winter ice edge here, the word 'winter' has been added in the sentence L80.

L103-105: It might be nice to have a Supplementary figure showing the climatology differences from each product across the full period, and reduced down to only the common period. This would support your assumption.

Our results later in the text confirm this assumption (for instance Fig.2). However, as suggested, we will add in the revised version as a supplementary figure (Figure R1.3) a comparison of the position of the ice edge for the 1993-2012 period used to define the position of the polar front, for the period 2013 to 2019 for which we have EKE data and the over the period 1979-2025 used in the majority of the other diagnostics. It confirms that the difference in ice edge position are small between the 3 periods compared to the differences between different longitudes.

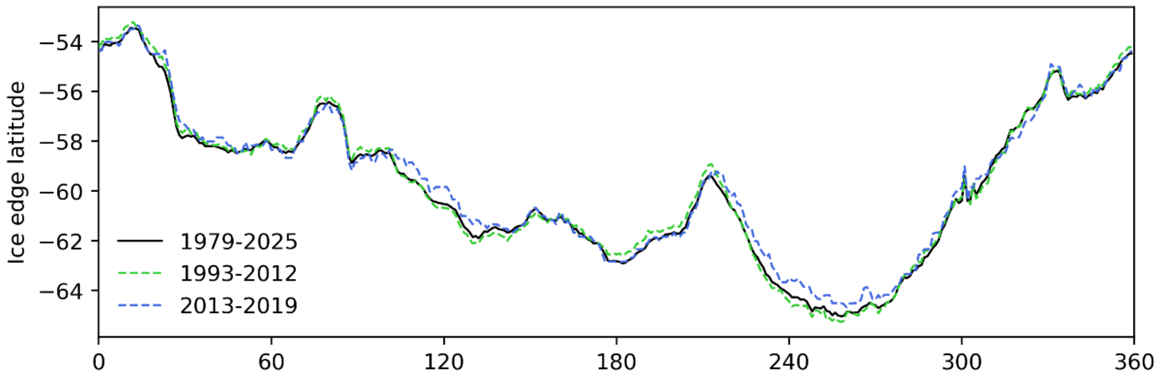


Figure R1.3. Latitude of the winter ice edge for three different periods corresponding to the availability of different datasets.

L124-125: Why did you choose a period different from the ERA5-constrained simulation?

Because in the CMIP6 protocol the so-called historical simulations ends in 2014 and, as the model is not constrained by observations, the interannual variability of any period is not supposed to follow the observed one, giving some freedom in the selection of the period studied.

L157-164: I found this paragraph a bit confusing. It could be helpful to include a Supplementary figure or schematic accompanying this description.

The goal of this paragraph was to have a very simple illustration of the magnitude of the variability of the ice edge position. We consider that adding a figure would attract more attention on this point than intended. We propose the following edits to clarify the illustrated example. If it is still confusing, we would remove the paragraph from the text to reduce confusion for the readers.

As studies devoted to the total ice extent are more standard than those focused on the sea ice edge, it may be useful to have an illustrative comparison between the magnitude of the variability of the ice edge position and the one of the ice extent, despite the two quantities having different units. For this purpose, imagine the very simple situation of a sea ice edge following exactly the 60°S latitude around Antarctica as its mean position. A shift of 1° in the ice edge position from the mean (i.e., the spatial mean of the standard deviation of the variability of the ice edge position) would be associated with an increase or decrease in the ice extent ice of 2.2 x $10^6$ $km^2$. This is very close to the magnitude of the largest anomaly in the ice extent measured in July 2023 (Abram et al. 2025) and more than 4 times the standard deviation of the ice extent in winter that reaches 0.5 x $10^6$ $km^2$ over the period 1979-2025 (estimated here from EUMETSAT OSI SAF). The large changes in ice extent associated with a 1° shift of the ice edge are of course due to the very simplified situation chosen here for the illustration: the ice edge is never moving in the same direction at all longitudes and each year is characterized by a specific pattern in which changes of the ice extent in one region are partly compensated by changes in another one.

Reference

Abram, N.J., Purich, A., England, M.H., McCormack, F.S., Strugnell, J.M., Bergstrom, D.M., Vance, T.R., Stål, T., Wienecke, B., Heil, P., Doddridge, E. W., Sallée, J.B., Williams, T.J., Reading, A.M., Mackintosh, A., Reese, R., Winkelmann, R., Klose, A.K., Boyd, P.W., Chown, S.L., and Robinson, S.A.: Emerging evidence of abrupt changes in the Antarctic environment. *Nature* **644**, 621–633 (2025). https://doi.org/10.1038/s41586-025-09349-5

L197-199: Is this only applicable in the regions of large bathymetric obstacles? Notably, the longitudinal range between 100-150° also has lower standard deviation but has seen a northward shift in ice edge.

We thank the reviewer for underlining this point that we missed in the discussion. Indeed, although the largest decrease is found at the longitude of the topographic obstacle (Kerguelen plateau here), a decrease in variance is also found in other longitudinal ranges such as between 100-150°. Another hypothesis is thus that there is a more direct role of the decrease in ice extent, as several studies have indicated a link between the mean state and the variability. This will be specified in the revised version.

Another hypothesis, potentially explaining why the decrease in variance is not restricted to the region with topographic obstacles and is also clear between 100° and 150°E, is a more direct impact of the change in the mean state on the variability. As mentioned in the introduction , several studies have indicated that the variance of the ice extent increases with the mean in summer (Goosse et al. 2009) and in winter if the ice extent is lower than a threshold about 10 x $10^6$ $km^2$ (Diamond et al. 2024). It is thus possible that an ice edge closer to the coast is more constrained and less variable that if it is located more offshore.

Diamond, R., Sime, L. C., Holmes, C. R., & Schroeder, D. (2024). CMIP6 models rarely simulate Antarctic winter sea-ice anomalies as large as observed in 2023. *Geophysical Research Letters*, *51*, e2024GL109265. https://doi.org/10.1029/2024GL109265

Goosse H., O. Arzel, C.M. Bitz, A. de Montety and M. Vancoppenolle, 2009. Increased variability of the Arctic summer ice extent in a warmer climate. Geophysical Research Letters 36, L23702, doi:10.1029/2009GL040546.

L317-319: Why did you use this definition instead of one using water mass characteristics/temperature gradient?

In Goosse et al. (2025), we tested the influence of the choice of the definition of the Polar Front and the results were nearly identical using the definition of Orsi et al. (1995) based on water mass characteristics and the one of Park et al. (2019), so we keep only one definition here for simplicity. This will be specified in the method section of the revised version :

However, as shown in Goosse et al. (2025), the results are similar if we use the definition of Orsi et al. (1995) based on water masses characteristics.

Orsi, A., Whitworth, T., and Nowlin, W.: On the meridional extent and fronts of the Antarctic Circumpolar Current, Deep-Sea Res. Pt. I, 42, 641–673, https://doi.org/10.1016/0967-0637(95)00021-W, 1995.

L321-322: Please clarify this sentence, do you mean "far enough away from the front"?

Yes. We will replace the previous formulation by the suggested one.

Fig 1a: It may be helpful to write “ice edge mean” for black line to highlight that this is the mean ice edge.

We will replace the caption by ‘ice edge mean’ as suggested.

Fig 1a: I would suggest converting longitude labeling on the map to 0-360° labeling to make the comparison with the ice edge variability plot in 1b easier.

We will use a 0-360° labeling for Figure 1a as suggested.

Fig. 6 It would be helpful to include longitude markers ranging from 0-360° to align with other figures.

We will add the longitude markers ranging from 0-360° on Fig. 6.

Technical corrections:

Fig 1a and Fig 6: Missing colorbar unit labels.

We will add the missing colorbar unit labels on Fig1a and 6.