Reply on RC2

Thank you for your comments concerning our manuscript. Those comments are all valuable and very helpful for revising and improving our paper. We have studied comments carefully and have made correction which we hope meet with approval. The main corrections in the paper and the responses to your comments are highlighted in blue and are as follows:

Material and method section

To enhance the Materials and Methods section, I would recommend adding several clarifications. First, it would be beneficial to include specific references, such as a DOI, for the gridded sea surface height datasets used in the study. While the datasets are listed in the references, explicitly citing them in this section would improve clarity and accessibility for readers.

Response: Thank you for your precious suggestion. The references or DOIs have been added in Section 2.1.

Line 69-71: The SWOT mission consists of two phases: the science phase, which conducted 21-day repeat sampling from September 7th 2023 to November 21st 2023, and the calibration and validation phase (CALVAL), which performed 1-day rapid sampling from April 1st 2023 to July 31st 2023 (AVISO/DUACS, 2024).

Line 78-80: The first ADT product (Fig. 1b) was produced using a $\pm$11 days time window Near Real-Time (NRT) Two-Dimensional Variation (2DVAR) method with a 1/12° grid resolution (https://doi.org/10.5281/zenodo.11219285).

Line 83-86: During the science phase of the SWOT mission, the AVISO merged map Delayed Time (DT) products utilized SWOT data as an input source (Copernicus Marine Service repository, 2023b). To maintain the independence of the datasets, we employed NRT products, which do not include SWOT data (Copernicus Marine Service repository, 2023a).

Additionally, please specify the time period used, as this information is essential for contextualizing the scope of the analysis. I was a bit lost when I read/interpreted the results since I was not sure which CMEMS (DT, NRT) dataset was used.

Response: I apologize for previously providing the time period and dataset information in a scattered and vague manner. Below, I have pasted the revisions that organize and summarize the information regarding the data time period and the CMEMS DT/NRT details.

Line 69-71: The SWOT mission consists of two phases: the science phase, which conducted 21-day repeat sampling from September 7th 2023 to November 21st 2023, and the calibration and validation phase (CALVAL), which performed 1-day rapid sampling from April 1st 2023 to July 31st 2023 (AVISO/DUACS, 2024).

Line 83-88: During the science phase of the SWOT mission, the AVISO merged map Delayed Time (DT) products utilized SWOT data as an input source (Copernicus Marine Service repository, 2023b). To maintain the independence of the datasets, we employed NRT products, which do not include SWOT data (Copernicus Marine Service repository, 2023a). Similarly, during the CALVAL phase of the SWOT mission, we used an older version of the DT products which do not include SWOT data as an input source.

Furthermore, a more detailed explanation of the differences between Near Real-Time (NRT) and Delayed Time (DT) products you are using would be helpful. Clarifying which processing mode (NRT, DT, or both) was used for the 2DVAR mapping would also improve transparency in your methodology and intercomparison.

Response: Thank you for your valuable suggestions. I will provide a brief description of the differences in the processing methods for NRT and DT, as well as the processing method for 2DVAR.

Line 88-92: The DT products are reanalysis datasets that incorporate the highest quality altimeter measurements and geophysical corrections to minimize the risk of mass loss or false signals over time. The NRT data provide ready-to-use, real-time published altimeter data from all available missions. In the data processing, the DT products are computed optimally using a centered computation time window of ±6 weeks around the date of the map to be computed. In the NRT processing, future data are not available; therefore, the computation time window covers the period from 7 weeks prior to the computation date.

Line 78-80: The first ADT product (Fig. 1b) was produced using a ±11 days time window Near Real-Time (NRT) Two-Dimensional Variation (2DVAR) method with a 1/12° grid resolution (https://doi.org/10.5281/zenodo.11219285).

Eddy identification section:

Since most of the results depend on the eddy identification algorithm, it would be helpful to provide additional details about the methodology employed in your study. Specifically, could you elaborate on the method proposed by Ni (2014)? It seems challenging to find this reference—would you be able to provide a DOI or further citation details? Additionally, I would appreciate it if you could clarify the specific time period during which the eddy identification and tracking were conducted.

Response: Thank you for raising this question. It has indeed highlighted a basic mistake—we failed to correctly cite the primary source when referencing the eddy identification method. Upon re-examining the article by Ni (2014), we found that the eddy identification method used in that study was based on the work by Chelton et al. (2011). Therefore, we have cited the primary source, Chelton et al. (2011), in this context. Additionally, the time period for eddy identification and tracking has been added to Section 2.2.

Line 116-119: Therefore, this research employed a sea surface topography method based on contour analysis for eddy identification in 2DVAR and AVISO ADT merged maps, as well as in SWOT maps during both phases of the SWOT mission (Chelton et al., 2011). The eddy tracking was adopted only during science phase because of the fixed observation area of CALVAL phase.

Eddy validation section:

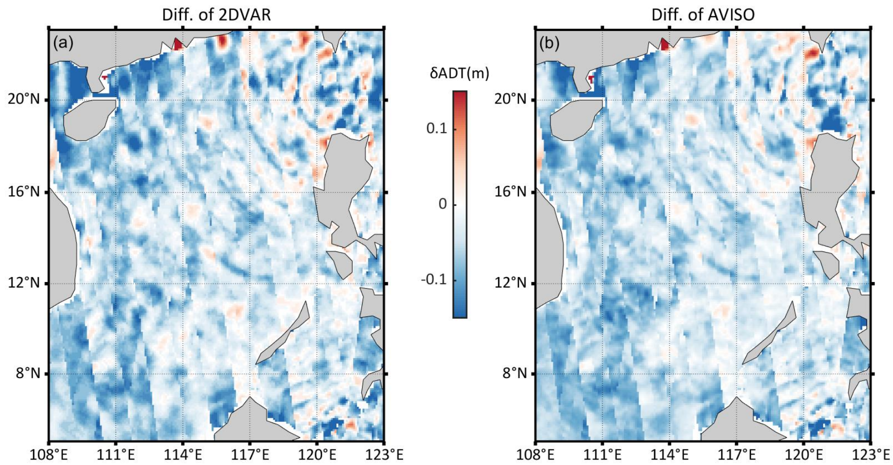
Since the eddy detection is specifically applied to the SWOT swath, it might be beneficial to undertake further validation to ensure its robustness. Conducting an intercomparison with independent datasets, such as SST or chlorophyll data, could provide valuable insights and help validate the eddy detection within the SWOT track. Additionally, the eddy detection performed along the SWOT track is inherently constrained by the SWOT swath extension, which is limited to 120 km. So, the eddy contours identified within the SWOT track are, by design, confined to this 120 km width. This raises an important question: what if the detected eddy contour corresponds to an isocontour of a larger eddy observed in broader maps (let’s say the upper part of a large eddy)? In other words, how reliable is the eddy detection within the SWOT track? Is the SWOT eddy contour really a true eddy boundary? Complementary investigations and discussions on this aspect should be carried out to further validate the eddy detection in SWOT products.

Response: Thank you for your valuable suggestions. Indeed, using SWOT for eddy detection is an exploratory endeavor. Currently, there is no perfect method to verify the accuracy of SWOT eddies, and we have considered using independent datasets for validation. However, sea surface temperature data lacks the capability to identify eddy structures, and chlorophyll data is also merged map. Both sea surface temperature and chlorophyll data are remote sensing products, and their accuracy is not higher than that of SWOT. Using these types of data may introduce additional errors. On the other hand, considering that the SWOT swath data already have a good ability to identify fine-scale features (Fu et al., 2024; Martin et al., 2024; Ubelmann et al., 2024; Verger-Miralles et al., 2024; Zhang et al., 2024), we believe that our current method is sufficient for validating eddies in the merged maps.

Results section:

It would be nice to have a figure with the difference of ADT between SWOT and the AVISO & 2DVAR products to illustrate the amplitude difference between observed SWOT measurement and reconstructed NRT & DT AVISO and 2DVAR products.

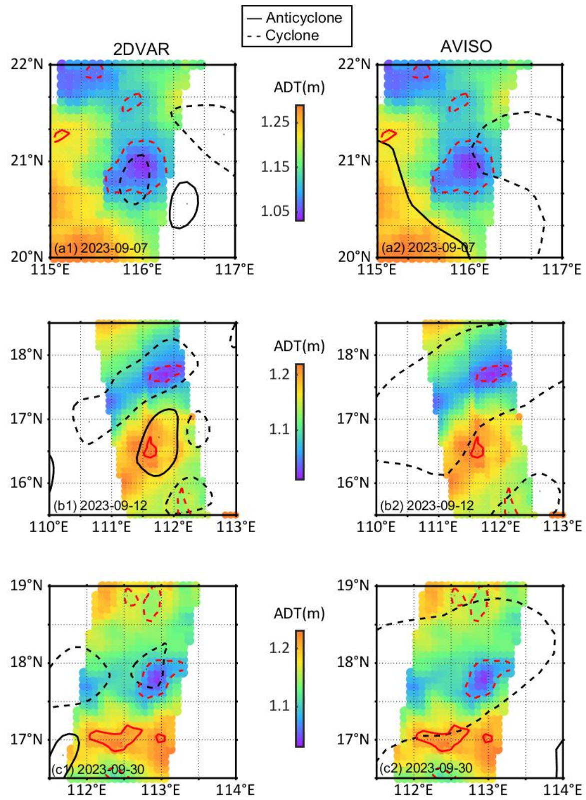
Response: Thank you for your valuable suggestions. We have generated a figure that illustrates the distribution of differences between the sea surface height (SSH) from the merged fields and that from SWOT data (S1). The SSH values in both merged maps are consistently lower than those from SWOT by 0 – 10 cm and exhibit a degree of variability (seems like internal waves). Considering the coherence of the article and the value it brings, I would appreciate your help in deciding whether this figure merits inclusion in the main text.



S1 Differences in Absolute Dynamic Topography (ADT) between the 2DVAR and AVISO products compared with that of the SWOT data.

Since the results rely on eddy matching between the SWOT track and the altimetry gridded product, it might be helpful to include an illustration of eddy detection for both the SWOT track and the altimetry gridded products, as shown in Figure 3. Or superimpose contour of detected eddies between SWOT products and altimetry gridded products

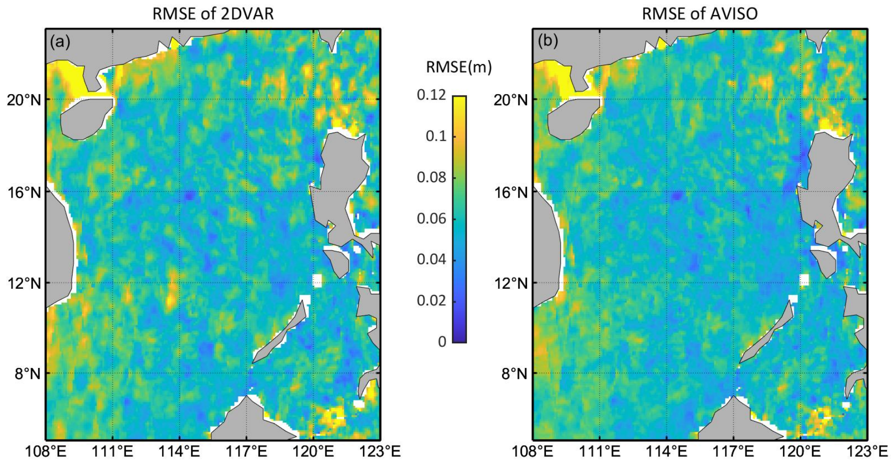
Response: Thank you for your suggestion. We have incorporated the eddies identified by SWOT into Figure 3 in the main text, overlaying them with the eddies identified by the merged products (see S2).



S2 The ADT observation data of SWOT with the eddies detected by SWOT (in red), 2DVAR (in black, a1-c1) and AVISO (in black, a2-c2). The solid line represents the anticyclonic eddies and dashed line represents the cyclonic eddies.

Additionally, incorporating classical statistical metrics (in addition to eddy detection metrics) to evaluate the gridded product at a finer scale would enhance the analysis. For instance, presenting results based on RMSE comparisons between the gridded product and L3 SWOT could provide valuable insight on the error level in the products. This would also help to illustrate and intercompare the performance between the AVISO maps and the 2DVAR maps in the region of interest.

Response: Thank you for your valuable suggestions. We have generated a map showing the RMSE distribution between the two merged maps and SWOT (S3). The majority of the RMSE values fall within the range of 0.04–0.08 m, similar to the difference distribution, and still reveal internal wave signals. Considering the coherence of the manuscript and the value added by this figure, I would appreciate your help in deciding whether this figure merits inclusion in the main text.



S3 RMSE of ADT for 2DVAR and AVISO compared with SWOT data.

In the abstract you mentioned that: "The findings indicate that SWOT provides an enhanced capability in resolving fine-scale and mesoscale eddies in the South China Sea compared with conventional in-situ data, such as drifting buoys." Could you clarify which result supports this finding?

Response: Thank you very much for raising the issue. We indeed do not have sufficient data to support this conclusion; it was merely an example to illustrate that SWOT is more effective in detailed eddy boundary comparisons due to its larger data volume and extremely high accuracy. Therefore, we have revised the abstract.

Line 24-25: The SWOT data possess a greater potential for conducting detailed comparisons of eddy boundaries across fine-scale to mesoscale structures compared with conventional in-situ data, such as drifting buoys.

Discussion section:

To improve the Discussion section, it would be valuable to address several key points.

- Could you elaborate on the limitations of AVISO maps in terms of their resolution within the region of interest? Additionally, it would be helpful to discuss the differences between Near Real-Time (NRT) and Delayed Time (DT) products, as well as their implications for the 2DVAR approach.

Response: Thank you for raising this valuable question. In our prior research, we computed the effective resolution for both the AVISO and 2DVAR products within the study region. The effective resolution indicates the minimum spatial scale of signals that the merged maps can theoretically resolve, although it does not necessarily correspond to the actual minimum scale. The average effective resolution of AVISO in the SCS is approximately 150 km, whereas that of 2DVAR is about 80 km. This

suggests that, typically, AVISO identifies larger eddies compared to 2DVAR. As a result, AVISO encounters greater limitations in identifying eddies across the mesoscale to fine-scale spectrum.
We have included this discussion in the relevant section. The distinctions between the Near Real-Time (NRT) and Delayed Time (DT) products have been detailed in Section 2.1.

Line 333-337: The effective resolution indicates the minimum spatial scale of signals that the merged maps can theoretically resolve, although it does not necessarily correspond to the actual minimum scale. The average effective resolution of AVISO in the SCS is approximately 150 km, whereas that of 2DVAR is about 80 km. This suggests that, typically, AVISO identifies larger eddies compared to 2DVAR. As a result, AVISO encounters greater limitations in identifying eddies across the mesoscale to fine-scale spectrum.

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- Could you explore potential reasons why only a limited number of eddies are detected in AVISO maps? This analysis would provide an important context for understanding the performance of different methodologies. Emphasizing the significance of developing regional configurations for merged sea surface height (SSH) products would also be a valuable addition, highlighting the potential for more accurate regional analyses.

Response: Your question is excellent, and we apologize for not addressing it in the text. The potential reason for the limited number of eddies detected in the AVISO maps is closely related to our previous work (Liu et al., 2023). Considering the small error correlation scales in high eddy kinetic energy regions such as the SCS and other coastal areas, the rational selection of the merged product's regional configuration is also very important. In terms of the trade-off between result performance, the background field time window for AVISO is selected as a multi-year average field, which leads to an increase in the scale of background error signals, and the scale of signals will be amplified during the mapping process. Therefore, the merged map has difficulty in reconstructing and identifying small-scale processes such as small-scale eddies, and will identify more large and mesoscale eddies. Due to the narrow swath of the SWOT track, the number of large and mesoscale eddies that can be identified by AVISO within this range is limited, which may ultimately lead to the limited number of eddies detected by AVISO.

Line 337-346: Considering the small error correlation scales in high eddy kinetic energy regions such as the SCS and other coastal areas, the rational selection of the merged product's regional configuration is also very important. In terms of the trade-off between result performance, the background field time window for AVISO is selected as a multi-year average field, which leads to an increase in the scale of background error signals, and the scale of signals will be amplified during the mapping process. Therefore, the merged map has difficulty in reconstructing and identifying small-scale processes such as small-scale eddies, and will identify more large and mesoscale eddies. Due to the narrow swath of the SWOT track, the number of large and mesoscale eddies that can be identified by AVISO within this range is limited, which may ultimately lead to the limited number of eddies detected by AVISO. In contrast, 2DVAR adopts a one-day background field time window, and the reduction in background error correlation scales allows for the reconstruction of more fine-scale to mesoscale signals.

- It would also be useful to consider the broader implications of your study. Are the conclusions drawn from your research applicable on a global scale? Could the proposed method be effectively applied at a global level? Do the findings regarding AVISO maps and the 2DVAR approach remain consistent at a global scale? Addressing these questions would provide a more comprehensive perspective. I would suggest for example performing similar analysis at global scale using CMEMS NRT & DT product and L3 SWOT data to illustrate the limitation of NRT products and test the method at global scale.

Response: Thank you for raising the question. Currently, work on a global scale is still in progress. Therefore, we can only limit the scope of this study to the South China Sea for now and revise the title to "Advances in Surface Water and Ocean Topography for Fine-Scale Eddy Identification from Altimeter Sea Surface Height Merging Maps in the South China Sea."

- In Figure 6, the eddies appear to remain relatively static over the 2 – 3 months of tracking analysis. It would be helpful if the authors could discuss whether these eddy structures might also be detectable or sampled by classical nadir altimeters and elaborate on the added value that SWOT brings compared to traditional nadir altimeters. What are (on average) observable length scale of nadir altimeter in this region? Maybe an illustration of all nadir track over specific region may highlight the difference or similarities between swot 2d product and nadir 1d products.

Response: Thank you very much for your valuable suggestions. Our previous description indeed failed to clearly highlight the differences between SWOT and traditional nadir altimeters. In fact, traditional nadir altimeters, due to their linear single-point sampling method, lack the capability to identify ocean eddies, which have a two-dimensional structure. To illustrate the distinction between SWOT's KaRIn and nadir observations, we have added the original nadir data in Fig. 1a and provided a zoomed-in view to clearly show the sampling intervals and effects of different observation methods. We added relative discussion in the relevant section about the differences in eddy structure detection between SWOT and traditional altimeters and the added value that SWOT can provide.

Line 365-368: Traditional nadir altimeters, due to their linear single-point sampling method, lack the capability to identify ocean eddies, which have a two-dimensional structure. Therefore, compared to traditional nadir altimeters, the advantage of SWOT lies in its ability to quantitatively analyze the observable scales of two-dimensional structures, such as eddies, within the study area.

- Including a section that describes the importance of the South China Sea (SCS) could also further strengthen the motivation for this study

Response: Thank you for your valuable suggestions. The significance of the South China Sea (SCS) as the study area has been added to the last paragraph of Section 2.1.

Line 98-106: The SCS is a significant dynamic marginal sea in the northwestern Pacific, featuring complex bathymetry, a large area, and multiple straits that facilitate water exchange with the Pacific and Indian Oceans(Chen et al., 2023). It serves as an exemplary model of an open ocean with well-defined continental shelves, shelf breaks, and a central deep basin. In the SCS, the first obliquely pressured Rossby deformation radius was less than 20 km in winter (Cai et al., 2008), suggesting a rich environment for fine-scale oceanic dynamical processes. Additionally, the SCS receives energy transport from the sub-mesoscale energy reservoir of the Kuroshio Current via the western boundary currents, resulting in a dense concentration of mesoscale and fine-scale processes on the 10-km scale (Lin et al., 2020; Ni et al., 2021; Zu et al., 2019). Thus, this study of the SCS holds substantial significance and reference value for understanding complex dynamic marginal seas and the broader northwestern Pacific region.