Referee Comment on "Seasonal impact of submesoscale eddies on the ocean heat budget near the sea ice edge"

General Comments

This manuscript presents an interesting and timely investigation of the role of submesoscale mixed-layer eddies (SMLEs) in modulating the seasonal ocean heat budget and sea ice evolution near the marginal ice zone (MIZ). By comparing eddy-resolving (3D) and non-eddy (2D) MITgcm simulations, the authors isolate the thermodynamical impacts of SMLEs, which are often neglected in coarse-resolution climate models. The study addresses a significant knowledge gap by quantifying how SMLEs influence sea ice melting and freezing processes through heat transport and feedback mechanisms.

The paper is generally well-motivated, clearly written, and scientifically sound. The approach is methodologically appropriate, and the results provide new insights into the coupling between submesoscale dynamics and polar climate processes. The identification of distinct summer and winter responses strengthens the contribution and highlights the necessity of submesoscale parameterization in climate models.

Overall, this is a contribution of interest to the polar oceanography and climate modeling communities. Some clarifications and improvements would further strengthen the manuscript before publication.

Specific Comments

[1] Introduction

The introduction provides a comprehensive overview of submesoscale dynamics and their relevance in polar regions. However, it is somewhat verbose and would benefit from streamlining to emphasize the central research question. The authors may consider shortening the general background on SMLEs, improving transitions between topics, and highlighting the novelty of their thermodynamic focus relative to previous studies.

While observational and modeling studies are well cited, the flow from general submesoscale theory to polar-specific impacts could be smoother. Adding brief linking sentences to connect classical SMLE mechanisms with polar sea ice interactions would enhance readability. Moreover, the main research gap, which involves quantifying the thermodynamic impacts of SMLEs across seasons and background stratifications, should be emphasized earlier, ideally before detailing the study objectives.

[2] Materials and Methods

The description of the model setup contains many technical details in long, complex sentences. For example, information on vertical and horizontal grid spacing, mixing schemes, and viscosity settings could be split into shorter sentences or a table. This would improve readability and make it easier for readers to understand the experimental design.

Some parameter choices, such as the Smagorinsky coefficient, horizontal eddy viscosity, and small horizontal diffusivity in winter, are described, but the rationale is brief. It would strengthen the manuscript to explain why these values were selected, particularly how they affect numerical stability and the development of SMLEs, and whether sensitivity tests were conducted.

While the 2D “no eddies” configuration is introduced, the description could clarify explicitly which processes are suppressed (e.g., lateral variations, baroclinic instabilities) and ensure the naming of the experiments is consistent (Arctic/Antarctic, summer/winter). Providing a concise summary table of the main experiments with initial conditions and key parameters would greatly enhance reproducibility.

The methods section contains a large amount of technical detail, including grid spacing, viscosity and diffusivity settings, and atmospheric boundary treatments. While these details are important for reproducibility, some of the more intricate numerical specifications could be moved to the Appendix. This would streamline the main text, improve readability, and allow readers to focus on the key experimental design and scientific rationale, while still providing full information for replication.

[3] Results

The Results section 3.1.1 provides a detailed description of SMLE development and their impact on the mixed layer during Arctic summer, including vertical stratification and buoyancy fluxes. While the simulations and analyses appear comprehensive, the presentation could be strengthened by improving the logical flow and emphasizing the physical interpretation. Currently, the text mixes descriptions of forcing, stratification, eddy development, and vertical fluxes in a single narrative, which can make it challenging for readers to follow the causal chain. Reorganizing the section to first describe the atmospheric and oceanic forcing, then the resulting stratification and MLD evolution, and finally the eddy dynamics and their restratifying or destratifying effects would improve clarity.

The analysis of the ML heat budget and eddy impacts (Section 3.1.2) is thorough and provides valuable insight into the mechanisms by which SMLEs redistribute heat between open and ice-covered regions. However, the presentation could be improved by emphasizing the causal interpretation and quantitative comparisons more clearly. For instance, the roles of MHT and Qnet are described in detail, but it would be helpful to explicitly highlight how the presence of eddies amplifies meridional heat transport compared to the 2D simulation, and how this relates to changes in ice melt or ML warming. Additionally, the text could more clearly distinguish between contributions from shortwave, longwave, and sensible fluxes in both regions, linking them directly to the eddy-induced heat redistribution. This would strengthen the physical interpretation and make the connection between eddies and observed heat budget changes more immediate for the reader.

The Antarctic results (Section 3.3) are presented clearly, with useful comparisons to Arctic simulations, but the section could benefit from emphasizing the physical interpretation of the differences. For example, the text could more explicitly link the faster ML deepening and weaker stratification in Antarctic winter to the smaller eddy impact on sea ice formation, and clarify why the summer eddy impacts are relatively insensitive to initial stratification. Including brief quantitative comparisons or ratios directly in the text (e.g., differences in MLD deepening or lateral density gradients) would help readers quickly grasp the relative magnitudes. Finally, a short discussion of the potential effects of neglected wind forcing on Antarctic results would strengthen the assessment of model limitations.

Technical Corrections

In Section 2, “Materials and Methods,” it is recommended to split the content into two subsections for clarity: 2.1 “Model setup” and 2.2 “Residual-mean framework.” This would improve the organization and make it easier for readers to follow the methods.