Reviewer 3

This manuscript attempted to summarize sea ice concentration (SIC) minima events for the Antarctic region and find out universal mechanisms that apply to all events. Results from this study provide important information for understanding the occurrence of Antarctic SIC minima events which might happen more frequently in the future in the context of climate change. The manuscript is overall well organized, with comprehensive analyses and clear interpretations of the results. There are some major issues to be addressed for this work to be published in The Cryosphere as follows.

We wish to thank you for review and for your valuable comments, we now plan to prepare a new version of the manuscript. Below you can find point-by-point replies to your major and minor points (in blue) with proposed changes to the manuscript (in grey). We hope that we have addressed all your concerns adequately.

1. While this study has made lots of efforts in revealing the control of major climate modes on the SIC minima events, as shown in the results, it is hard to attribute the occurrence of these events to a universal anomalous pattern of any single climate mode or a combination of climate modes. The authors finally attributed these events to north-westly wind anomalies in the Weddell Sea and south-westerly wind anomalies in the Ross Sea. These conclusions are to some extent useful, but probably not so helpful if we want to predict future SIC minima events. In fact, in addition to SAM and ASL, there are other climate modes that can affect the sea ice anomalies in the Ross Sea and Weddell Sea, such as ENSO, PSA, PSA2, zonal wave 3, etc. While there are interactions among these climate modes, I still suggest the authors to further examine the patterns of climate modes other than SAM and ASL and see if a systematic anomalous pattern of these modes or their combinations can be found for the SIC minima events. If such a pattern can be found, the information would be much more useful for the scientific community to understand the future occurrence of SIC minimum events.

Thanks for raising this point. We agree that it would be beneficial for the community to relate SIE minima to some specific and known modes of climate variability, such as ENSO. Indeed, previous case-studies have related single SIE minima to specific ENSO, SAM, ZW3 or even stratospheric polar vortex configurations (e.g. Stuecker et al. 2017, Schlosser et al. 2018, Wang et al. 2019). However, it is not easy to find a common remote driver for these events. For instance, the 2022 event corresponded to La Niña conditions, while the previous one (2019) coincided with an El Niño. As you mention, it is likely "a combination" rather than a single mode that may be, eventually, identified as a systematic driver. This is also what we conclude in our manuscript: the predominant winds that we identify as related to summer SIE minima may arise from the superposition of different modes of variability. While very interesting for prediction applications, trying to identify such systematic forcing would imply a different approach and an entire new analysis that would likely constitute a paper itself. Furthermore, our current limited sample of five main events would not be suitable. We hope that you will understand that this is out of our scope for this study, but we are happy to take this suggestion as inspiration for future work.

Schlosser, E., Haumann, F. A., and Raphael, M. N.: Atmospheric influences on the anomalous 2016 Antarctic sea ice decay, The Cryosphere, 12, 1103–1119, https://doi.org/10.5194/tc-12-1103-2018, 2018.

Stuecker, M. F., C. M. Bitz, and K. C. Armour (2017), Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season, Geophys. Res. Lett., 44, 9008–9019, doi:10.1002/2017GL074691.

Wang, G., Hendon, H.H., Arblaster, J.M. et al. Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. Nat Commun 10, 13 (2019). https://doi.org/10.1038/s41467-018-07689-7

2. Lines 140-141: Separating the processes controlling the tendency of SIC into a dynamical term and a thermodynamical term is a simple way. Though the authors mentioned more detailed terms in the texts that are included in the dynamics and thermodynamics (Lines 145-140), it is better to analyze these terms in Section 3.5 (Sea ice budgets), so the readers could know which specific terms are dominant as well as the physical processes behind these terms.

Thanks for this comment. While it is not possible to separate all the physical processes contributing to the dynamic and thermodynamic terms, we agree that a more detailed discussion of their meaning and interpretation is needed. Thus, following this and the other reviewer's comments, we propose to expand Section 3.5.

In particular, we propose to clarify what processes are accounted for in the dynamic and thermodynamic terms in our framework. For instance, the albedo feedback (ocean warming due to sea ice being transported away leading to more melting) could in principle be initiated by the dynamic movement of ice, but in this framework, it would result in an increased thermodynamic term. On the other hand, at the local scale the two terms are comparable and often linked simply because as more sea ice is moved away from a point, less sea ice remains for melting. This is a limitation of our diagnostics that we propose to clarify with the following text to be place in Section 3.5 (L306):

Note that the dynamic and thermodynamic terms and are not mutually independent as they influence one another both directly and indirectly and it is not possible to strictly separate them. For instance, an anomalous transport of sea ice away from a given point, thus driven by dynamics, would be compensated by opposite anomalies in the thermodynamic term as less sea ice becomes available for melting. In turn, leads created by sea ice transport, effectively a dynamic process, induce warming and melting associated with the albedo-temperature feedback (e.g. Goosse et al., 2023), which is the dominant mechanism in spring. However, this melting is accounted for in the thermodynamic part in the framework proposed here, and the information about the role of dynamics is not explicitly retained. Hence, the thermodynamic and dynamic terms must be interpreted carefully and particularly the modulation of the thermodynamic component by its dynamic counterpart, which includes direct compensation of the anomalies but also more complex feedback mechanisms. With this in mind, it is not surprising to see that, locally, both terms contribute to the anomalous sea ice loss during the months preceding a summer minimum (Fig. R1.6). In fact, the negative tendency anomalies in the inner Ross and Weddell Seas arise from the combined influence of dynamic and thermodynamic processes, which have comparable strength at the local scale as they sustain one another.

3. As there exist notable differences between the modelled and observed SIC anomaly patterns in the Weddell Sea and the Ross Sea (Figs. 2 and 3), the authors should discuss how the model performance would affect the sea ice budget analysis in the discussion section.

Thanks for this comment. More details on the model's performance and limitations have also been asked by the other reviewers. To address all these concerns, we propose to first add a detailed description and quantification of the main model's biases in the SIE/SIC seasonal cycle (end of Section 2.1):

A full description and evaluation of the model can be found in Pelletier et al. (2022; specifically, we use the same configuration as in their PAROCE experiment). Documented issues include systematic biases in the SIE seasonal cycle, which are related to well-known NEMO-LIM features (Vancoppenolle et al., 2012; Rousset et al., 2015). Particularly, the simulation used here reproduces well the observed growth from March to July (Fig. R1.3), but eventually overestimates the extent around the winter peak (1.1 million km2 more than the observations in September). Very little melting occurs before November, after which a steep decrease follows, with most of the melting happening between December and January. Due to the excessive winter extent and the short melting season, December is also the month with the strongest bias in the mean SIE, with a the difference between the model and the observations of about 4.4 million km 2. In summer, in contrast, too little sea ice is left in the model. A lack of 1.9 million km2, compared to the observations, is typically present in February, while the difference is smaller in January and March (the average January-March bias is -1.5 km2). The positive winter SIE bias is mostly related to a sea ice excess in the Bellingshausen-Amundsen Sea and eastern Indian/western Pacific Ocean, but the Ross Sea also contributes (Fig. R1.4). In summer, a lack of SIC is observed in almost all sectors. Particularly relevant for this study is the fact that the Ross Sea is virtually ice-free in February, and that a substantial portion of sea ice is also missing in the western Weddell Sea through the whole season. In the eastern Weddell sector, in contrast, the model seems to systematically overestimate the SIC and extent, particularly in January.

Then, we would also return to this point in the discussion (Section 4), when we remark the limitations of our model (from L390):

We have also discussed the model's biased climatology and how it is related to the model's poor performance in capturing the exact distribution of SIC anomalies, particularly in the Weddell Sea. Nevertheless, the main processes explaining the occurrence of minima in the model are consistent with the ones derived from observations and thus both support our conclusions. Our budget analysis relies on the model only and is thus also affected by its biases, such as the overestimated surface melting in the Weddell Sea mentioned in Sect. 3.5. Furthermore, the underestimate of the negative anomalies at the sea ice edge in the Weddell Sea could also impact the budget and alter the role of ice transport. However, the overall results are consistent between the Ross Sea and Weddell sectors and in agreement with previous results, as discussed above, which further endorses our conclusions.

We also propose to add more details on the interpretation of the lack of negative anomalies in the Weddell Sea in the model's composite map (L189-19, Sect. 3.2):

This difference may be related to the model biases in the summer climatology discussed in Section 2, which result in limited sea ice left in the eastern Ross Sea in JFM (see Fig. S1). While the positive signal in the Weddell Sea that is evident in the observations is also reproduced by the model, only *sparse negative anomalies are found in the model in the single years (Fig. 3a-d) and are almost lacking in the composite map (Fig. 3f). Again, this may be related to the model's systematic summer biases. The observed negative anomalies in the western part of the sector are in fact located in regions where the model usually does not have sea ice at all (cf. anomalies in Fig 2 with the model's climatological sea ice edge in Fig. 3, dashed lines). In contrast, the lack of negative anomalies in the eastern part may be due to the model's tendency to overestimate the sea ice presence there, as discussed in Section 2 (see Fig. R. 1.4).*

Specific comments

4. Lines 137-139: It is hard to understand the two criteria for selecting SIC minima events in the Weddell Sea, especially why different thresholds much be chosen for observations and model results for either criterion, and the authors should provide more explanations.

We understand your concern and we hope we can clarify this. This result is a choice made after several tests. One option, for instance, would be to use the same threshold for both the model and the observations, such as 1σ, but this would lead to a selection of only 2 total minima (as currently mentioned in L124). Another idea would be to apply the criteria separately (e.g. below -1σ in the observations, regardless of what the model is doing, and vice versa). This would lead to a selection of different years for the model and the observations, some of which are shared, some are not. In that case, one risk is to select modelled minima that are only related to the model's own variability and do not provide useful information of the physical mechanisms driving "real" SIE minima. These are just some examples. In the end, the selected criterion was, in our view, the best choice in order to have a reasonable sample of physically insightful events.

We propose to clarify this in the discussion (Section 4, L382):

Note that alternative selection criteria for the minima could be used. For instance, Turner et al. (2019) simply considered the lower quartile of sea ice annual minimum extents. The method does not strongly affect the final collection of years in the observations, where the total minima could be identified almost by eye (Fig. 1a), but in our case it is relevant for the comparison with the model. We have tested various criteria, such as different thresholds or the selection of distinct years for the observations and the model, but they typically lead to too small or inconsistent samples, since the model sometimes simulates SIE minima that are not observed, and vice versa. The final selection of events is based on concurrent conditions for both the observed and modelled time series to ensure the analysis of a reasonable number of observed events that are also captured by the model.

5. Lines 145-146: In my mind divergence results from advection, and the two terms should not be treated separately, though I do see such separations in other literatures. I hope this can be clarified here.

We propose to add a short description of what the two terms mean in that same sentence, hoping this helps to clarify:

Typically, the dynamic term encapsulates the effect of ice motion, namely advection (local *import/export of sea ice) and divergence (openings/closures in the pack), while the thermodynamic term represents local ice melting and formation.*

6. Line 280: ENSO is not examined in this study in a straightforward way so this sentence needs to be revised. Meanwhile, though ENSO can have influence on the ASL, I still suggest the authors to examine ENSO separately.

We propose to remove the explicit mention of ENSO from this sentence, which would then read:

Though it is challenging to identify common large-scale circulation anomalies, we have shown that the regional wind conditions in the Ross and Weddell sectors share some similarities across the minima.

7. Lines 283-284: Southwest wind anomalies can actually bring colder air masses from the Antarctic continent to the Ross Sea and increase the ice freezing, rather than causing "thermodynamic melting" mention here. So how to understand the ice melting?

This sentence was placed before the actual budget analysis and was meant as a bridge between the two sections, but it is true that without the context (and particularly the revision of Sec. 3.5 proposed here) it could be confusing. To avoid misunderstandings, we propose to reformulate it:

The exact roles of dynamics and thermodynamics in leading to the summer SIC anomalies are examined in detail in the next section, for both regions.

8. Lines 314-315: Any explanations for southerly wind in 2017 over the Weddell Sea, which is different from the wind patterns in other years?

We agree that these anomalies are interesting, but we do not have an explanation for them, other than what is suggested in the literature. The event of 2017 has been shown to be linked to an exceptionally strong negative phase of the SAM in November-December, preceded by a positive ZW3 pattern from May to August (Stuecker et al. 2017, Schlosser et al. 2018). Influences of tropical forcings from the Pacific and Indian Ocean (Stuecker et al. 2017, Purich and England, 2019; Schlosser et al. 2019, Meehl et al. 2019) and the stratospheric polar vortex (Wang et al. 2019) have been suggested as favouring factors.

Meehl, G.A., Arblaster, J.M., Chung, C.T.Y. et al. Sustained ocean changes contributed to sudden Antarctic sea ice retreat in late 2016. Nat Commun 10, 14 (2019). https://doi.org/10.1038/s41467-018-07865-9

Purich, A., & England, M. H. (2019). Tropical teleconnections to Antarctic sea ice during austral spring 2016 in coupled pacemaker experiments. Geophysical Research Letters, 46, 6848– 6858. https://doi.org/10.1029/2019GL082671

Schlosser, E., Haumann, F. A., and Raphael, M. N.: Atmospheric influences on the anomalous 2016 Antarctic sea ice decay, The Cryosphere, 12, 1103–1119, https://doi.org/10.5194/tc-12-1103-2018, 2018.

Stuecker, M. F., C. M. Bitz, and K. C. Armour (2017), Conditions leading to the unprecedented low Antarctic sea ice extent during the 2016 austral spring season, Geophys. Res. Lett., 44, 9008–9019, doi:10.1002/2017GL074691.

Wang, G., Hendon, H.H., Arblaster, J.M. et al. Compounding tropical and stratospheric forcing of the record low Antarctic sea-ice in 2016. Nat Commun 10, 13 (2019). https://doi.org/10.1038/s41467-018-07689-7

9. The legend or caption of Fig.7 should also explain the cross symbols in the two panels.

Thanks, we will fix this in the revised version of the manuscript.

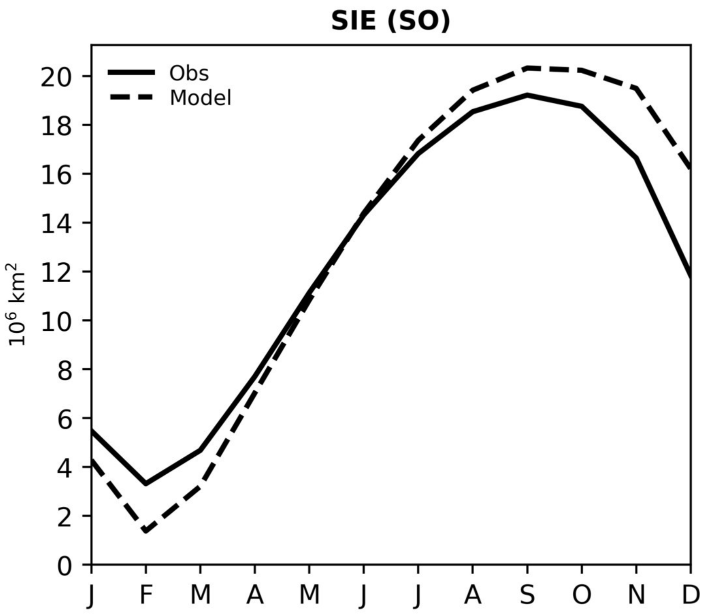

Figure R1.3: Seasonal cycle of the total Antarctic SIE in the observations (solid line) and in the model (dashed line). This figure will be added to the supplementary material.

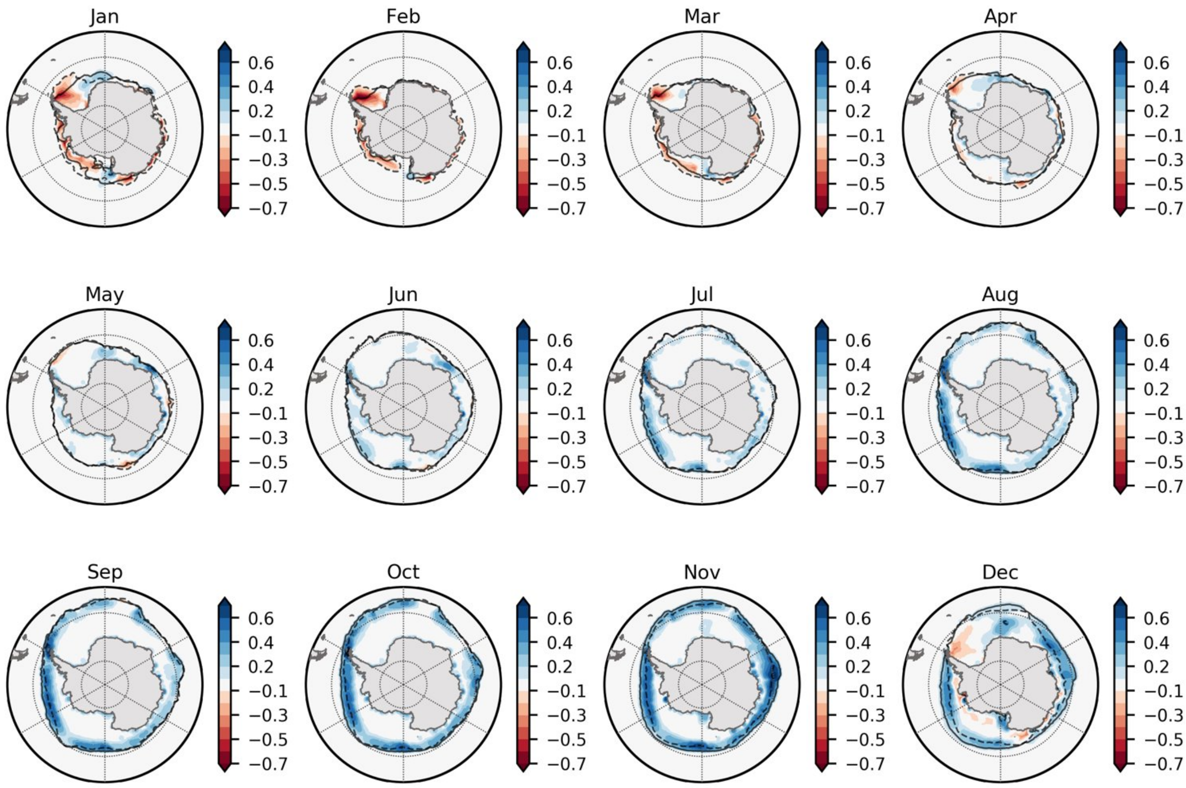

Figure R1.4: Differences in the monthly SIC climatology between the model and the observations. This figure will be added to the supplementary material.

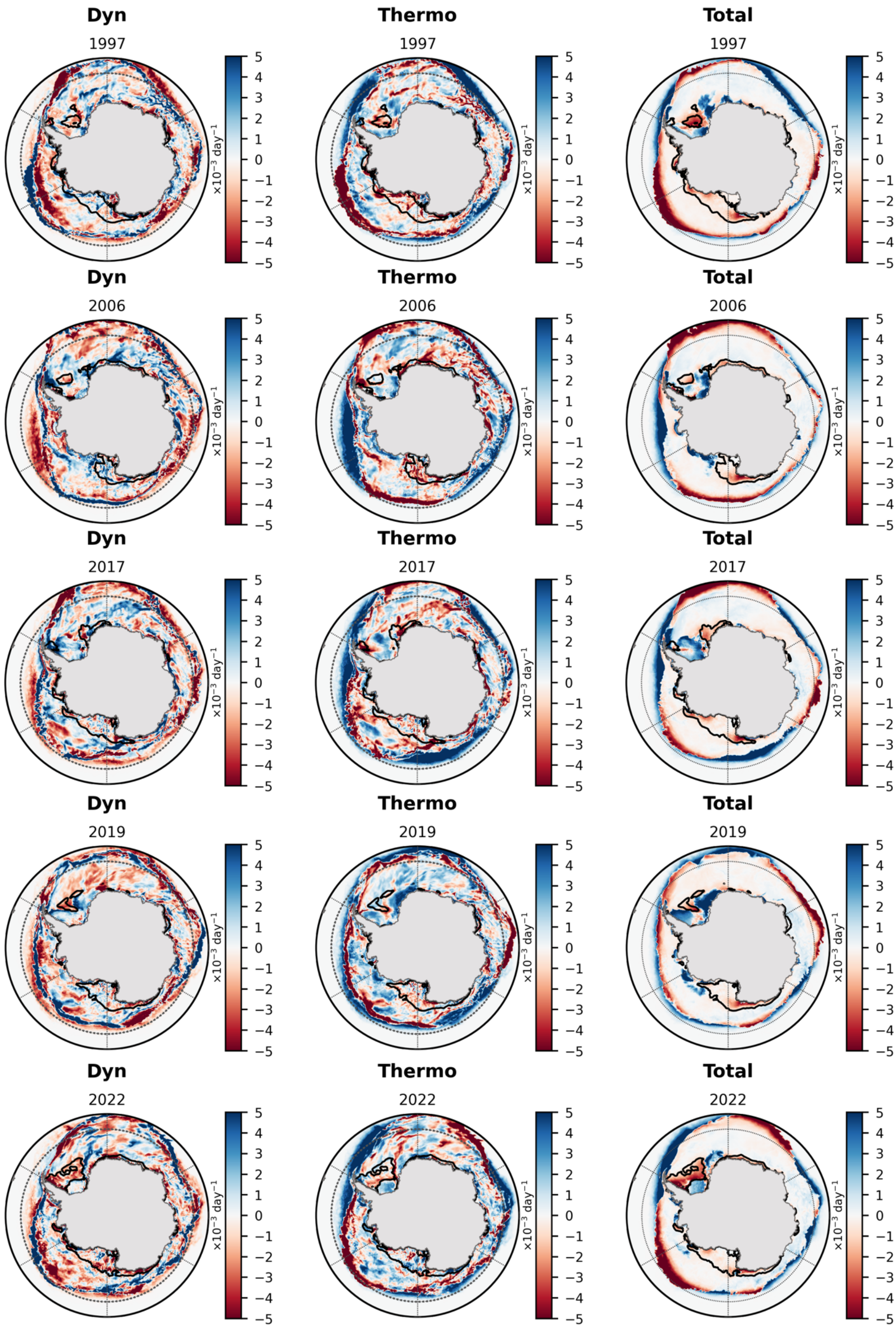

Figure R1.6: Shading: NDJ anomalies of the dynamic (left), thermodynamic (middle) and tendency (right) terms in the years with total SIE minima. Contours: areas with anomalous SIC = 0.1 in the corresponding year in JFM. This figure will be added to the supplementary material.