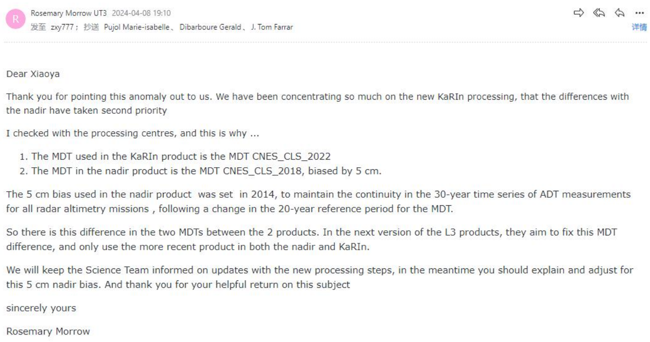
Reply on RC1

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:

Major comments:

1) The authors are using SWOT data from a pretty old version now (v0.3 on L 100). Two improved versions have been released for both CALVAL and Science phase: v1.0 or v1.0.2. I want to bring the authors attention on the fact that a new improved version of SWOT data (v2.0) is going to be released around December 2024. This new version (v2.0) is of particular interest because it is going to include a MDT correction that will improved SSH (and therefore ADT) estimates of about 5 cm. I believe this correction is of great interest for this study. I would thus recommend to re run the SWOT analysis using the latest version v2.0 (when available) or at the very least to use v1.0.2.

Response: Thank you very much for your valuable suggestion on the data version update. Regarding the issue of data quality correction in the new version (2.0) of SWOT that you mentioned, I had already raised concerns about the nadir data quality of the SWOT mission to the team leader, Dr. Morrow, in April 2024. I pointed out that in the same version of the SWOT product, there were significant and unreasonable deviations between the KaRIn data and the nadir data at similar locations. In response, Morrow indicated that this discrepancy was due to the nadir data using an earlier version of the Mean Dynamic Topography (MDT) (i.e., the 2018 version), which was estimated to have a bias of 5 cm (see the email reply content below in S1). The 5-cm error improvement in the MDT estimation mentioned in the SWOT v2.0 version is precisely aimed at addressing this issue. Since we identified this problem early on, in the actual implementation of this study, we had already excluded all traditional nadir observational data and conducted experiments using only KaRIn data. Therefore, the update of the MDT in version 2.0 will not affect our experiments. Additionally, as of January 9, 2025 (our last check date), the v2.0 data had not yet been released on the official website. Consequently, we proceeded to download the v1.0.2 version to replace the previous v0.3 version data and re-conducted all SWOT-related experiments using the new data. Please review the relative changes illustrated in the figures in the revised manuscript.


Rosemary Morrow UT3 2024-04-08 19:10
发至 zxy777； 抄送 Pujol Marie-isabelle、 Dibarboure Gerald、 J. Tom Farrar
详情

Dear Xiaoya

Thank you for pointing this anomaly out to us. We have been concentrating so much on the new KaRIn processing, that the differences with the nadir have taken second priority

I checked with the processing centres, and this is why ...

1. The MDT used in the KaRIn product is the MDT CNES_CLS_2022
2. The MDT in the nadir product is the MDT CNES_CLS_2018, biased by 5 cm.

The 5 cm bias used in the nadir product was set in 2014, to maintain the continuity in the 30-year time series of ADT measurements for all radar altimetry missions , following a change in the 20-year reference period for the MDT.

So there is this difference in the two MDTs between the 2 products. In the next version of the L3 products, they aim to fix this MDT difference, and only use the more recent product in both the nadir and KaRIn.

We will keep the Science Team informed on updates with the new processing steps, in the meantime you should explain and adjust for this 5 cm nadir bias. And thank you for your helpful return on this subject

sincerely yours

Rosemary Morrow

S1 Email from Morrow

2) Section 2.3: I have several questions about the methodology to compare the performances of 2DVAR and AVISO with SWOT data:

- First the authors, only compare the eddies that are detected by conventional altimetry and SWOT. But I think a real and very interesting point would also be to quantify how much of the eddies observed by SWOT are NOT detected by conventional altimetry and 2DVAR ? And probably to compute a metric showing the better performance of 2DVAR in identifying fine scale features observed by SWOT and not by the conventional product.

Response: Thank you for your nice suggestion about the metric of eddy identification. To quantify the number of eddies observed by SWOT but not captured by the merged map, we have included the total number of identified eddies in the upper-left corner of Figure 3 and simultaneously updated the eddy identification ratio in Table 1. We have also added the following description in the text.

Line 209-214: We also calculated the eddy identification ratio based on the eddy quantity in the merged map compared to that in the SWOT data. The results demonstrate that as the SWOT observation radius increases, the eddy identification ratio of the 2DVAR method rises from 25% to 40%, while the identification ratio of AVISO remains relatively stable at around 11%. This leads to a significant increase in the gap between the two methods, from 2.5 times to 4 times. This contrast highlights the superior performance of the 2DVAR method in detecting eddies using SWOT data, especially in capturing fine-scale to mesoscale features that AVISO may miss.

- I understand how the method can identify eddy center and boundary (L 126-140) with a gridded product such as AVISO or 2DVAR but I do not get how the author can estimate eddy center/boundary using SWOT data considering that they only exhibit data on the swaths and that eddies can be partly outside of the observational bands of SWOT. Please provide more information.

Response: We apologize for not clarifying this part. In fact, the eddy identification method used in the SWOT data is consistent with the method used in the merged map product. However, this method does have certain limitations in identifying eddies within the SWOT swath, specifically those eddies that are only partially included in the SWOT swath and cannot be identified by the closed-contour method. These eddies are indeed not identified and tracked. Nevertheless, the primary focus of this study is to use the SWOT data to validate the capabilities of the merged map, rather than to focus on the number or quality of eddies that SWOT itself can identify. Therefore, we believe that this eddy identification method is sufficient to support the research presented in this paper.

Line 119-120: It is worth noting that, due to SWOT observation data limitations, we are currently unable to identify eddies located at the edges of the swath or outside the swath.

- The authors normalize the position of eddy center and boundary by using SWOT data. This technique smooth the differences between gridded product and SWOT data based eddy identification. Why would one want to do that if the point is to compare the performances of the different gridded product to adequately represent high resolution observation from SWOT ?

Response: Your question is excellent, and I apologize for not explaining the purpose of this operation clearly. In fact, the normalization process applied in this study is used for all eddies identified by SWOT. The purpose is to smooth out the differences among various SWOT eddies to facilitate a highly statistical representation of all SWOT eddies (as shown by the black dashed circles in Figure 2). Meanwhile, we applied the same normalization coefficients derived from the SWOT eddies to the eddies in the two merged maps (2DVAR and AVISO) and performed a linear scaling proportional to the SWOT eddies, preserving the relative differences between the merged maps and SWOT. This normalization and proportional scaling allow us to statistically synthesize the differences of tens of thousands of eddies into a single standard grid composite map, which is an effective way to depict the statistical characteristics of the radius differences between the merged maps and SWOT eddies (i.e., the differences between the colored parts and the dashed circles in Figure 2). We have made corresponding modifications in the original text regarding this issue.

Line 147-151： The operation aims to standardize SWOT eddies of diverse sizes and proportionally scale the eddies in the 2DVAR and AVISO merged maps relative to those in SWOT, thereby retaining the relative differences between the merged maps and SWOT. This normalization and proportional scaling allow the statistical synthesis of differences among thousands of eddies into a single standard grid composite map, effectively characterizing the radius discrepancies between the merged maps and SWOT eddies.

3) Section 3.1: The analysis of Fig.2 needs more explanations as it is not always straightforward to understand what is represented on Fig. 2. For example the colorbar ranges are different in all plots, I don’t understand if the colors represent a number of eddies or the eddy radius ?

Response: Thank you very much for pointing this out. The color bar in Figure 2 represents the eddy count, and a corresponding description has been added to the caption.

Line 230-233: Composite maps of normalized eddy identified from 2DVAR (left column) and AVISO (right column) merged maps, the color on the grid points shows the density of covered eddies, with the higher the density of the grid points, the darker the orange. The dashed circles mark the normalized SWOT eddies with a radius of less than 10 km (a), 10 to 20 km (b), and more than 20 km (c). The total number of eddies detected by each map is on the left up corner.

4) Section 3.2 "Eddy boundaries verification in space and time": The authors show one example of GDP drifter comparison with 2DVAR and AVISO. It is a good illustration however I think the authors should provide more statistics with a systematic comparison of drifters during the science phase to clearly demonstrate the better accuracy between in situ and 2DVAR compared to AVISO.

Response: Thank you very much for your valuable suggestions. This study focuses primarily on the enhanced and more accurate data that SWOT can provide compared to traditional in situ observations for validating the quality of merged maps. Therefore, Figure 5 in Section 3.2 is designed to illustrate the efficiency difference between the latest altimetric techniques and traditional altimetry in examining eddies in merged maps. On the other hand, due to the limited and concentrated distribution of drifter data within the study area, and considering that velocities are derived from sea surface height inversions, which have higher sampling requirements and thus introduce additional errors (Pascual, 2007), we did not consider using statistical data for validation.

5) Section 3.3: These results seem inherently due to the different products resolution, so not really surprising. I think one of the main result of the study, listed also on L282, is mainly due to the fact that SWOT do not capture features > 120 km due to the swaths limitation, as stated by the authors on L 295. So I am not sure this result should appear like a main point of the paper since it is something that is limited by the data.

Response: Thank you for your valuable feedback on the conclusion. If the conclusion you are referring to is: "Eddies identified in the 2DVAR demonstrated superior coherence and agreement with SWOT data, especially for fine-scale eddies, compared to AVISO," then we appreciate the opportunity to clarify further. Indeed, we have already unified the grid resolution of the different data sources to 1/12° prior to eddy identification. Despite this uniform grid resolution, differences in eddy identification persist. This suggests that the source of these differences does not stem from data resolution but rather from the differences in the fusion methods used.

Line 121-122: To avoid the influence of grid resolution, different merged maps were interpolated to a high-resolution grid with the same resolution (1/12°).

Minor comments:

L 33： “a kind of” , I would state “is an estimate of sea surface height (SSH) above geoid.”

Response: Thank you for your correction. The original text has been revised.

Line 33: These processes are primarily revealed through the absolute dynamic topography (ADT), which is an estimate of sea surface height (SSH) above the geoid.

L 37：Conventional altimetry does not really provide “high resolution” mapping since the resolved processes are mesoscale features (75-100 km). I would remove “high resolution” from the sentence and add “…tracking large and mesoscale ocean dynamic signals (Chelton…” .

Response: Thank you for your correction. The original text has been revised.

Line 38: Global satellite altimeters offer systematic ADT measurements and mapping of ocean topography, currently providing the most effective data for detecting and tracking large and mesoscale ocean dynamic signals (Chelton et al., 2007; Mason et al., 2014; Zhang et al., 2023).

L 42： Worth mentioning the interpolation techniques (Pujol et al., 2016).

Response: Thank you for your suggestions on the literature review. We have added a description of the interpolation methods used in the merged maps.

Line 42-45: The main techniques of data assimilation typically include the homogenization and cross-calibration of multi-source altimetry data, continuous calibration of reference orbits, cross-calibration between altimeters, long-wavelength error correction, and error budget modeling. Finally, optimal interpolation is used for gridding to generate daily gridded products and derived products (Pujol et al., 2016).

L 67-69：Please define the period for CALVAL and Science Phase for SWOT mission. I believe not all readers are aware of that (CALVAL: Mar-July 2023; SP: from August/September 2023). It seems to be done on Lines 106-107 but should appear when the terms are first used.

Response: Thank you very much for pointing out the issues. We have moved all the introductions related to SWOT data to the first paragraph of Section 2.1 and have correspondingly adjusted the order of the figures. The following are the modifications related to SWOT.

Line 69-77: 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. The CALVAL phase data were used exclusively in the second part of Section 3.2 to analyse the temporal evolution of eddies. In contrast, the science phase data were the primary datasets for examining the spatial dynamic structures and for performing statistical analyses of eddy characteristics. Although the CALVAL phase sampled a limited sea surface area due to its fixed rapid-sampling orbit, this orbit covered part of the South China Sea (SCS) and facilitated the capture of time-evolving fine-scale eddy structures in the SCS. The nadir observation points, located between two slices of KaRIn observations (Fig. 1(a)), were excluded in both phases due to their high error rates and our focus on the advanced KaRIn technology.

L 75："fine scales" are not defined previously in the text. Please give details (maybe in the introduction?). Are the authors referring to submesoscales ? Or more classically to the transition scale between meso to submesoscales ?

Response: Thank you for raising the issue. We have now defined "fine scales" in the Introduction section.

Line 59-60: Fine-scale ocean processes are characterized by spatial variability of 1 to 100 kilometres and temporal variability of days to months (Lévy et al., 2024).

L 87-88：There are different types of eddy identification methods: physical, geometric, Lagrangian or hybrid based methods. The authors need to provide some references here (among MCWilliams, 1990; Okubo, 1970; Weiss, 1991; Chelton et al., 2011; Sadarjoen and Post, 2000; Mkhinini et al., 2014; Laxenaire et al., 2018 …).

Response: Thank you for your correction. We have improved the literature review of the eddy identification methods, and the references have been added.

Line 111-115: Currently, the main methods for eddy identification based on satellite altimeters include the Okubo-Weiss (OW) parameter from the velocity field method, the curvature center method, the surrounding angle method, the local extreme of sea surface topography method, the local and normalized angular momentum method, and the Lagrangian coherent structure (LCS) method (Chelton et al., 2011; Laxenaire et al., 2018; Mcwilliams, 1990; Mkhinini et al., 2014; Okubo, 1970; Sadarjoen and and, 2000; Weiss, 1991).

L 94: Is it based on Chelton et al., 2011 method ?

Response: Yes, the eddy identification method used in this study is based on the method described in the article by Ni, which in turn is derived from the method proposed by Chelton et al. (2011). Therefore, we have updated the references to cite the primary source by Chelton et al. (2011) .

Line 116-118: 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 (Chelton et al., 2011).

L 95-97: I guess the steps and amplitude in mm and cm are referring to distances on the maps. Can you please give the actual distance in kilometer to make a connection with data resolution ?

Response: I apologize for causing confusion with my wording. Actually, the step in mm refers to the elevation difference (1 mm) between contour lines set for retrieving the contour lines in the ADT maps, not the real distance on the map. The amplitude in cm refers to the difference in ADT between the eddy center and the boundary contour line in the possible eddies that had been identified in the previous steps. I will revise it to a more reader-friendly expression.

Line 122-127: The outermost circle of the closed contours with 1mm step in ADT difference containing the unique centre was recognized as the ‘quasi-eddy edge’, and only a minimum of three points were retained. Each quasi-eddy edge was then contracted inward until it corresponded to a single centre. Lastly, the geometric centre of the innermost circle of the closed contours was identified as the eddy centre. This process allowed the determination of the eddy boundary, type, radius, and amplitude. All possible eddies with an difference in ADT between the eddy center and the boundary contour line of less than ±2 cm were excluded from further analysis.

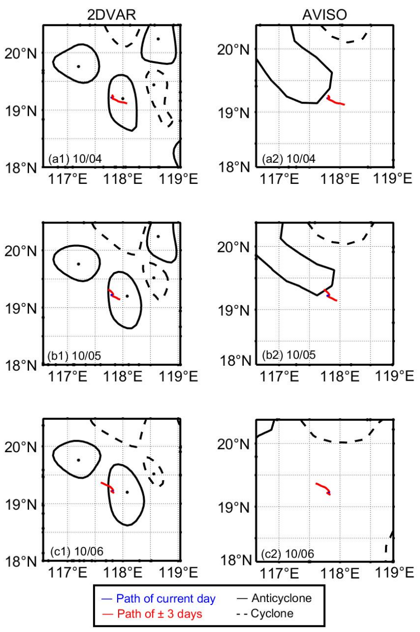
L 109-110: “.. and lack of interest in traditional technology”. I would remove this comment since nadir data are still being used and methodologies developed to assess fine scale improvements near the coasts (Birol et al., 2021).

Response: I apologize for any confusion caused. The original wording was indeed unclear. What I meant to convey is that, due to the instability of the Nadir-type data in the SWOT dataset and its irrelevance to the research interests of this study, these data were excluded from our analysis prior to conducting the research.

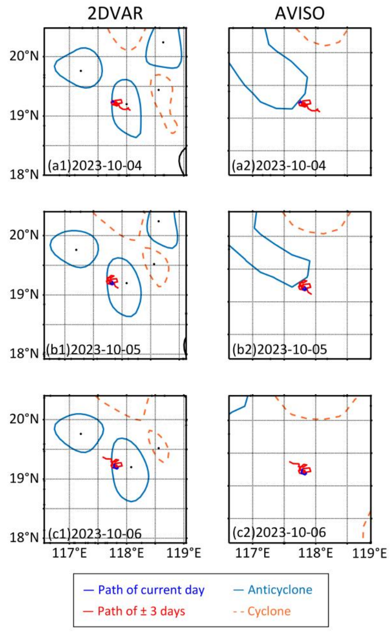
Line 75-77: The nadir observation points, located between two slices of KaRIn observations (Fig. 1(a)), were excluded in both phases due to their high error rates and our focus on the advanced KaRIn technology.

L 150: Did the authors performed any kind of treatment on the drifter trajectories (GDP)? For example, are the inertial oscillations removed from the trajectories before comparison ?

Response: Thank you for raising the technical issue. Following your suggestion, I applied a low-pass filter with a 3-day time window to eliminate high-frequency inertial oscillation signals. Comparing the plot after removal (S2) with the plot before removal (S3), the dynamic effect of the drifter orbiting within the eddy is significantly reduced. Therefore, I believe that not applying any additional processing better illustrates the relationship between the drifter rotating along the eddy boundary.



S2 GDP paths after filtering.



S3 GDP paths before filtering.

L 158: Depending on the authors definition of submesoscale, mesoscale and fine-scale (see previous comment) I would rather classify as “ submsesoscale (Fig. 2a), fine-scale (Fig. 2b) and mesoscale (Fig. 2c)” .

Response: Thank you very much for your suggestion. We have revised the classification as per your advice, changing the middle category to submesoscale. Since fine-scale encompasses the smallest eddy identification scales (1-100 km), we have categorized the first class as fine-scale.

Line 184-186: All identified eddies were categorized into three groups based on the radii of SWOT eddies: those with radii below 10 km, between 10 km and 20 km, and exceeding 20 km were classified as fine-scale (Fig. 2a), submesoscale (Fig. 2b), and mesoscale (Fig. 2c) eddies, respectively.

L 166-169: I do not understand the reasoning here, please detail and rephrase.

Response: Thank you for your question. I apologize for the lack of clarity in my explanation. The reasoning in this paragraph is based on the comparison between the eddy boundaries in different subplots and the normalized SWOT eddy boundaries (marked by dashed circles). I will revise the sentence to make it clearer and easier to understand.

Line 194-201: Since the same colorbar is applied to the eddy ensembles of the two merged maps for the same scale range, the distribution and concentration of eddies can be judged by the intensity of the colors. It is evident that the area of the colored region outside the normalized SWOT eddies (marked by black dashed circles) in the 2DVAR merged map is smaller especially in Fig. 2b and 2c. Meanwhile, despite the number of eddies identified by 2DVAR being 2 to 3 times that of AVISO, the color outside the normalized eddy circles remains a light shade of purple (means no more than 10 eddies). These results suggest that the concentration of 2DVAR eddies within the normalized SWOT eddies is higher, and the eddy boundaries maintain a higher degree of consistency.

L 175: I do not think that AVISO can catch eddies down to 15 km. Conventional altimetry typically see mesoscale features with diameter of about (75-100 km).

Response: Thank you for your insightful comments. We are very happy to further discuss with you the issue of whether traditional altimetry methods can identify eddies smaller than 75 km. Although the data providers do not explicitly state that they can, I found a study that identified eddies as small as 19 km using data with a 1/8° grid resolution (S4), and half of the identified eddies had radii smaller than 30 km (Wang, 2021) . Therefore, I believe it is possible for us to identify smaller eddies as well.

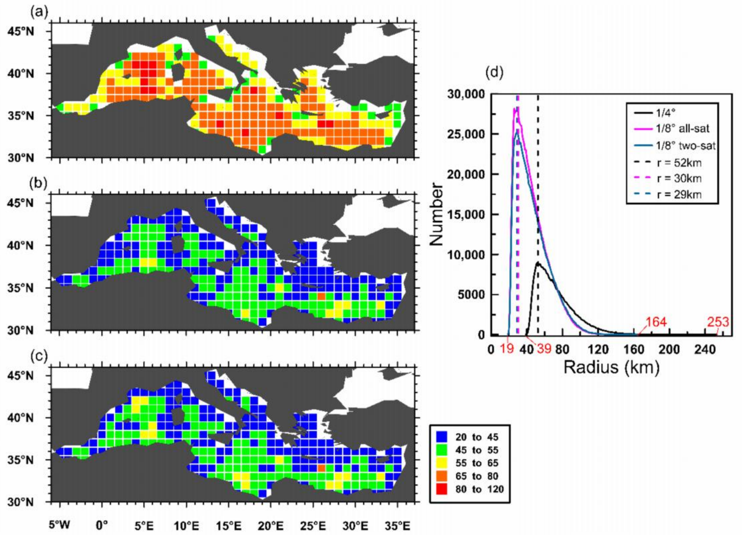


Figure 4. Eddy radius distribution maps and radius histogram of the Mediterranean Sea: (**a**) 1/4°; (**b**) 1/8° all-sat; (**c**) 1/8° two-sat. The colored squares represent the range of eddy radii, as shown in the legend. The histogram (**d**) represents the relationship between eddy radii and number in the different datasets, where the black line represents the eddies identified using the 1/4° data, and the magenta (desert blue) line represents eddies identified using the 1/8° all-sat (two-sat) data.

S4 Eddy radius distribution and radius histogram. (Wang, 2021)

L 188-189: I think the maximum amplitude of SWOT eddies might change when the 5 cm bias will be corrected from MDT in the new SWOT data version 2.0… Worth checking out when the new data are available!

Response: Thank you for your valuable suggestions. Since this study did not utilize the Nadir data based on the older version of MDT, which is known to have significant errors, the new version is unlikely to have a substantial impact on the data (please refer to the response to the first question for details).

L 200: "The coloured slices are .." ?

Response: Thank you for pointing out the issue. What we intended to convey was "colored points in the figure." We have revised the sentence to express it more clearly and accurately.

Line 238-239: The coloured points in the figure showed the Level-3 ADT observations directly from the KaRIn measurement on SWOT satellite.

Fig. 3: SWOT data seems to be interpolated between swaths. Please provide information. Please specify in the caption that solid and dashed lines represent the contours of eddies as detected by 2DVAR and AVISO.

Response: Thank you for your questions and suggestions. The SWOT data have been down-sampled through a 1/12° grid average to align with the merged products and to fill the gap between the two KaRIn instrument measurement swaths caused by the removal of Nadir data. The caption of Figure 3 has been corrected to indicate that the lines represent the eddy contours detected by 2DVAR and AVISO, while the colors indicate the SWOT height data.

Line 249-250: Figure 3. 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.

L 217: Do the authors have any clue why the contour of the 16.2N anticyclone is very different on the 04/07 while the contours are pretty consistent in the other days ?

Response: Thank you for raising this question; it is highly relevant. Both the 2DVAR and AVISO products exhibit inconsistent identification of the anticyclone at 16.2°N, with fluctuations in size. This suggests that the merged maps derived from both methods inadequately reconstruct sea surface height at this location during the specified time period, leading to errors such as misrepresenting a small eddy as a larger one. Additionally, in the underlying SWOT data, although it fails to identify an eddy that is only partially within the swath, the color map indicates a noticeable expansion of the orange area on 04/07. This implies that the anticyclone at this location should indeed be larger. If the SWOT data coverage were more extensive, I believe we would observe a similar sudden enlargement of the eddy at 16.2°N on 04/07, akin to what is seen in the 2DVAR product.

Line 260-265: To be noticed, both the 2DVAR and AVISO products exhibit inconsistent identification of the anticyclone at 16.2° N, with fluctuations in size. This suggests that the merged maps derived from both methods inadequately reconstruct sea surface height at this location during the specified time period, leading to errors such as misrepresenting a small eddy as a larger one. Additionally, in the underlying SWOT data, although it fails to identify an eddy that is only partially within the swath, the color map indicates a noticeable expansion of the orange area on 04/07. This implies that the anticyclone at this location should indeed be larger.

L 218: I would change "high agreement" by "good agreement".

Response: Thank you for your correction. The text has been revised.

Line 258-259: These anticyclones were in good agreement with the colour boundaries in the bottom SWOT data.

L 224: It is not really surprising that AVISO does not identify 50 km eddies.

Response: Thank you for raising the question. Given that previous studies have demonstrated the capability of traditional AVISO products to identify eddies smaller than 20 km (Wang, 2021), the inability to detect eddies of 50 km remains a noteworthy issue. Moreover, considering that both 2DVAR and AVISO are traditional altimetry data merged fields based on the Optimal Interpolation (OI) principle, the fact that 2DVAR can identify eddies of 50 km while AVISO cannot is a significant finding. This may suggest inherent differences between different merged field products.

L 237: The section is not correctly numbered, it should be Section 3.3.

Response: Thank you for your correction. The numbering in Section 3.3 has been revised.

L 250: add space between "eddies" and "identified".

Response: Thank you for pointing out the typographical error. The correction has been made.

Line 295-297: However, there was a significant discrepancy in the number of eddies identified by the two merged maps: 2DVAR identified approximately four times as many eddies as AVISO, both in terms of the total number of eddies from September to

November and the daily number of eddies (Fig. 6c).

Fig. 6-7: Please provide the period range for the analysis during the Science phase (also the number of SWOT passes used ?)

Response: I apologize for not providing this information. The time range for the science phase is from September 6, 2023, to November 21, 2023, and the pass numbers are 003-006.

Line 284-288: Figure 6. Eddies and tracks identified during the SWOT science phase (cycle number from 3 to 6, time period from 2023/09/06 to 11/21) in (a) 2DVAR and (b) AVISO merged maps. The red (yellow) and blue (green) lines represent the anticyclone and cyclone tracks in the 2DVAR (AVISO) merged maps, respectively. The black circles and crosses indicate the start and end positions of the eddies, respectively. (c) The number of eddies over time. The red (yellow) and blue (green) lines represent the daily count of anticyclones and cyclones, respectively, as identified in the 2DVAR (AVISO) merged maps.

Line 300-303: Figure 7. Distributions of eddy radius (top) and amplitude (bottom) for SWOT (left column), 2DVAR (middle column), and AVISO (right column) from 2023/09/06 to 11/21 are presented. The colour intensity is proportional to the radius, with darker colours indicating larger radii. Similarly, the colour intensity is proportional to the amplitude, with darker red (blue) indicating larger positive (negative) amplitudes.