Reply to Comments

Table of Contents

Reviewer 1

1. Comment 1 1
2. Comment 2 2
3. Comment 3 4
4. Comment 4 5
5. Comment 5 5
6. Comment 6 5
7. Comment 7 5
8. Comment 8 6
9. Comment 9 6
10. Comment 10 6
11. Comment 11 6
12. Comment 12 7
13. Comment 13 7
14. Comment 14 7
15. Comment 15 7
16. Comment 16 7
17. Comment 17 9
18. Comment 18 9
19. Comment 19 9
20. Comment 20 9
21. Comment 21 10
22. Comment 22 11
23. Comment 23 11
24. Comment 24 12

Reviewer

The article employs wavenumber spectral analysis to conduct experiments and introduces a novel method for global data statistics. It compares data derived from four distinct satellite types, thereby highlighting the advantages of the SWOT satellites. Additionally, the authors analyze global ocean-scale changes by defining a new parameter and utilizing SWOT satellite data. While the proposed methodology and the new parameter are intriguing, they require further clarification and validation. The English writing should be further polished. I recommend that this manuscript be considered for publication, contingent upon addressing the following modifications.

Dear reviewer:

The author's team would like to thank you for reviewing the paper and providing useful feedback and suggestions. We have carefully read and responded to your comments. Your comments are in black font, our explanatory response is in blue font, and the corresponding revision in the manuscript is in red font.

1. Comment 1

The paper does not sufficiently demonstrate the significant advantages of the authors' improvements to the algorithm compared to existing methods. To better emphasize the necessity and effectiveness of the proposed enhancements, it is recommended that a comparison with the traditional averaging method be included.

We have noted the shortcomings you pointed out in demonstrating the advantages of the algorithm improvement compared with the existing methods. To better emphasise the necessity and effectiveness of the proposed improvement, we will add a comparison experiment with the traditional averaging method in the revised draft to analyse in detail the difference in detection performance between the two and further verify the advantages of the improved process.

The manuscript was revised as follows.

To compare the difference between the new method of calculating the slope and the previous method, we used the HY2B satellite and calculated the global SSH spectrograms for both methods (Figure 2). We can observe from Figures 2a,2c. When counting the global distribution maps, distance-weighted averaging can reflect the spatial correlation of geographic phenomena more accurately by assigning distance-based weights to the observation points. This method not only reduces the bias caused by local outliers or uneven data distribution, but also enhances the regional representativeness of the distribution map. Figure 2b,2d shows the zoomed-in local area, and it can be clearly observed that the distance-weighted method can more accurately bring out the detailed part of the SSH slope map. In contrast, the traditional equal-weighted averaging method assigns the same weight to all observations, ignoring the effect of distance on the statistical results. This approach tends to lead to excessive smoothing of the signal, especially when analysing subtle changes such as slope, and may mask important local features, thus reducing the accuracy and explanatory power of the distribution plot. Therefore, the use of the distance between trajectories to adjust the weights improves the accuracy and reasonableness of the global distribution statistics and provides a more reliable basis for subsequent analyses.

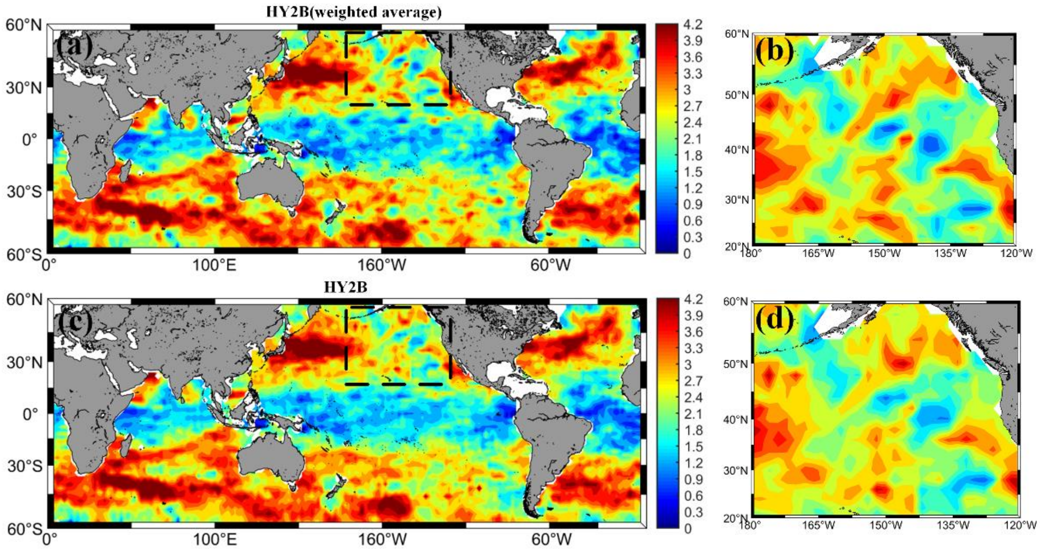

Figure. 2 Distribution plots of weighted versus equal weighted averaging (a. Results of weighted averaging using distances between satellite tracks, b. Plot of results averaged using the same weights, c and d are areas enlarged by the black boxes in a and b, respectively)

2. Comment 2

The averaging method presented in Appendix A employs distance-weighted averaging across a range of orbital data. However, it is crucial to assess whether this method is scientifically sound. I request a detailed explanation supported by appropriate examples and a discussion of the statistical weight distribution involved in this approach.

Assessing the scientific validity and reasonableness of the averaging method is critical to the credibility of the study. The averaging method presented in Appendix A is based on calculating the distances between a series of trajectory data and averaging them by weighting the distances. In order to explain the method more clearly, we will describe in detail how the distances were determined and illustrate the principles of weight distribution, while further exploring the distribution of statistical weights.

Further explanation of the method: The core idea of the distance-weighted averaging method is to calculate the distance between the target grid points and the trajectory so as to more accurately reflect the spatial distribution of the data. Specifically, data closer to the target point will be given a higher weight, while data further away from the target point will be given a lower weight. Since the power spectral density of each grid point is calculated based on the average power spectral density of all trajectories within a large 10 ° × 10 °area, the grid points are located at a distance of 5 °from the boundary, as shown in Fig. 1#. We classify the trajectories based on the minimum distance from the trajectory to the grid point.

In addition, considering that we are counting 2 ° × 2 ° resolution data for the global ocean between 60 °N~60 °S, when the distance from a trajectory to a grid point is less than or equal to 1 °, we set it to a distance of 1 °by default, i.e., we assign the same weight to all points within a circle with a radius of less than 1 °(the green part of Fig. 1#). With each 1 °increase in circle radius, the corresponding hollow circle region is also assigned the same weight. The black region of the outermost circle has its distance set to 5 °because it is the furthest away and has a smaller weight share.

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (1)$$

where w_i is $1/D_i$, W_i is the weight of each track involved in the calculation of the PSD. D_i is the distance (°).

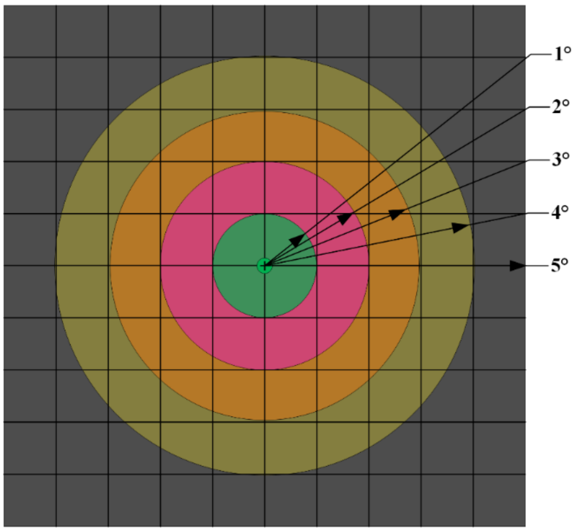

图 1#

2. Discussion of statistical weight distribution:

In order to better demonstrate the scientific validity as well as the necessity of the method, we have counted the distribution of trajectory distances of the four satellites involved in the calculation of the global ice-free regions, respectively. Following the way of defining the distances above, it can be seen from Fig. 2# and Fig. 3#. There are roughly the same number and percentage of satellite trajectories at 10 ° × 10 ° participating in the calculation with distances from 1 °-4 ° to the grid points, and a smaller number and percentage with distances of 5 °. This is because the length of the along-track data at the boundary may be smaller than the length of the data used to calculate the power spectral density, resulting in a lower percentage. It can also be demonstrated in Figure. 2# and Figure. 3# that the distance distribution of the trajectories involved in the averaging calculation is large, so distance-weighted averaging is necessary. In practical applications, we believe that the spatial differences between data points of different trajectories can be better handled by such a weighting method, thus improving the accuracy of data analysis.

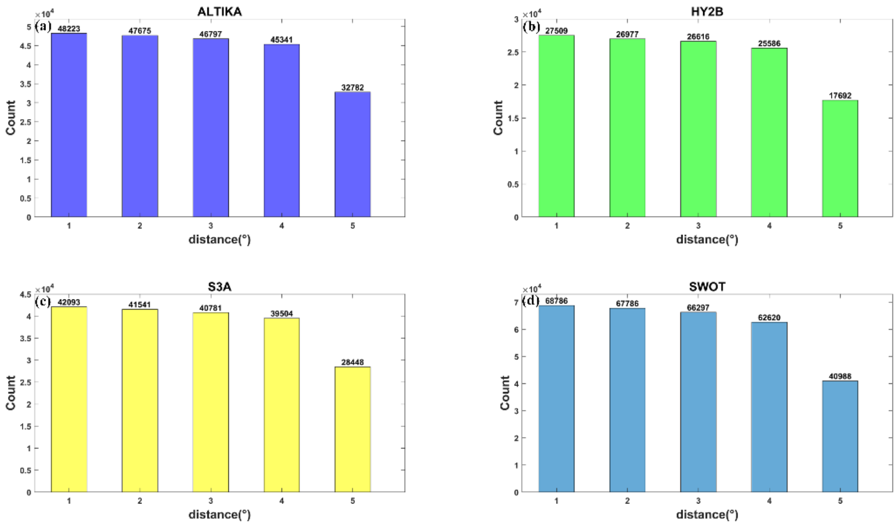

Figure 2# Distribution of numbers at different distances

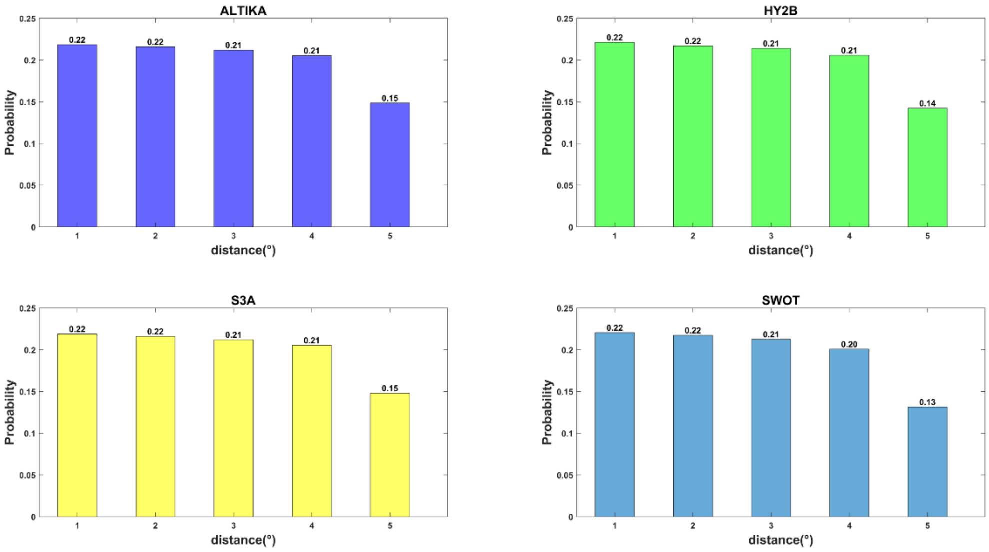

Figure 3# Probability distribution at different distances

3. Comment 3

Footprints of SWOT, HY2B, Sara and S3A are different. The resolutions of SSHs for these 4 missions are also different. How about the effects of different resolutions on the results?

Different sampling resolutions have a significant effect on the calculated power spectral density. Specifically, the following are the potential effects of different resolutions on the results:

Satellites with higher spatial resolution (e.g. SWOT) are able to capture more details, especially at smaller spatial scales, which results in the power spectral densities of the higher frequency part remaining in line with the predicted trend of Boas et al (2022) (Figure 4#). Satellites with lower spatial resolution (e.g., HY2B), on the other hand, miss some of the smaller-scale variations, and thus the portion of their power spectral densities that follows the same trend as in Fig. 4# is mainly concentrated in the lower-frequency region. The high-frequency part is mainly signals generated by noise, so the PSD is flatter. To summarise, high-resolution satellites provide finer spatial data and are able to capture more details, whereas low-resolution satellites may only capture larger-scale variations, resulting in significant differences between the two mainly in the high-frequency part. The calculated PSD slope plots for satellites with different resolutions are roughly the same, except that the frequency intervals in which the slopes are located are in different ranges. The noise level of each satellite is also different, so the final results of the calculated 1D mesoscale resolution capability are also different.

Reference:

Boas A B V, Lenain L, Cornuelle B D, et al., 2022a. A Broadband View of the Sea Surface Height Wavenumber Spectrum[J]. GEOPHYSICAL RESEARCH LETTERS, 49(4): e2021GL096699.

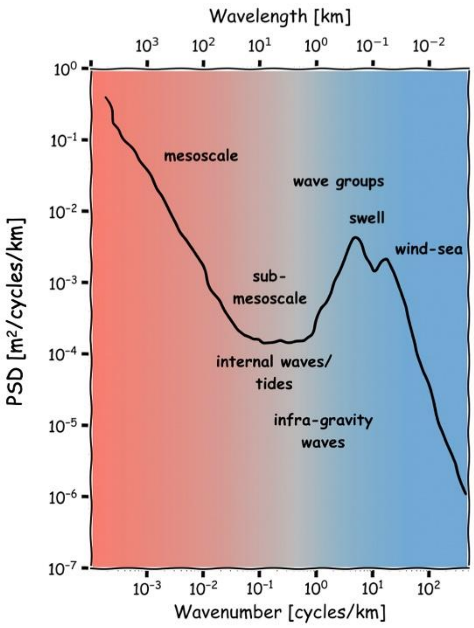

Figure 4# Schematic SSH wavenumber spectra. (from Villas Boas et al.(2022), Figure 1)

4. Comment 4

line 55: Xu Y et al. -> Xu et al.

Thanks to the reviewer for pointing this out. We have amended 'Xu Y et al.' in line 55 to 'Xu et al.' to comply with formatting requirements.'

5. Comment 5

line 68: Vergara O et al. -> Vergara et al.

We have amended 'Vergara O et al.' in line 68 to 'Vergara et al.' to comply with formatting requirements.

6. Comment 6

section 2.1: Time spans for different satellite altimetry missions are different.

Thank you for your feedback. To avoid misunderstanding, we would like to clarify the period in the paper. The period of the altimetry missions is the same for the different satellites, which may have been misunderstood due to a lack of clarity in our previous explanation. In the experiment, data from all satellites come from 1 October 2023 to 1 November 2023, so the data from the different satellites we use are all partial cycles within that period. We have revised the manuscript accordingly to ensure a more accurate representation of the paper.

The manuscript was revised as follows.

Line109: In this paper, we use SGDR data for HY2B, with a time horizon of October 2023.

Line119: Finally, SARAL/AltiKa data with a time span of October 2023 was selected.

Line127: The data for S3A in October 2023 was selected.

7. Comment 7

line 103: What is an uncorrected data product?

Content in the paper is derived from the HY2B datasheet at https://osdds.nsoas.org.cn/home. HY-2B satellite radar altimeter secondary products include Operational Geophysical data record (OGDR), Interim geophysical data records (IGDR), Sensor geophysical data records (SGDR), and geophysical data records (GDR). Sensor geophysical data records (SGDR), and geophysical data records (GDR). IGDRs are uncorrected data products obtained using MOE orbiting data and waveform reconstruction. The data mainly include effective wave heights, surface wind speeds, sea surface heights, and the relevant correction parameters for the calculation of sea surface heights. IGDR data products are produced and distributed within 55 hours after the reception of the satellite data. GDR is a fully corrected data product obtained by using POE orbiting data and waveform reconstruction methods. The data mainly include effective wave height, sea surface wind speed, sea surface height, and related correction parameters for calculating sea surface height, and the GDR data products are produced within 30 days after satellite data acquisition.

IGDR takes the raw observations and does some preliminary processing, but does not yet perform all the fine corrections, such as precision orbit corrections, atmospheric delay corrections, waveform fitting corrections, etc. These corrections are essential for ensuring the accuracy of the data. These corrections are essential to ensure the accuracy and reliability of the data, so IGDR usually needs to be further processed into a fully corrected data product, such as GDR, before it can be used for scientific research and applications. So IGDR is called uncorrected data.

8. Comment 8

line 104: What is an uncorrected data product?

I am very sorry that there was an error in the presentation of this sentence and I was not able to remove the sentence in time due to my carelessness. See comment 7 for a specific explanation.

9. Comment 9

line 105: What is an uncorrected data product?

I am very sorry that there was an error in the presentation of this sentence and I was not able to remove the sentence in time due to my carelessness. See comment 7 for a specific explanation.

10. Comment 10

line 106: What is a full corrected data product?

See comment 7 for a specific explanation.

11. Comment 11

line 113: What about the frequency of SSHs used? 40Hz or 20Hz?

Apologies for the unclear interpretation of the original article. Redundant statements have been deleted. The description is only intended to illustrate the characteristics of the SARAL/AltiKa satellite itself, while the sampling rate of 1hz has been chosen for the conventional one-dimensional satellites in this paper. The sampling rates of the selected satellites are described in the last paragraph of section 2.1.

The along-orbit SSH (HY2B, SARAL/AltiKa, S3A) observations were kept at their original 1hz observation positions at intervals of about 7km and corrected for all instrumental, environmental, and geophysical corrections.

The manuscript was revised as follows.

Using Ka-band allows for reduced size, lower ionospheric attenuation delays, and higher measurement accuracy than conventional Ku-band altimeters (Quartly et al., 2015).

12. Comment 12

line 128: The sentence may repeat.

The author has removed redundancies and re-combined sentences to improve clarity of expression.

13. Comment 13

line 131: What is the nadir-stellar point?

The paper refers to a 20-km gap centered on the satellite ground track. Words that were not clearly expressed have been reworked.

The manuscript was revised as follows.

SWOT adopts Ka-band radar interferometry (KaRIn) for measurements over a narrow strip of 120 kilometers (a 20-kilometer gap along the track and the centre of this area is sampled by conventional altimeters at a low resolution).

14. Comment 14

line 140: along-orbit SSH -> along-track SSH.

We have changed 'long-orbit SSH' to 'long-track SSH' on line 140.

15. Comment 15

line 154: What is the SSH anomalous wavenumber power spectral density?

The original article was incorrectly worded and it should have been an SSH anomaly. All power spectral densities calculated later in this paper were calculated by SSH anomaly, also known as SSHA.

The manuscript was revised as follows.

We calculated the SSH anomaly wavenumber power spectral density (PSD) for each mission globally in a 10 °x10 °box.

16. Comment 16

Line 165: What are these three parameters in detail?

Parameter 1 (SSH error level)：

As stated by Dufau et al. (2016), the 1 Hz SSH error level is estimated from a horizontal fit to the spectral flat noise level present in the PSD plot for wavelengths below 23.5 km (Figure 5#). The energy level at those wavelengths in the 1Hz SSH PSD corresponds to the sum of the instrumental white noise and a ''hump-shaped spectral artifact''. This artifact is more intense in certain regions because it originates in inhomogeneities in the radar backscatter coefficient within the altimeter footprint leading to an erroneous estimation of the SSH and creating a larger spectral noise. Therefore, the first parameter value of is the error level of the satellite.

Parameter 2(the SSH spectral slope in the mesoscale bands)：

Dufau et al. (2016) calculated the PSD slopes by a least squares regression to the spectra for a fixed wavelength band between 95 and 280 km. Diverse methods for calculating the Power Spectral Density (PSD) can result in minor discrepancies in the slope range (Vergara et al., 2019) Additionally, data sampled at varying frequencies may also engender subtle variances in the estimated PSD slope range. Hence, for the first three conventional missions, we chose wavelengths in the range of 70-250 km and fitted the slope of the PSD by least squares. For the SWOT mission, its cross-correction process filters out some noise, resulting in a spectral profile that continually drops, as shown in Figure 6#. Due to the presence of many sub-mesoscale phenomena at 15-40km, such as internal waves and tides, etc.(Boas et al., 2022). Therefore, a wavelength of 40-125 km was selected for calculating the PSD slope for the SWOT mission.

Parameter 3(one-dimensional mesoscale resolution capability)：

The crossing point where the error level and spectral slope intersect, sets the wavelength at which the PSD of the smallest-scale signal is equal to the error level. we call the one-dimensional mesoscale resolution capability.

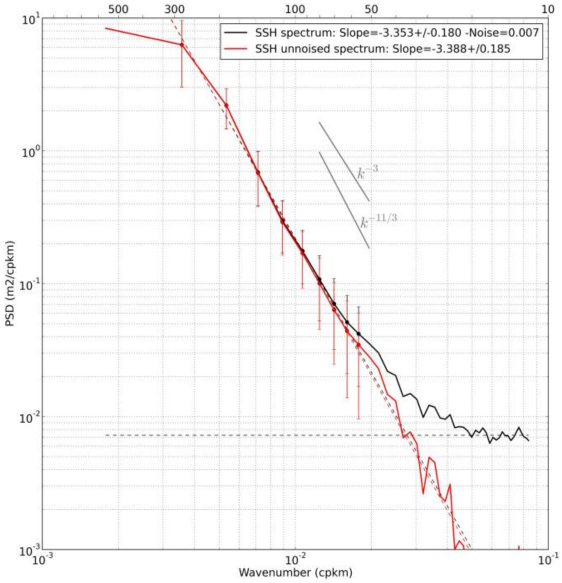

Figure 5# Mean SSH PSD for 7 months of Jason-2 data in a 10 ° × 10 ° box located in the Gulf Stream Current system centered in [294 °E, 39 °N]. The red curve is the unbiased spectrum with the constant noise level removed (horizontal dashed line) from the original spectrum (black curve). The vertical lines are 90% confidence intervals. (from Dufau et al. (2016), Figure A1)

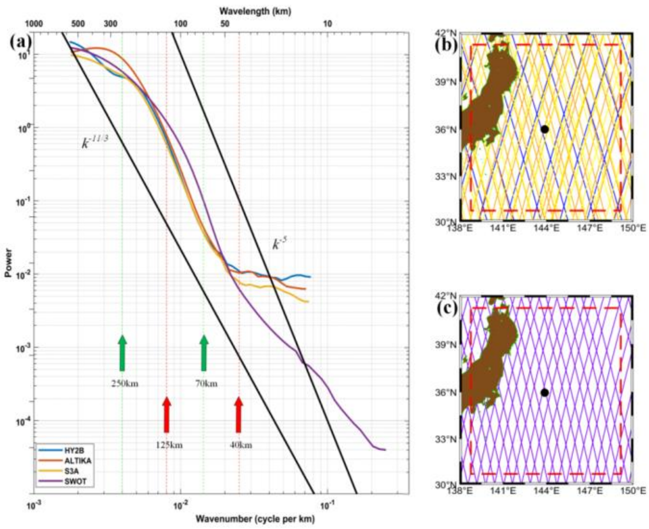

Figure 6# Calculate the spectral range of the slope

Reference:

Dufau C, Orsztynowicz M, Dibarboure G, et al., 2016. Mesoscale resolution capability of altimetry: Present and future[J]. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS, 121(7): 4910-4927.

Vergara O, Morrow R, Pujol I, et al., 2019. Revised Global Wave Number Spectra From Recent Altimeter Observations[J]. JOURNAL OF GEOPHYSICAL RESEARCH-OCEANS, 124(6):

3523-3537.
Boas A B V, Lenain L, Cornuelle B D, et al., 2022a. A Broadband View of the Sea Surface Height Wavenumber Spectrum[J]. GEOPHYSICAL RESEARCH LETTERS, 49(4): e2021GL096699.

17. Comment 17

fig. 2: How to define and determine the slope? This is not global.

Q1: How to define and determine the slope?

In this paper, slope specifically refers to the slope of the power spectral density (PSD) of the along-track data in the mesoscale range. This is shown in Figure 4#. In the mesoscale to sub-mesoscale range of wavenumber, the slope of the power spectral density curve usually behaves as a constant. In order to accurately determine this slope, a least-squares fit based on the relationship between wavenumber and power spectral density was used to obtain a straight line that best fits the data. The coefficient of the primary term of this straight line is the slope sought. It is important to note that the two variables involved in the slope calculation represent the logarithmic values of the wavenumber and the power spectral density (i.e., logarithms with a base of 10), not the actual wavenumber values.

Q2: This is not global.

To avoid further confusion, we have reworked the presentation and made it clear that it is region-specific data, not global results.

The manuscript was revised as follows.

Accordingly, this paper presents an updated analysis of the global SSH spectral slope between 60 °N and 60 °S, using data from various altimetry missions.

18. Comment 18

fig. 3: This is not global.

To avoid further confusion, we have reworked the presentation and made it clear that it is region-specific data, not global results.

The manuscript was revised as follows.

Figure. 4 Noise levels of different satellites ((a) HY2B, (b) SARAL/ALTIKA, (c) S3A, (d) SWOT)

19. Comment 19

fig. 4: This is not global.

To avoid further confusion, we have reworked the presentation and made it clear that it is region-specific data, not global results.

The manuscript was revised as follows.

Figure. 5 Distribution of eddy kinetic energy calculated by MDT2022

20. Comment 20

fig. 5: This is not global. In line 275, the colorbar units in Figure 5c are absent. Please ensure that the units are indicated for clarity and proper interpretation of the data.

We have made the following changes to the issues you raised:

fig. 5: This is not global. The beginning of the paper is already redefining ‘global’. We have amended the relevant statement in the manuscript to ensure greater clarity on this point.

Units for Figure 5c: We have added missing units to the colorbar in Figure 5c to ensure clarity and correct interpretation of the data.

The manuscript was revised as follows.

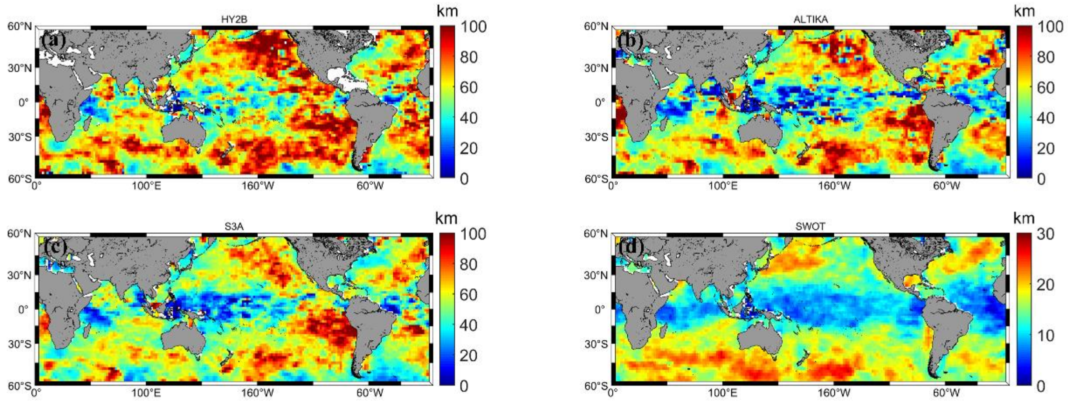

Figure. 6 Resolved wavelengths for different satellites (a. HY2B, b. SARAL/ALTIKA, c. S3A, d. SWOT)

21. Comment 21

Section 4 introduces a new parameter; however, the experiments are conducted exclusively using data from the SWOT 21-day repeat cycles. Is it feasible to conduct experiments using data from the SWOT one-day repetition cycles for specific locations? This approach would more effectively illustrate SWOT's contributions to understanding ocean sub-mesoscale dynamics.

We are grateful to the reviewers for their in-depth consideration of our research methodology. Regarding the feasibility of using site-specific SWOT one-day repeat cycle data for experiments, we believe this is a very valuable suggestion. In the current study, we used SWOT 21-day repetitive cycle data mainly because it can cover a wider spatial range, which helps to fully assess ocean dynamics scale variability. However, experiments using SWOT one-day repeat cycle data do help to provide insights into analysing ocean dynamics scale variability over short periods of time, in particular the contribution to sub-mesoscale dynamics. We will add to the original manuscript a discussion of the use of SWOT one-day repetition cycles. and explore how it can further improve the precision of our study and our understanding of sub-mesoscale dynamics.

The manuscript was revised as follows.

To better illustrate the role of SWOT one-day repetitive cycle data, we utilised two repetitive cycle trajectory data, SWOT_L3_LR_SSH_Expert_478_021_20230402T142629_20230402T151735_v1.0.nc and SWOT_L3_LR_SSH_ Expert_479_021_20230403T141706_20230403T150812_v1.0.nc. During the analysis, we divided the SWOT data into two strips along the track direction for the calculation. Of the multiple along-track data within each strip, we selected 100 data points as the data length for calculating the reciprocal power spectrum. The calculation results for each strip were obtained by averaging the data from multiple along-track directions. As shown in Figure 8, the reciprocal power spectra computed using the same pass data on these two days reveal the scale differences in the ocean dynamics variations at different locations. Figures 8b, 8c and 8d, 8e show the magnified images of sea surface height anomalies at the same locations on 2 April 2023 and 3 April 2023 for regions 1 and 2 in Figure 8a, respectively. As can be seen from Figure 8a, region 2 experienced a scale change of about 30-35 km wavelength in just two days, while region 1 had a smaller scale change of about 20-25 km. This suggests that there are significant differences in the scale of ocean dynamics in different regions, even within the same time period. In addition, within the same region, the variability varies between strips, mainly because different regions are affected by different sub-mesoscale phenomena. Sub-mesoscale dynamics variability in the ocean is constantly occurring, which leads to differences between the left and right SWOT strips. However, this experiment only considered the direction along the satellite track and analysed the scale variation of ocean dynamics in the one-dimensional direction along the track. At the same time, the averaging of data from multiple along-track directions may diminish the significance of ocean dynamics scale variations within a local region. The aim is to provide a feasible framework for subsequent related studies and to lay the foundation for more in-depth ocean dynamics studies. Subsequent work will continue to be devoted to the study of ocean dynamics scale variability in two dimensions using SWOT.

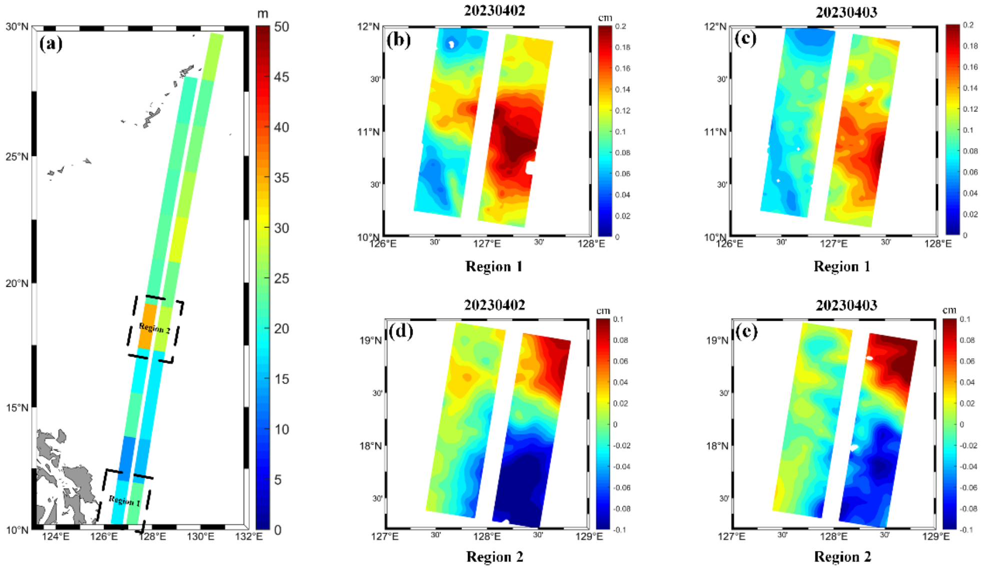

Figure. 8 Ocean dynamics scale changes calculated using SWOT one-day repeat cycle data

22. Comment 22

How to show the dynamic mechanism?

By ‘dynamic mechanism’ we mean the scale of ocean dynamics that occurs in a given region over a given time frame. By analysing the reciprocal power spectra of two data cycles, we aim to assess the correlation between the data and infer the ocean dynamics characteristics of the region. A high correlation between the data of the two cycles indicates that the scale of the ocean-dynamic phenomena is small, while a poor correlation may imply that ocean-dynamic phenomena are occurring at a larger scale in the region. By setting a correlation threshold of 0.5, we were able to determine that the region would have at least that wavelength scale of dynamical changes. Based on this idea, we propose the parameter ‘ocean dynamics scale variability’, which is used to describe the minimum scale of ocean dynamics variability that occurs within a certain period worldwide between 60 °N~60 °S. We hope that this interpretation can clarify the meaning of the term ‘ocean dynamics scale variability’.

It is hoped that this explanation will clarify the definition and application of ‘dynamic mechanism’ in this study.

23. Comment 23

fig.6: This is not global.

To avoid further confusion, we have reworked the presentation and made it clear that it is region-specific data, not global results.

The manuscript was revised as follows.

Figure. 7 Ocean mesoscale and sub-mesoscale scale changes over four seasons

24. Comment 24

The reference cited at the end of line 72 is incorrect, and the reference formatting at the end of line 55 is inconsistent. Please review the reference formatting throughout the manuscript to ensure uniformity.

Thank you to the reviewers for their careful review of the reference format. We have made the following changes based on your suggestions:

References in line 72: we have verified and corrected the references cited at the end of line 72 to ensure that they are accurate.

Line 55 reference formatting: we have standardised the formatting of the reference at the end of line 55 to make it consistent with the other references.

We have thoroughly checked and standardised the formatting of all references in the manuscript to ensure consistent formatting.