Summary of Revisions

We thank all two reviewers for their constructive feedback on our original manuscript. We hope these major updates address all reviewer concerns and improve the clarity, scientific rigor, and reproducibility of our study. Detailed replies for each reviewer follow below:

Reply to Referee Comment #1 (RC1):

The authors would like to thank the referee for the invaluable comments and suggestions. The following are the replies to each point raised, together with specific revisions that are made. The original comments are in *blue italic* font and listed in paragraphs, with our reply following each paragraph separately. The revisions are also highlighted in the revised manuscript in blue and marked by ***RC1***.

General comments

This study synthesized current knowledge on the drivers and impacts of Weddell Sea polynyas (WSPs), as the open-ocean polynyas that rarely exist in Antarctica. Given their importance in atmosphere-ocean energy and mass exchange, sea ice production, and formation of AABW, it is necessary to systematically review previous studies to draw pictures on the formation and cessation of the polynyas, their driver mechanisms, climate impacts, as well as current gaps in observations, modellings and knowledge. This study would benefit a deeper understanding of the roles of the open-ocean polynyas in the air-sea ice-ocean interactions in Antarctica, especially in the context of the fast-declining Antarctic sea ice in recent years.

The paper is well-written and organized. The research progresses and current knowledge of WSPs are summarized sufficiently. However, some revisions should be made before it is accepted for publishing:

1. *Section 3.4. It is suggested to add some quantitative summaries of the changes in biogeochemical parameters due to the appearance of WSPs, e.g., the oxygen concentration, carbon concentration, nutrients, etc.*

The quantitative information on changes in oxygen concentrations, carbon concentrations, and primary productivity associated with WSPs, below emphasised in *purple italics*, has been added to the following sentences of Section 3.4:

- [...] chimneys of anomalously high dissolved oxygen concentrations in the region reaching depths of 4000 m (Gordon, 1978; Foldvik et al., 1985), *with concentrations >5.6 mL L^{-1} c.f. 5.0-5.4 mL L^{-1} in surrounding waters (Gordon, 1978)*.
- [...] the measurements reveal high oxygen anomalies to about 1000 m depth *(e.g., +10 µmol kg^{-1} at ca 650 m)* following the opening of MRP in 2017 (Campbell et al., 2019) [...]
- End of paragraph 3: *In the model used by Bernardello et al. (2014), the cessation of Weddell Sea convection contributes 5% (-4.3±1.9 PgC) and 18% (-10.1±3.9 PgC), respectively, of the global climate-induced reduction in total and anthropogenic ocean CO2 uptake, despite only constituting 1% of the global ocean area.*
- Around the Maud Rise, chlorophyll (Chl-a) levels are *~2-4 times* higher than in the surrounding areas, *with mean annual maximum levels (2002-2018) exceeding 2.7 mg m^{-3} (von Berg et al., 2020), likely due to topographically-induced mixing (Meredith et al., 2003; Prend et al., 2019)*.
- Satellite data confirm that this was associated with unprecedented surface levels of Chl-a for this time of year, *reaching up to 4.7 mg m^{-3} during 2017* (Jena et al., 2020).
- von Berg et al. (2020) further demonstrate that a longer growing season allows for increased annual net community production *by up to 100\% over Maud Rise*, and thus suggest that the open-ocean polynya likely leads to enhanced carbon export to the ocean interior.

Citations mentioning the increase in iron supply to the surface layer as a contributing factor to increased productivity do not give precise quantifications of this iron supply. Therefore, no such quantifications have been added here.

2. *Section 6. The Conclusion needs to be further improved. In my view the conclusion needs to summarize the following four parts: 1) the drivers of the formation and cessation of the WSPs,*

2) the impact of WSPs on energy and mass exchange between the coupled atmosphere-sea ice-ocean system, 3) future projections of WSPs in response to global warming, and 4) current uncertainties and gaps in observations, modellings, and understandings in WSPs. The current version is more like the part 4 only.

We revised the Conclusion to provide a more structured synthesis, now clearly addressing the four points suggested:

- Drivers of WSP formation and cessation: summarized from both oceanic and atmospheric processes (Sections 3.1-3.2).
- Impacts on energy and mass exchange: discussed based on observational and model studies (Section 4.1), including their local confinement and short-lived nature (Ayres et al., 2024).
- Future projections: expanded in Section 5 with a clearer framing of the competing processes affecting WSP likelihood.
- Uncertainties and knowledge gaps: kept in the Conclusion, but now also moved into a new standalone section (see below).

3. Additionally, it is recommended to add a new section before Conclusion, discussing the current uncertainties and gaps in observations, modellings, and understandings in WSPs and future perspectives. It will be even better to list a table summarizing the differences (quantitatively or qualitatively) between study results on WSPs in terms of, e.g., formation and duration period, ice productions, heat release, climate impacts, projected occurrence frequencies, etc. This would help the readers quickly understand the progress and uncertainties in current WSPs studies.

Reply: Following this suggestion, we added a new Section 5: "Uncertainties and future perspectives." This section synthesizes observational, modeling, and process-based uncertainties in WSP research and elaborates on the need for fully coupled high-resolution models and enhanced in-situ observations. We also include Table 1, which summarizes key findings across multiple studies, including formation conditions, heat fluxes, and climatic impacts, highlighting both agreement and divergence across methods and time periods.

Specific comments
P: page, L: line

P4, L110. The authors are suggested to add some descriptions of how previous studies identified and quantified the WSP or MRP events in 2016 and 2017 (e.g., by in-situ observations, satellite observations, or modellings).

Reply: We revised this section to specify that the 2016 and 2017 MRP events were identified through satellite passive microwave observations (e.g., AMSR2, SSMIS) and quantified using in-situ hydrographic profiles (e.g., ARGO floats), consistent with Campbell et al. (2019). We replaced the citation to Gordon and Sarukhanyan (1982), as they did not directly discuss WSP, and instead refer to Carsey (1980), who used satellite imagery to track the 1970s WSP and its westward propagation.

P8, L243. Better briefly describe the patterns/features of the three Zonal Wave patterns 1-3.

Reply: We added a concise description of Zonal Wave patterns: these represent large-scale atmospheric circulation features, where ZW1-3 refer to the number of alternating high- and low-pressure centers around Antarctica. A shift from ZW1 or ZW2 to ZW3 in 2016-2017 is associated with enhanced meridional heat and moisture transport from lower latitudes, which promoted cyclonic activity in the Weddell Sea and favored polynya development.

P9, L286. The authors summarized the study of Ayres et al. (2024) that the atmospheric response to the 1974 WSP is "localized, vertically confined to the boundary layer, and short-lived". Are there any quantitative statistics, e.g., the extent, area, height, and duration?

Reply: We expanded this section to include specific numbers from Ayres et al. (2024): turbulent heat fluxes peaked at ~150 W/m^2, surface temperature increased locally by up to 7.5 K, with warming up to 100 km northeast of the polynya. Precipitation increased by ~1 mm/day directly over the polynya, and pressure dropped by ~4 hPa. These anomalies were short-lived and largely dissipated following polynya closure in late austral spring.

Reply to Referee Comment #2 (RC2):

The authors would like to thank the referee for the invaluable comments and suggestions. The following are the replies to each point raised, together with specific revisions that are made. The original comments are in *green italic* font and listed in paragraphs, with our reply following each paragraph separately. The revisions are also highlighted in the revised manuscript in green and marked by ***RC2***.

The Weddell Sea polynya, first observed in the mid-1970s through early satellite microwave imagery, is a highly intriguing phenomenon within the coupled atmosphere–sea ice–ocean system and has been the focus of several studies. However, it did not reappear for several decades, and due to a lack of observational data—particularly in situ measurements—research on the phenomenon remained limited. However, during the winters of 2016 and 2017, although on a smaller spatial and temporal scale, a region of open ocean re-emerged over the Maud Rise area, prompting renewed investigations from various perspectives.

This manuscript provides a comprehensive synthesis and integration of numerous previous studies on this fascinating natural phenomenon, resulting in a highly valuable review. To further enhance the quality of this review paper, I would like to provide the following comments.

P.1, L.1. "Abstract": Polynyas are generally described as open water areas within sea ice regions. However, in reality—particularly for coastal polynyas during winter—they are more often characterized by areas of frazil ice or new/thin ice. I believe this distinction should be described more precisely to reflect the actual conditions.
Reply: We agree and appreciate the clarification. We have revised the definition of polynyas in the abstract to read: "Open-ocean polynyas, areas with little or no sea ice,…"

P.2, L.32 "less frequent": Compared to coastal polynyas that appear almost daily during winter in the same region, sensible heat polynyas occur far less frequently and are regarded as extremely rare phenomena. Therefore, the term "less frequent" may be too mild, and a stronger expression such as "rare" or "very infrequent" would more accurately reflect the true nature of their occurrence.
Reply: We have replaced the phrase "less frequent" with "rarer" to better reflect the low frequency of open-ocean (sensible heat) polynya events, as compared to coastal polynyas.

P.2, L.51 "the current unprecedented decline in Southern Ocean sea ice": The rapid decline in sea-ice extent in the Southern Ocean has emerged as a particularly prominent topic in recent years. In this context, it would be valuable to also address the potential relationship between this decline and polynya occurrences, especially in connection with the future projections discussed later in the modeling results. Including such a discussion could provide a more comprehensive review and further strengthen the overall impact of the manuscript.
Reply: Thank you for this insightful suggestion. We added a brief discussion at the end of Introduction, acknowledging that although the 2016 MRP occurred during a period of sea ice decline, no similar polynyas were observed in 2022-2023 despite record-low ice extent. This suggests that extreme ice loss does not necessarily lead to polynya formation, possibly due to the lack of sufficient preconditioning or altered atmospheric patterns. We note the absence of dedicated studies on this topic and propose it as an important avenue for future research.

P.6, L.156 "Fig. 5": Figure 5 is introduced prior to Figure 4, creating a mismatch between the figure numbering and the order in which they appear in the text. For clarity and to improve reader comprehension, it would be preferable to present the figures in the same sequence as they are referenced.

Reply: We have corrected the figure order in the text to ensure that Figure 4 is referenced before Figure 5.

P.6, L.163-164 "Taylor Cap" and "warm-water Halo": If possible, visually indicating these characteristic structures in Figure 3 would greatly enhance reader understanding. In addition, labeling "Maud Rise" on the figure would help readers more easily connect the figure with the corresponding discussion in the text, making the illustration more informative and user-friendly.
Reply: We have updated Figure 3 to include annotations for "Taylor Cap," "warm-water Halo," and "Maud Rise."

Paragraph beginning on P. 11, L. 320 – Comment: The melt–freeze cycle described in this paragraph appears to be a plausible process and likely plays an important role in the maintenance of the polynya. However, even with increased sea-ice production in such cases, the salinity of the underlying water may already be too low to allow the formation of sufficiently dense water necessary for Antarctic Bottom Water (AABW) formation. Including a brief discussion of this aspect could further enrich the overall argument.
Reply: We have expanded the paragraph to briefly note that despite enhanced sea ice production, the resulting brine rejection may be insufficient to increase surface salinity to levels required for effective AABW formation. This is especially true if the background stratification is strongly freshwater-influenced, a condition increasingly common under projected future meltwater input scenarios.

P.13, L.413 "A minor component of the observed abyssal warming since the 1990s (Purkey and Johnson, 2010) could be linked to recovery from the mid-1970s WSP event (Zanowski et al., 2015).": This statement is quite intriguing; however, the roughly 20-year time gap between the events makes the proposed causal relationship somewhat difficult for readers to intuitively grasp. Including a brief explanation of the mechanism by which such an effect could emerge after such a long interval would help strengthen the argument and improve clarity.
Reply: We have clarified this point in the text by briefly explaining the proposed mechanism: the deep convective event during the 1970s WSP injected cold, dense water into the abyssal ocean. Over subsequent decades, as the anomalous cold water mass equilibrated and upwelled, it could have contributed to the delayed warming signal observed in the deep Southern Ocean. This lag is consistent with abyssal circulation timescales and has been simulated in multi-century coupled model runs (Zanowski and Hallberg, 2017).