Author’s Response to Reviewers

Manuscript Title: Forcing-dependent submesoscale variability and subduction in the coastal sea area (Gulf of Finland, Baltic Sea)

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We thank both reviewers for their thoughtful and constructive feedback. In response, we have made extensive revisions to improve the clarity, structure, and scientific rigor of the manuscript. Key changes include rewriting large sections for clarity and flow, improving the presentation of the study’s motivation and novelty, clarifying definitions of key concepts, strengthening the analysis with new quantitative metrics and figures, and adding a dedicated Conclusion section. We believe these changes address all major concerns and significantly improve the manuscript’s clarity and scientific value.

A lot of the reviewers’ comments converge on similar aspects of the manuscript that have now been addressed.

<u>General Comments</u>

We acknowledged that language, grammar, and structure needed thorough revisions throughout the manuscript.

We have substantially revised the Introduction to clarify the narrative and strengthen the study’s motivation and context. The updated text provides a clearer explanation of the relevance of submesoscale processes and the use of spice to characterise them in stratified estuarine systems, such as the Gulf of Finland. We also highlight one aspect of the novelty of our study in terms of combining glider-based observations with a regional high-resolution model to investigate the vertical structure and evolution of spice anomalies, which has not been previously addressed in the Gulf of Finland context or similar basins.

We have revised the manuscript to introduce key concepts, such as spice, tracer variance, Rossby number, and buoyancy gradients, earlier in the text, with clearer definitions and more consistent terminology throughout.

Use of Observations vs. Model: We have published an earlier paper based solely on glider data from 2018. We incorporated two more glider missions from the study area to characterize SMS variability in relation to forcing and mesoscale background and used model data to extrapolate (generalize) the findings over a larger spatial area and temporal extent. While the numerical model provides the spatial and temporal coverage necessary to explain the development of submesoscale processes, we have revised the manuscript to better emphasize the role of glider observations beyond validation. Specifically, we state that glider observations revealed maxima of spice above the maximum vertical density gradient during spring missions and below it during the late summer mission. Also, glider data indicated high spice in the sub-surface layer in the case of forcing conditions favourable for coastal upwelling and formation of a long-coastal baroclinic current. Both of these findings were generalized, and potential mechanisms were suggested using model data from a larger area and extended periods.

Figures: We have revised several figures to improve clarity and comparability, for example, by harmonizing axes across related plots and adding subplots showing vertical velocity and horizontal currents. In response to reviewer comments, new figures have been introduced, which has changed the figure sequence compared to the previous version. These enhancements provide a clearer view of subduction processes and allow for a more effective assessment of the physical mechanisms discussed in the manuscript.

The Discussion section has been reorganized to directly reference relevant figures and results and includes a more focused comparison with previous studies. These changes improve the cohesion of the manuscript and highlight how our findings contribute to understanding submesoscale dynamics and vertical structure in the GoF.

We have added a Conclusion section that clearly summarizes the main findings and implications of the study.

<u>Specific Comments:</u>

<u>Abstract</u>

We have reformulated the abstract to stress better the main findings and differentiate what is well founded by data and what can be suggested but must be studied in more detail in the future as was suggested by the reviewers.

<u>Introduction</u>

Both reviewers noted that the Introduction lacked clarity, structure, and clear motivation. In response, we thoroughly revised the section to improve grammar, sentence flow, and paragraph organization. We now emphasize the importance of submesoscale processes from the outset and clarify their links to key physical and biogeochemical processes. Key concepts such as SMS dynamics, spice, and tracer variability are now introduced earlier, defined more clearly, and connected to the study objectives. We restructured the Introduction to present a logical narrative: starting from the relevance of SMS flows, moving through the regional context of the Gulf of Finland, and leading to the rationale for combining glider observations and high-resolution modeling. We also clarified why gliders are used, the mission timeframes, and the advantages and limitations of the modeling approach. Hypotheses are now clearly formulated to guide the study and are tested in the Results. Collectively, these revisions provide a clearer background and stronger justification for the work.

<u>Methods</u>

Both reviewers requested clarification and improvement in the description of glider missions and data processing. In response, we now explicitly state the exact dates, transect orientation, and depth coverage of each glider mission. While originally conducted for different objectives, the missions collectively form the observational basis of this study. We clarified why transect orientations varied and included new details on the vertical profiling behavior of the glider.

Reviewer 1 asked for a description of data quality control procedures and interpolation methods; we now specify that quality control followed adapted Argo protocols and that interpolation was performed in time-pressure coordinates with a vertical resolution of 0.5 dbar and a horizontal resolution of 10 minutes. We also explained the rationale for time-based interpolation (raised by Reviewer 2), noting that it aligns with the glider's time-indexed sampling method.

Terminology was revised for clarity, including replacing "YOs" with "up- and downcasts" (Reviewer 2), and we clarified the model's adaptive vertical coordinate system and vertical interpolation of boundary conditions (Reviewer 1). Tense inconsistencies were corrected throughout. In response to a comment on Figure 1 (Reviewer 1), we slightly extended the map for better regional context.

<u>Analysis</u>

Both reviewers asked for justification of the 4 km horizontal averaging scale used for glider-derived spice. In response, we now clarify that this scale aligns with the internal Rossby deformation radius in the Gulf of Finland (Alenius et al., 2003) and offers a balance between preserving submesoscale signals and suppressing noise. To assess the sensitivity of our results to this choice, we provided additional figures 1 and 2 comparing spice distributions using 2 km, 4 km, and 7 km averaging. These demonstrate that key frontal features are robust across scales, though amplitude varies with smoothing.

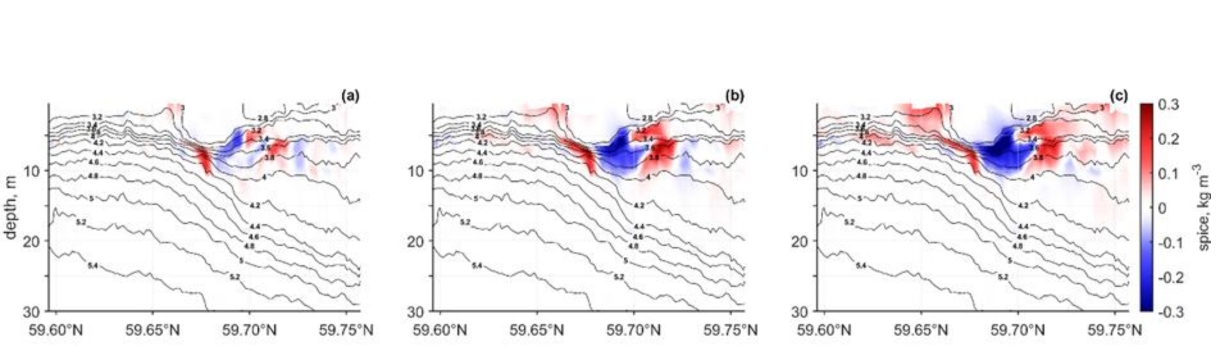

Figure 1 shows an example of spice distribution using horizontal averaging scales of 2 km (a), 4 km (b), and 7 km (c). Each panel displays the same section, overlaid with density contours at 0.2 kg m⁻³ intervals. The data are based on glider observations from 24–25 May 2018.

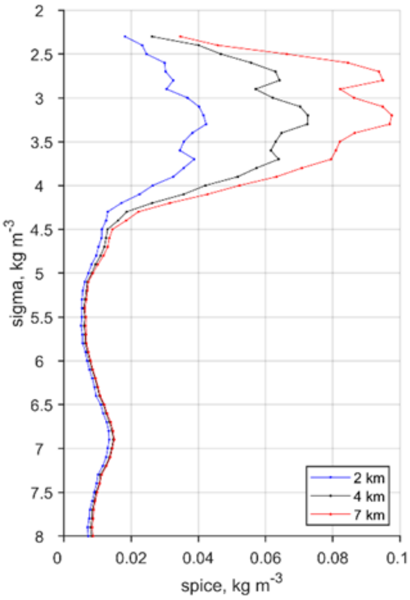

Figure 2 shows the standard deviation of spice calculated from the glider mission conducted between 9 May and 6 June 2018. The colours indicate the horizontal averaging scales used for spice: 2 km (blue), 4 km (black), and 7 km (red).

Reviewer 2 requested that the spice equation be set apart for clarity, and a citation for TEOS-10 was added. Reviewer 1 asked us to specify how vertical buoyancy gradients (N^2) were computed; we now clarify that they were calculated using 2 m intervals. In response to both reviewers' suggestions, we harmonized axes in related figures to improve comparability, including converting spice plots to depth space where applicable.

Additional reviewer 1 requests included explaining the use of a 6-hour Gaussian filter on wind components (now clarified as a means to reduce high-frequency noise), and rephrasing or moving sentences that previously introduced results too early (now relocated to the Results section). Reviewer 2 suggested using glider data to estimate more SMS characteristics; we note that while possible, model output offers more continuous spatial and temporal coverage. This complements our earlier glider-only work (Salm et al., 2023).

<u>Results</u>

Both reviewers emphasized the need for clearer presentation and more quantitative comparisons between observations and model output. In response, we revised the language throughout the Results section for clarity and corrected missing or ambiguous terms (e.g., replacing "slight" with numerical differences). We now provide standard deviations alongside mean values (e.g., for UML, CIL, and maximum N^2 depths), and specify depths at which the model fails to capture observed secondary maxima. Reviewer 2's concern about the significance of model–observation mismatches has been addressed by clearly stating the magnitude of differences and their potential implications.

The figures were revised to better match the glider and model domains, remove gaps, and harmonize axes (e.g., depth vs. density space). We replaced mission-averaged spice fields with more representative cross-sections (Figs. 3 and 4 in revised version), and added markers to figures to highlight key events and periods referenced in the text.

Both reviewers asked for improved treatment of submesoscale indicators and a more quantitative discussion. Accordingly, subsection 3.3 was revised extensively to add quantifications where possible, and a new subsection 3.4 was developed to expand on specific events. Although some conclusions remain qualitative (e.g., the influence of coastal currents and topography on offshore spice maxima), we now support them with additional figures and mechanistic discussion. While a full quantitative attribution remains difficult, we clearly state the limitations and avoid overinterpreting model outputs.

Discussion

Both reviewers found that some parts of the Discussion were too general or disconnected from the study's findings. In response, we revised the section to focus more tightly on results from the present study and removed or rephrased general or speculative statements (e.g., Lines 367–374, 400–403, and 444–452 in previous version). Reviewer 1's concern about referencing vertical velocities was addressed by including vertical velocity plots in the revised figures (Figs. 11 and 13). Reviewer 2 requested clarification on "elongated regions" of spice; we specified that these are horizontal structures and added figure references.

Both reviewers questioned the inclusion of winter SMS dynamics, noting that the study only covers spring–summer. We agreed and removed related content to avoid confusion about the study's scope. We also now explicitly state a key methodological limitation: spice, as used here, is most appropriate during seasons when both temperature and salinity significantly contribute to density. Reviewer 1's question about strong claims based on limited cases led us to soften language and clarify that our conclusions are drawn from specific events rather than broader statistics. Where relevant, we now indicate whether statements are literature-based or derived from our results.

Overall, the Discussion has been streamlined, more directly tied to the presented findings, and refined to better reflect the study's seasonal scope and methodological constraints.

Conclusion

Both reviewers noted the absence of a dedicated conclusion summarizing the key findings. In response, we added a Conclusion section that synthesizes the main results, responds to the reviewers' expectations and strengthens the manuscript's overall structure.