Responses to reviewer 2#'s comments point by point

MS No.: essd-2025-384

Title: A Black Hole Eddy Dataset of North Pacific Ocean Based on Satellite Altimetry

Author(s): Fenglin Tian et al.

Dear Reviewer,

We highly appreciate the detailed and valuable comments of the referee on our manuscript entitled "A Black Hole Eddy Dataset of North Pacific Ocean Based on Satellite Altimetry (ID: essd-2025-384)". These comments are all valuable and helpful for revising and improving our paper, as well as providing important guidance for our research. In the past few days, we have referred to the comments and improved the paper.

As follows, we would like to clarify some of the points raised by the Reviewer. The original comments begin with "**Comment**" and are quoted in italicized font, the responses begin with "**Response**" in normal font, the original sentences and phrases are in blue letters, the revised sentences and phrases are in red letters, and the line number in the revised manuscript is highlighted in yellow. We appreciate the Reviewer's warm work and taking the time to review the manuscript, and we hope that the corrections will meet with approval.

Yours Sincerely,

Fenglin Tian, Yingying Zhao, Lan Qin, Shuang Long, Ge Chen

2025-9-30

Comment:

It is nice to see components of the methodology developed in our paper (Jones-Kellett & Follows 2024; https://doi.org/10.5194/essd-16-1475-2024) implemented in this work. I was excited to read this preprint due to the related topic and the need for increased computational efficiency for Lagrangian eddy tracking. In reading it, however, I noticed that several pieces of text appear to be copied from our manuscript, and similar figures were reproduced without appropriate attribution. Out of curiosity, I ran a comparison with another foundational paper to this work that was published in ESSD (Liu & Abernathey 2023; https://doi.org/10.5194/essd-15-1765-2023) and found that some parts of the text are also eerily similar to that manuscript. For the sake of time, I did not compare the preprint directly with any other texts. I documented the incidents I found here. Since I read the paper quite closely, I also provided other comments and scientific inquiries that I hope will serve to improve the manuscript.

Response:

We are also extremely grateful to you for the thorough and insightful feedback. The detailed comments, including the critical points raised regarding textual overlap, are invaluable for improving the quality and integrity of our work.

We were deeply concerned to learn of the textual similarities between our manuscript and the works of Jones-Kellett & Follows (2024) and Liu & Abernathey (2023) that you identified. We have conducted a rigorous internal review and verified your findings. This falls short of the academic standards we strive for, and we take full responsibility.

During the drafting process, notes taken from source materials were inadvertently incorporated into the text without proper paraphrasing and citation. This was a critical failure in our manuscript preparation process, and we have already implemented new procedures to prevent recurrence.

Following the insightful suggestions, we have also made significant scientific improvements to the manuscript. Once again, we are grateful for the opportunity to rectify our mistakes. We believe the revised manuscript is now not only free of the previously identified issues but is also a much stronger scientific contribution.

Below, we have addressed each of the comments point-by-point.

Reference:

Liu, T. Y. and Abernathey, R.: A global Lagrangian eddy dataset based on satellite altimetry, Earth System Science Data, 15, 1765-1778, https://doi.org/10.5194/essd-15-1765-2023, 2023.

Jones-Kellett, A. E. and Follows, M. J.: A Lagrangian coherent eddy atlas for biogeochemical applications in the North Pacific Subtropical Gyre, Earth System Science Data, 16, 1475-1501, https://doi.org/10.5194/essd-16-1475, 2024.

Instances of replicated text and missing attribution:

Comment:

① *Lines 126-7: "previous studies found that fewer and smaller structures maintain coherency for longer timescales"; Text copied directly from Jones-Kellett & Follows 2024 (page 1477), please rephrase in your own words.*

Response: We are deeply grateful for your diligence in catching this critical error. The verbatim inclusion of text from another source was a serious mistake in our manuscript preparation process, and it should not have happened. We have completely rephrased the sentence in our own words to accurately convey the scientific finding while ensuring originality. The revised sentence now reads:

- Original sentence:

"Previous studies found that fewer and smaller structures maintain coherency for longer timescales."

- Revised sentence:

"Coherent structures that persist for longer durations tend to be fewer in number and smaller in scale."

(Please see Line 144-145)

Comment:

② *Lines 131-2: "eddy atlases can answer these questions, revealing how the coherent properties of mesoscale features manifest in space and time." ; Text copied directly from Jones-Kellett & Follows 2024 (page 1477), please rephrase in your own words or quote the text with a citation to the source.*

Response: We are profoundly grateful to you for pointing this out, which has uncovered a systemic and unacceptable issue in our manuscript preparation. we have added a citation to Jones-Kellett & Follows (2024) in the main text. (Please see Line 151)

Comment:

③ *Figure 3: The premise of this figure was replicated from Jones-Kellett & Follows 2024 (Figure 3), with embellishments, namely the symbolic particles. I suggest citing the original study at the end of the sentence in lines 358-9.*

Response: Thank you for this important suggestion. You are correct that the conceptual premise of our Figure 3 (now in Figure 5) is based on the excellent visualization in Jones-Kellett & Follows (2024), and we agree that proper attribution is essential. As suggested, we have added a citation to Jones-Kellett & Follows (2024) in the main text where Figure 3 (now in Figure 5) is introduced. (Please see Line 431)

Reference:

Jones-Kellett, A. E. and Follows, M. J.: A Lagrangian coherent eddy atlas for biogeochemical applications in the North Pacific Subtropical Gyre, Earth System Science Data, 16, 1475-1501, https://doi.org/10.5194/essd-16-1475, 2024.

Comment:

④ *Lines 405-8: Nearly identical text as in Liu & Abernathey 2023 pg. 1771*

Response: Thank you for pointing this out. We have completely rephrased the sentence in our own words to accurately convey the scientific finding while ensuring originality. The revised sentence now reads:

- Original sentence:

"BHE v1.0 consists of two components. First, the general features of coherent eddies are detailed in the directory named "Eddyidentification". The information regarding 30-day and 90-day eddies is stored separately in three JSON files, each containing the relevant data."

- Revised sentence:

"The BHE v1.0 dataset is composed of two main components. The first component, located in the 'Eddyidentification' directory, provides the general features of the coherent eddies. This information is organized by integration duration, with data for 30-day and 90-day eddies stored in two distinct JSON files." (Please see Line 481-485)

Comment:

⑤ *Lines 459-62: Nearly identical text as in Liu & Abernathey 2023 pg. 1771*

Response: Thank you for pointing this out. We have completely rephrased the sentence in our own words to accurately convey the scientific finding while ensuring originality. The revised sentence now reads:

- Original sentence:

"An interesting phenomenon is that the eddy in Figure 11a and Figure 12a is not initially located around a closed SLA contour or LAVD contour, but a coherent structure does exist."

- Revised sentence:

"An interesting phenomenon is observed in Fig. 13a and Fig. 15a: the Naked Black Hole Eddy is not initially located around a closed SLA or LAVD contour. Nevertheless, a coherent structure is still present, suggesting that traditional Eulerian and RCLVs boundaries may not always capture the full extent of coherent transport." (Please see Line 574-579)

Comment:

⑥ *Lines 459-62: Figure 10: This presentation of results was replicated from Jones-Kellett & Follows 2024 (Figure 4, pg 1483). Please provide appropriate attribution, including a citation to the original study. Note that the caption to this figure is also nearly identical to that of the analogous figure from Jones-Kellett & Follows 2024.*

Response: We are profoundly grateful to you for highlighting this critical issue of attribution concerning our analysis framework and figure. We have now added a clear statement at the beginning of this section to explicitly credit Jones-Kellett & Follows (2024) for developing the classification framework we used. "To investigate the relationships between the different eddy types, we adopt the classification framework proposed by Jones-Kellett and Follows (2024). This approach categorizes BHEs based on their spatial overlap with eddies identified by the Eulerian (SLA) and RCLV methods." (Please see Line 566-568)

Reference:

Jones-Kellett, A. E. and Follows, M. J.: A Lagrangian coherent eddy atlas for biogeochemical applications in the North Pacific Subtropical Gyre, Earth System Science Data, 16, 1475-1501, https://doi.org/10.5194/essd-16-1475, 2024.

Comment:

⑦ *Figure 11: The second sentence of this caption is copied directly from the Figure 5 caption of Liu & Abernathey 2023, corresponding to a similar figure presentation without attribution.*

Response: We are very grateful to you for their meticulousness in identifying these significant scholarly oversights. The thoroughly revised caption now reads:

"Figure 13. Evolution of an anticyclonic Naked Black Hole Eddy (red particles). The background contours show the Absolute Dynamic Topography (ADT) field." (Please see Line 594)

Comment:

⑧ *Lines 482-3: Nearly identical text as in Jones-Kellett & Follows 2024 pg. 1484*

Response: We are very grateful for your meticulous review, which has been crucial for improving the integrity of our manuscript. This sentence has been completely rewritten as part of the exhaustive, manuscript-wide audit we have conducted to ensure full originality. The revised text now reads:

- Original sentence:

"In Figure 13a, eddy frequency was calculated from the number of times each BHE core and RCLVs eddy core within 1° × 1° grids over 30 years."

- Revised sentence:

"Figure 17 displays the geographic distribution of BHE and RCLV frequency across the North Pacific Ocean. We computed this frequency by binning the positions of all identified eddy cores from the 30 years dataset into1° ×1° grid cells and counting the number of occurrences in each cell." (Please see Line 610-612)

Comment:

⑨ *Lines 492-4: This text was copied directly from Jones-Kellett & Follows 2024 (page 1484), except* *for the citation (Chaigneau et al., 2008). Here, the incorrect paper is cited for defining the polarity probability, given that Chaigneau et al., 2008 make no mention of this metric. The appropriate citation is Chaigneau et al., 2009: https://doi.org/10.1016/j.pocean.2009.07.012*

Response: We are profoundly grateful to you for identifying this serious issue, which involves both replicated text and a critical citation error. We are especially thankful for the reviewer providing the correct reference to Chaigneau et al. (2009); this correction is invaluable and has significantly improved the accuracy of our manuscript. The revised sentence now reads:

- Original sentence:

"The polarity probability (P) is defined $P=\frac{(F_A-F_C)}{(F_A+F_C)}$, where F_A is the frequency of anticyclones, and F_C is the frequency of cyclones (Chaigneau et al., 2008). When $P > 0$ ($P < 0$), anticyclonic (cyclonic) eddy polarity is more common at the given location. Figure 14 shows the geographic distribution of polarity probability of BHE and RCLVs."

- Revised sentence:

"To quantify the local dominance of either cyclonic or anticyclonic eddies, we compute the polarity probability index P, following Chaigneau et al. (2009). This index is calculated as $P=\frac{(F_A-F_C)}{(F_A+F_C)}$, where F_A and F_C are the respective frequencies of anticyclonic and cyclonic eddies in a given grid cell. Consequently, positive values of P indicate a prevalence of anticyclones, while negative values denote a prevalence of cyclones. The geographical distribution of this index for BHEs and RCLVs is shown in Fig. 18." (Please see Line 622-626)

Reference:

Chaigneau, A., Eldin, G., Dewitte, B: Eddy activity in the four major upwelling systems from satellite altimetry (1992–2007), Progress in Oceanography, 83, 117-123, https://doi.org/10.1016/j.pocean.2009.07.012, 2009.

Comment:

⑩ *Lines 500-1: "reveals two stark Lee Eddy pathways depending on the polarity, whereas RCLVs Lee Eddies have a more diffuse polarity probability"; text copied directly from Jones-Kellett & Follows 2024 (page 1484); please rephrase in your own words or quote the text with a citation to the source.*

Response: We are very grateful for your meticulous work in identifying these issues. As part of the exhaustive, manuscript-wide audit we have conducted, this sentence has been completely rewritten to ensure full originality. The revised sentence now reads:

- Original sentence:

"... reveals two stark Lee Eddy pathways depending on the polarity, whereas RCLVs Lee Eddies have a more diffuse polarity probability..."

- Revised sentence:

"The BHE method successfully outlines two distinct pathways for Lee Eddies, clearly segregated by their polarity. In contrast, the RCLV method identifies Lee Eddies with a more scattered or mixed polarity signal in the same region." (Please see Line 630-639)

Comment:

⑪ *Figure 14: Caption structure copied directly from Figure 10 of Jones-Kellett & Follows 2024.*

Response: Thank you for the meticulousness work. As part of the comprehensive, manuscript-wide audit we have performed, this caption has been entirely rewritten to ensure originality.

The revised caption now reads:

- Original sentence:

"Figure 14. Polarity probability in 1° × 1° grids from 1993 to 2023 for (a)BHE and (b) RCLVs. $P < 0$ (blue) indicates more cyclonic activity, and $P > 0$ (red) more anticyclonic activity."

- Revised sentence:

"Figure 16. Spatial distribution of the dominant eddy polarity for (a) BHEs and (b) RCLVs from 1993 to 2023. The polarity probability (P) is calculated on a 1° × 1° grid. Blue shading indicates a dominance of cyclonic activity (P<0), while red shading indicates a dominance of anticyclonic activity (P>0)." (Please see Line 642-645)

Comment:

⑫ *Lines 513-4: "consistent with previously noted summer peaks of eddy kinetic energy in subtropical gyres (Zhai et al., 2008)"; text copied directly from Jones-Kellett & Follows 2024 (page 1482), please rephrase in your own words.*

Response: We are grateful for your thoroughness in catching this. The sentence has been completely rephrased as part of our comprehensive, manuscript-wide audit to ensure full originality and proper attribution. The revised sentence now reads:

- Original sentence:

"...consistent with previously noted summer peaks of eddy kinetic energy in subtropical gyres (Zhai et al., 2008) ..."

- Revised sentence:

"Our observation of a summer peak is in agreement with the seasonal cycle of eddy kinetic energy in subtropical gyres identified by Zhai et al. (2008)." (Please see Line 654-655)

Reference:

Zhai, X. M., Greatbatch, R. J., and Kohlmann, J. D.: On the seasonal variability of eddy kinetic energy in the Gulf Stream region, Geophysical Research Letters, 35, https://doi.org/10.1029/2008GL03641210.1029/2008GL036412, 2008.

Comment:

⑬ *Figure 15: This presentation of results was replicated from Jones-Kellett & Follows 2024 (Figure 6, pg 1485). Please provide appropriate attribution, including a citation to the original study. Note that the caption is nearly identical to that of the analogous figure from Jones-Kellett & Follows 2024.*

Comment: We are grateful to you for pointing out this significant scholarly oversight. To rectify this, we have taken the following steps:

We have completely rewritten the caption for Figure 15 to be in our own words and added a clear attribution within the new caption, crediting Jones-Kellett & Follows (2024) for the analysis framework. We have revised the caption as follows:

- Original caption:

"Figure 15. (a) BHE and RCLVs rolling mean frequency from 1993 to 2020. Frequency refers to the number of eddies per 7 day time step. (b) Monthly average BHE and RCLVs frequency."

- Revised caption:

"Figure 19. Time series of eddy counts for BHEs and RCLVs from 1993 to 2020. (a) Interannual variability, showing the number of eddies detected in each 7-day time step. (b) The mean seasonal cycle, showing the monthly average number of eddies. This presentation of results is adapted from Jones-Kellett and Follows (2024)." (Please see Line 665-667)

We have also revised the accompanying text that interprets the figure to ensure originality and clarity. We have revised the text as follows:

- Original sentence:

"Figure 15. (a) BHE and RCLVs rolling mean frequency from 1993 to 2020. Frequency refers to the number of eddies per 7 day time step. (b) Monthly average BHE and RCLVs frequency."

- Revised sentence:

"Figure 19a illustrates the interannual variability in the number of detected eddies. While both BHEs and RCLVs follow similar long-term trends, the total count of RCLVs is consistently higher than that of BHEs. This suggests the criteria for identifying BHEs are more rigorous, resulting in a smaller population of the most coherent structures. A notable difference in polarity preference is also observed: more anticyclonic BHEs are found than cyclonic ones, which aligns with previous statistics (Chelton et al., 2011b), whereas the opposite is true for RCLVs. The mean seasonal cycle for both eddy types is shown in Fig. 17b. Both methods show a clear peak in eddy occurrences in late summer (July-August) and a minimum in late winter (January-February). Our observation of a summer peak is in agreement with the seasonal cycle of eddy kinetic energy in subtropical gyres identified by Zhai et al. (2008)." (Please see Line 648-655)

Reference:

Chelton, D. B., Schlax, M. G., and Samelson, R. M.: Global observations of nonlinear mesoscale eddies, Progress in Oceanography, 91, 167-216, https://doi.org/10.1016/j.pocean.2011.01.00210.1016/j.pocean.2011.01.002, 2011b.

Zhai, X. M., Greatbatch, R. J., and Kohlmann, J. D.: On the seasonal variability of eddy kinetic energy in the Gulf Stream region, Geophysical Research Letters, 35, https://doi.org/10.1029/2008GL03641210.1029/2008GL036412, 2008.

⑭ *Figure 16: Figure caption mostly replicated from Figure 8 caption of Liu & Abernathey 2023, pg. 1774.*

Response: Thank you for pointing this out. Your exceptional diligence has been instrumental in helping us purge our manuscript of these unacceptable scholarly errors.

In addressing this, we have completely rewritten the caption for Figure 16 (now in Figure 20). Furthermore, during this revision, we also identified and corrected a significant scientific inaccuracy in our original caption's description of the box plot elements. The new caption is therefore not only entirely original but also scientifically precise. The thoroughly revised caption now reads:

- Original caption:

"Figure 16. Statistics of radius for BHE and RCLVs. The box plot shows statistics of all eddies in 10° bins. The box and the whisker span the min value to the max of the distribution. The line in the box indicates the median. The means of all eddies in a bin are shown using dashed lines, blue for BHE and green for RCLVs."

- Revised sentence:

" Figure 20. Latitudinal distribution of eddy radius for BHEs and RCLVs, presented in 10° bins. The violin plots show the probability density of the radius, with the vertical lines indicating the min-max range. The dashed lines connect the median values for bins each bin." (Please see Line 689-691)

Comment:

⑮ *Line 597: "It is convenient to load the data using Python or other language." Phrasing replicated from Liu and Abernathey 2023 on pg. 1775 (Section 4)*

Response: Thank you for pointing this out. The sentence in question has been completely rephrased to be more informative and original. The new sentence reads:

- Original caption:

"The identification dataset is saved in JSON format and the tracking dataset is saved in Pickle format. It is convenient to load the data using Python or other language."

- Revised sentence:

"The identification dataset is saved in JSON format and the tracking dataset is saved in Pickle format, ensuring straightforward compatibility with common scientific programming languages like Python, MATLAB, and R." (Please see Line 775-778)

Major Comments:

Comment 1: *Section 2.1.1: The authors claim to have used Level 3 data, yet the link provided is to a Level 4 product (Line 158). Additionally, they used a near-real time product, which is made for short-term monitoring and is inappropriate for a long-term study, for which the delayed time products are preferred (e.g., see the Quality Information Manuals provided by CMEMS). The product that is linked in Line 158 only has spatial coverage from 2022-2025, yet the study covers 1993-2023. The authors build a new eddy dataset in this work that they compare to a previous product developed by some of the same authors (Tian et al. 2022; https://doi.org/10.1175/JTECH-D-21-0103.1), which used Level 4 delayed-time data. If the authors are actually using the same data as in Tian et al. 2022, this entire paragraph needs to be rewritten.*

Response: We are profoundly grateful to you for this extremely detailed and critical comment. This was a regrettable error during the manuscript preparation, where an incorrect data description was inserted.

Your assessment was exactly right: we did, in fact, use the same high-quality, delayed-time (reprocessed) data as in the Tian et al. (2022) study, and not the near-real-time product. The original paragraph was completely inaccurate.

To correct this, we have completely rewritten Section 2.1.1. The revised section now accurately:

- Identifies the product we used as the Level 4 reprocessed dataset (SEALEVEL_GLO_PHY_L4_REP_008_047) with a 1/4° resolution.
- Clarifies that it is the delayed-time version, appropriate for our long-term study.
- Provides the correct description for our analysis period.
- Adds a crucial note for reproducibility, explaining that this specific 1/4° product has since been decommissioned by CMEMS and superseded by a newer 1/8° version, ensuring future readers

understand the data landscape.

- Original paragraph:

"This study utilizes the global gridded ADT data published by the Copernicus Marine Environment Monitoring Service (CMEMS). The ADT was determined through optimal interpolation, leveraging measurements from various altimeter missions at the Level 3 stage. This partially processed data has global applicability and provides additional variables, including ADT and both absolute and anomalous geostrophic currents. The ADT data included in this dataset were employed in our study. Processed by DUACS multi-mission altimeter data processing system, the data is intended for near-real-time applications. The spatial resolution of the data is 0.25° ×0.25° , and it offers a temporal resolution of one day. The dataset is publicly available at: https://data.marine.copernicus.eu/product/SEALEVEL_GLO_PHY_L4_NRT_008_046/description."

- Revised paragraph:

"This study utilizes the Level 4 global ocean gridded sea level reprocessed (delayed-time) product, version SEALEVEL_GLO_PHY_L4_REP_008_047, which was distributed by the Copernicus Marine Environment Monitoring Service (CMEMS) at the time of our analysis. This dataset provided data on a 0.25° × 0.25° global grid and was generated by the DUACS multi-mission altimeter data processing system. It merges measurements from all available satellite altimeter missions (e.g., TOPEX/Poseidon, Jason series, Sentinel series) through optimal interpolation. For our analysis, we used the ADT)and the associated absolute geostrophic velocity fields, covering the period from 1 January 1993 to 5 May 2023. It should be noted that this specific 1/4° resolution product has since been decommissioned by CMEMS and superseded by a higher-resolution 1/8° version (SEALEVEL_GLO_PHY_L4_MY_008_047). "

(Please see Line 171-178)

Comment 2: *Section 3.2, Figure 8 & 9: The authors highlight two BHEs to draw general conclusions about the coherence of all BHEs. However, the regions analyzed in Figs 8 and 9 are problematic due to the decreasing accuracy of satellite-derived geostrophic currents near the equator (Fig 8), and near coastlines (Fig 9). Especially with only two qualitative examples of the difference in coherence, the authors should provide examples from regions with lower known errors in the satellite products. I am especially confused about Figure 8 being used as a demonstration of the difference in the coherence of BHEs and RCLVs (e.g. Line 438), given that the eddies, as opposed to 28-day? In Line 553, the authors switch to 28-day results for the transport analysis. Furthermore, if the authors have weekly BHEs tracked, why are the results only being shown for one time interval? That seems to defeat the purpose of tracking* *the features over their full lifetimes. The authors only provide a dataset for BHEs with T=30- and 90-day lifespans (Line 610), rather than the weekly dataset described in the methods.*

Response: We are extremely grateful to the reviewer for this critical and insightful comment. The reviewer is absolutely correct. Our original choice of case studies in Figures 8 and 9 was poor, as these regions near the equator and coastlines are known to have significant uncertainties in satellite altimetry products. Using these examples to draw general conclusions was inappropriate, and we agree that this fundamentally weakened our argument.

To address this major flaw, we have completely replaced the original Figures 8 and 9 with two new case studies (now in Figure 10 and Figure 11), from open-ocean, mid-latitude regions where the satellite data is robust and reliable.

Furthermore, you highlighted a point of confusion regarding the time intervals shown in the figure panels. We agree that our original presentation was inconsistent. Our initial choice of a ~15-day interval was arbitrary and intended only for qualitative visualization. To improve the methodological consistency, we have revised the analysis for our new figures. The snapshots of the eddy evolution are now shown at 14-day intervals. This interval was deliberately chosen because it corresponds to exactly two of our 7-day (weekly) data snapshots, making the visualization directly relatable to the temporal resolution of our underlying dataset. We have clarified this in the new figure captions. (Please see Line 560-570)

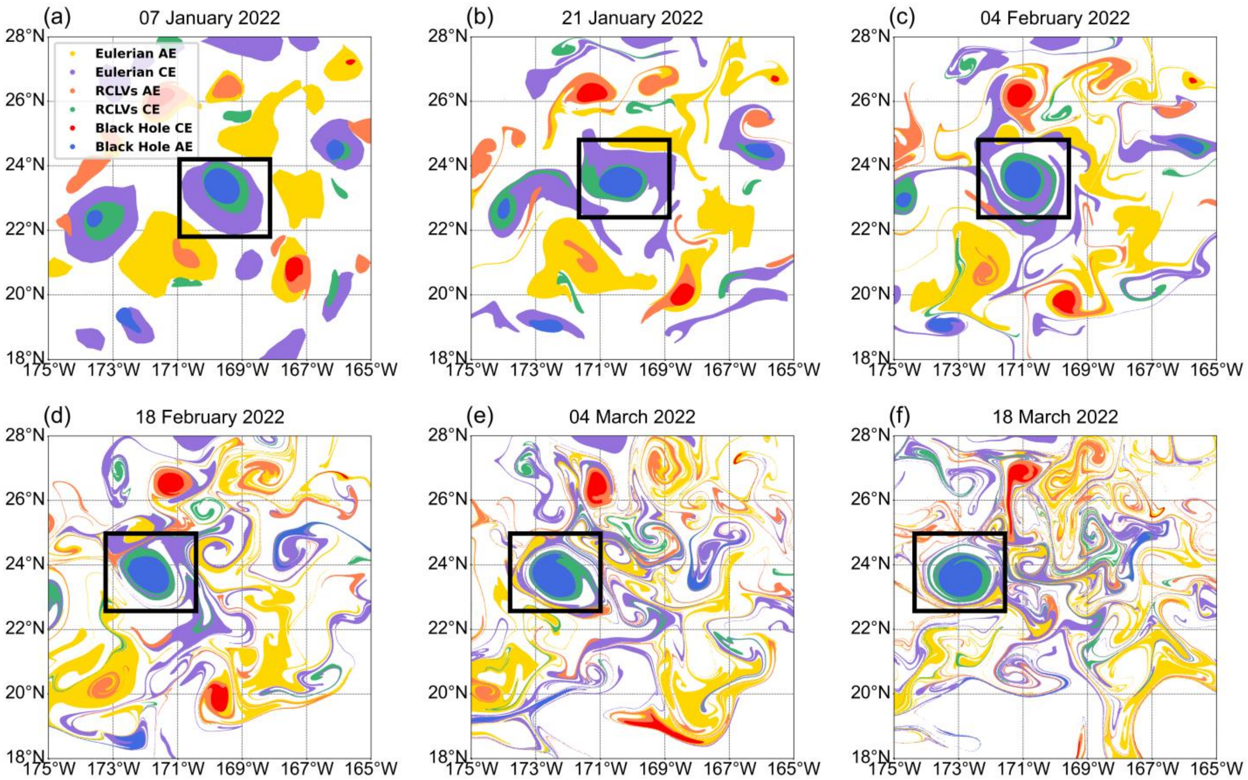

Figure 10. Evolution of an cyclonic eddy in the open, mid-latitude North Pacific, comparing the coherence of different eddy definitions. Particles are initialized within the boundaries of a Eulerian eddy, an RCLVs, and a BHE on 07 January 2022. Panels (a)-(f) show the subsequent advection of these particle sets at approximately 14-day intervals.

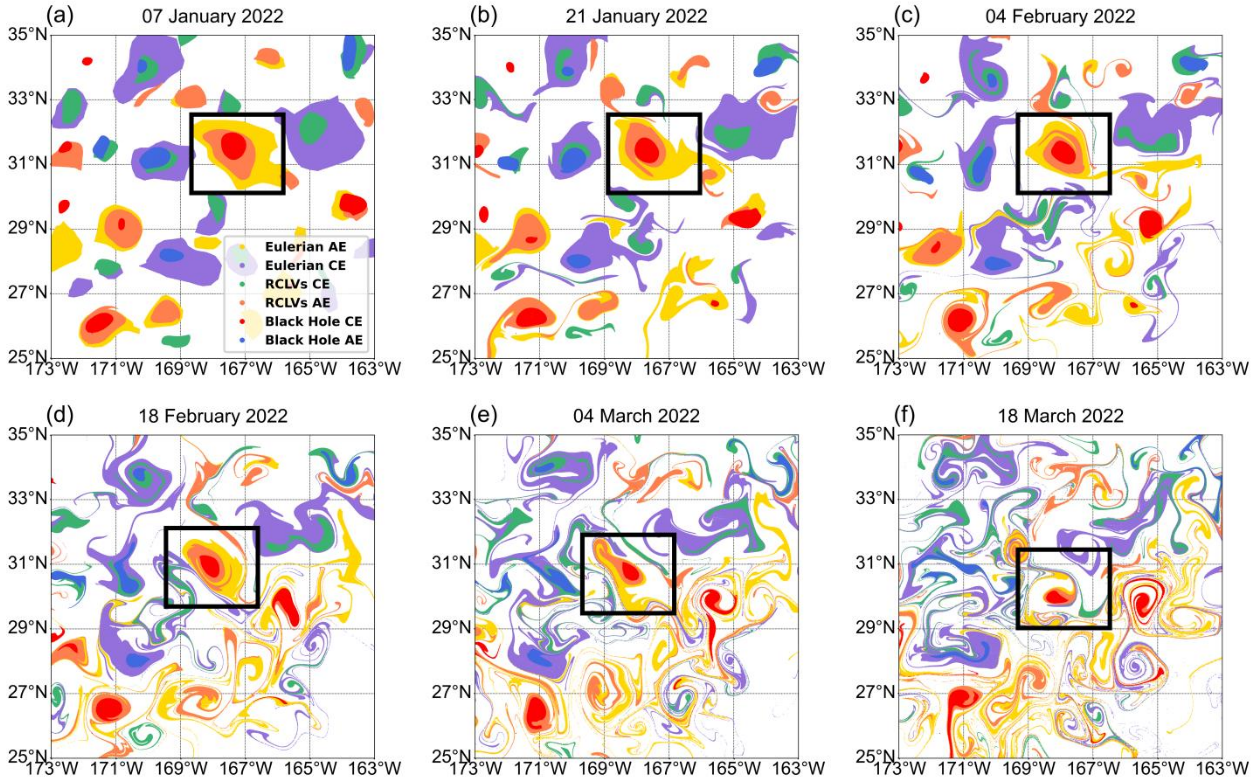

Figure 11. Evolution of an anticyclonic eddy in the open, mid-latitude North Pacific, comparing the coherence of different eddy definitions. Particles are initialized within the boundaries of a Eulerian eddy, an RCLVs, and a BHE on 07 January 2022. Panels (a)-(f) show the subsequent advection of these particle sets at approximately 14-day intervals.

Regarding the '28-day' results in our transport analysis (Line 553), it was a typographical error in our description. Our analysis did not use eddies of only 28 days, but rather included all eddies with a lifetime of 28 days or longer. We have corrected the text in the manuscript to accurately state this criterion, which clarifies that we are analyzing all eddies that persist for a significant duration. The revised sentence now reads:

- Revised paragraph:

"For the analysis period of 1993-2020, we selected a minimum lifetime threshold of 28 days for both BHEs and RCLVs. This duration was chosen as it corresponds to four consecutive 7-day time steps in weekly dataset, ensuring that the analyzed eddies exhibit sustained coherence over a significant number of observations." (Please see Line 732-734)

These new, more reliable examples now clearly and robustly illustrate our original point regarding the differences in coherence between BHEs, RCLVs, and Eulerian eddies. The corresponding text in Section

3.2 has been entirely rewritten to describe and analyze these new cases. The revised sentence now reads:

- Original paragraph:

"We randomly initialized Lagrangian particles within Black Hole anticyclonic\cyclonic eddy on January 1 and tracked their movement over time(Figure 8 and Figure 9). At the initialization (Figure 8a and Figure 9a), the yellow\purple particles are located inside the Eulerian anticyclonic\cyclonic eddy boundary but outside the anticyclonic\cyclonic RCLVs, while the pink\green particles are situated within the anticyclonic\cyclonic RCLVs but outside the Black Hole anticyclonic\cyclonic eddy. In the case of Eulerian anticyclonic eddy, distinct vortex filaments begin to develop on 15 January (Figure 8b), just two weeks after initialization. These filaments extend and wrap outward, indicating that material inside the Eulerian boundary begins interacting with the surrounding environment shortly after initialization. After 30 days advection, the deformation intensifies, leading to a complete loss of the eddy's coherent structure and extensive mixing with surrounding waters. For anticyclonic RCLVs, filamentary structures appear slightly later. After 30 days advection (Figure 8c), clear signs of deformation can be observed, as particles begin to stretch and form elongated structures outside the anticyclonic RCLVs boundary. Although the anticyclonic RCLVs demonstrate stronger material retention than Eulerian eddies, they too undergo gradual mixing, and after 90 days (Figure 8e), the filaments become prominent, indicating a loss of coherent transport. In contrast, anticyclonic BHE maintains its coherent structure throughout the entire tracking period. The anticyclonic BHE boundary serves as an effective barrier to material transport, firmly enclosing particles and preventing exchange with the surrounding fluid. Even after four months (Figure 8f), particles within the BHE remain tightly bound, and no filamentation or mixing is observed. Example of cyclonic eddy also reveals the same phenomenon (Figure 9).This comparison highlights the strong material coherence of BHEs over Eulerian eddies and RCLVs. The region between the RCLV and Eulerian eddy boundaries can be considered a transition zone, where eddy-like motions occur but without coherent material retention. Recognizing such spatial distinctions helps refine our understanding of mesoscale eddy structure and provides a pathway for exploring submesoscale dynamics embedded within these systems."

- Revised paragraph:

"Figure 10 shows the evolution of a cyclonic eddy in the North Pacific. A set of passive tracers is initialized within the boundaries of the Eulerian eddy, the RCLVs, and the BHE on 07 January 2022 (Fig. 10a). The subsequent evolution clearly demonstrates a hierarchy of coherence. After only 14 days (Fig. 10b), the Eulerian eddy already shows significant filamentation, indicating that material inside the Eulerian boundary begins interacting with the surrounding environment shortly after initialization, while the RCLVs appear slightly filamentary structures and BHE remains highly coherent. By day 28 (Fig. 10c), the original Eulerian eddy structure has largely disintegrated, and the RCLVs also begins to exhibit distinct material leakage through filaments. Although the RCLVs demonstrate stronger material retention than Eulerian eddies, they too undergo gradual mixing, and after 56 days (Fig. 10e), the filaments become prominent, indicating a loss of coherent transport. This trend continues, and by the end of the two-month period, the Eulerian tracers are widely dispersed and the RCLV shows significant material loss. In contrast, the BHE boundary acts as a robust material barrier, remaining perfectly coherent and tightly trapping all its initial tracers throughout the entire period (Fig. 10f).

A similar analysis for a cyclonic eddy, shown in Fig. 11, the Eulerian eddy is highly dispersive, the RCLVs is moderately coherent but still leaky, while the BHE perfectly retains its initial water mass. This comparison highlights the strong material coherence of BHEs over Eulerian eddies and RCLVs. The region between the RCLVs and Eulerian eddy boundaries can be considered a transition zone, where eddy-like motions occur but without coherent material retention. Recognizing such spatial distinctions helps refine our understanding of mesoscale eddy structure and provides a pathway for exploring submesoscale dynamics embedded within these systems.” (Please see Line 523-539)

Comment 3: *How the authors were able to compare BHEs tracked weekly with the RCLV dataset from Tian et al. 2022 (https://doi.org/10.1175/JTECH-D-21-0103.1) is never described in this preprint. Tian et al. 2022 derive RCLVs over fine times every 90 days. Do the authors subset the weekly BHE dataset to match the RCLV dataset for figures 10, and 13-19? If so, that means the comparison is made every 3 months, which will affect the results. However, Fig. 15 states "frequency refers to the number of eddies per 7 day time step", suggesting that the authors somehow obtained weekly RCLV boundaries. In general, the comparison between these datasets is questionable, given the apparent difference in satellite products used and the difference in detection frequency of the Lagrangian eddies. The size threshold may also have been different (see Major Comment #5).*

Response: Thank you for these very detailed and important questions, which have highlighted a major omission in our Methods section. We did lack of clarity regarding how the comparison between our BHE dataset and the RCLVs dataset from Tian et al. (2022) was performed.

To clarify the points raised and resolve the apparent inconsistencies:

1. **Frequency of the RCLVs Dataset**: your confusion is entirely understandable given the missing information in our manuscript. The RCLVs (doi:10.12237/casearth.63369940819aec34df2674d7) we used is not generated every 90 days. We utilized their specific product which is defined with a 30-day integration time (T=30) and generated with a 7-day time step (i.e., a weekly frequency). This weekly

frequency perfectly matches that of our BHE dataset. Therefore, no subsetting of our BHE data was necessary, and the comparison was performed on a consistent weekly basis.

2. **Satellite Products and Size Thresholds**: We have now explicitly stated in the manuscript that both datasets are based on the same Level 4 delayed-time altimetry product (as clarified in our response to Comment 1) and that the same size and lifetime thresholds were applied to both datasets before comparison.

Here is a revised version paragraph, which clarifies the temporal resolution and methodology. It clearly states that the RCLV dataset has a weekly frequency and explains how you extended it for a consistent comparison.

- Original paragraph:

"The RCLVs dataset used in this study is based on the work of Tian et al. (2022), who proposed an SLA-based orthogonal parallel detection method to identify rotationally coherent Lagrangian eddies at the global scale. Unlike traditional Eulerian eddy detection methods, this Lagrangian approach ensures material coherence by identifying vortices that maintain their structure and boundary over time, based on objective criteria derived from finite-time rotation. The RCLVs dataset is constructed from satellite-derived daily SLA fields with a resolution 0.25°×0.25°, covering the global ocean. The algorithm efficiently tracks eddies over time, providing information on eddy boundaries, lifetime, polarity, and coherent transport properties. The data include only vortices that meet strict rotational coherence conditions, making them particularly suitable for studies focusing on long-lived, materially coherent eddy structures. The dataset can be accessed from website at: https://data.casearth.cn/dataset/63369940819aec34df2674d7."

- Revised paragraph:

"For a comparative analysis, this study utilizes the global RCLVs dataset from Tian et al. (2022). We specifically selected their data product generated with a 30-day integration time (T=30) and a 7-day time step, resulting in a weekly dataset that is directly comparable to our BHE analysis. Unlike traditional Eulerian eddy detection methods, this Lagrangian approach ensures material coherence by identifying vortices that maintain their structure and boundary over time, based on objective criteria derived from finite-time rotation. The RCLVs dataset is constructed from satellite-derived daily SLA fields with a 0.25°×0.25° resolution, covering the global ocean from 1993-2020. The algorithm efficiently tracks eddies over time, providing information on eddy boundaries, lifetime, polarity, and coherent transport properties. The dataset can be accessed from website at: https://data.casearth.cn/dataset/63369940819aec34df2674d7." (Please see Line 225-233)

Thank you for helping us significantly improve the transparency and completeness of our methodology.

Comment 4: *The authors claim to have tracked the BHEs weekly, but then provide results from 30-day intervals in Figs 13 and 14. Since 30 is not divisible by 7, how did the authors obtain 30-day eddies, as opposed to 28-day? In Line 553, the authors switch to 28-day results for the transport analysis. Furthermore, if the authors have weekly BHEs tracked, why are the results only being shown for one time interval? That seems to defeat the purpose of tracking the features over their full lifetimes. The authors only provide a dataset for BHEs with T=30- and 90-day lifespans (Line 610), rather than the weekly dataset described in the methods.*

Response: Thank you for this insightful comment, which has highlighted a significant lack of clarity in our description of the methodology. We have thoroughly revised the Methods and Results sections to clarify this. To address the specific points raised:

1. **Clarification of '30-day' vs. 'weekly'**: you are correct that 30 is not divisible by 7. This is because these two numbers refer to different aspects of our methodology.

- **The '30-day' (or '90-day') value is the forward integration time (T) used as a parameter to define a BHE.** A '30-day BHE' is a boundary identified at a start time t_0, that remains materially coherent for the subsequent 30 days. It is a measure of the structure's coherence strength.

We have added the text as follows:

"T denotes a forward integration time to qualify the coherence of BHE. In this study A BHE defined with $T = 30$ (or $T = 90$), is a material boundary identified at a start time t_0, that traps all fluid particles within it for subsequent 30 (90) days." (Please see Line 286-289)

- **The term 'weekly' refers to the temporal resolution of our BHE identification analysis.** We perform this BHE detection calculation repeatedly, with a new analysis starting every 7 days. This results in a time series of BHE 'snapshots' with a 7-day frequency. The tracking of eddies is then performed as a post-processing step by linking these weekly snapshots.

We have revised the text as follows:

- Original sentence:

"(1) Input data: The algorithm starts by ingesting Black Hole identification data obtained through from January 1, 1993 to May 5, 2023."

- Revised sentence:

"(1) Input data: The BHE identification process described in Section 2.2.1 was applied repeatedly to generate the input data for our tracking algorithm. Specifically, a new set of BHEs was identified every 7 days, creating a time series of BHE 'snapshots' covering the period from January 1, 1993, to May 5, 2023.

This weekly dataset of identified BHEs is the primary input for the tracking steps detailed below." (Please see Line 425-429)

2. **Reasons for the '28-day' analysis**: you are right to question the switch to a 28-day threshold for the transport analysis. We have now clarified our reasoning in the manuscript. Our BHE identification fields are generated at a 7-day frequency. When these weekly snapshots are linked to form tracks, the resulting eddy lifetimes are measured in multiples of 7 days. We selected a minimum lifetime threshold of 28 days because it corresponds to exactly four weekly time steps (4×7 days). This provides a methodologically consistent cutoff, ensuring that the eddies included in the transport analysis have maintained their coherence over a significant number of consecutive snapshots. We have revised the text to make this rationale explicit.

We have revised the text as follows:

- Original sentence:

"Here, BHEs and RCLVs only include eddies that are 28 days are considered from 1993 to 2020."

- Revised sentence:

"For the analysis period of 1993-2020, we selected a minimum lifetime threshold of 28 days for both BHEs and RCLVs. This duration was chosen as it corresponds to four consecutive 7-day time steps in weekly dataset, ensuring that the analyzed eddies exhibit sustained coherence over a significant number of observations." (Please see Line 732-734)

3. **Use of full lifetime information & Dataset content:** As clarified previously, our final product is a dataset of fully tracked eddies with complete life cycles. The results shown in the figures are statistical analysis derived from the entire population of weekly BHE snapshots (defined with $T = 30$ days), and the full lifetime information of each tracked eddy is used in analyses like the transport calculation. While our dataset contains BHEs defined with both $T = 30$ and $T = 90$ days, the eddies that maintain coherence for a 90-day period are significantly fewer in number. Therefore, to ensure statistical reliability, we presented the results for the much larger and more representative population of T=30 day BHEs. We have thoroughly revised the Methods section to make the distinction between the BHE definition parameter (T) and the dataset's temporal resolution (7-day) explicit. Thank you for helping us significantly improve our manuscript."

Comment 5: *Figure 16 & Lines 521-524: It is difficult to visually see the difference between these statistics in panels (a) and (b) because the y-axis changes. Plotting the data together in one plot may help. The conclusion that RCLV is weakly influenced by latitude is confusing (Lines 523-4 and 639-40), considering that RCLVs on average decrease in size with increasing latitude, whereas BHEs appear not* *to have a latitudinal dependence above latitudes of 20N in Figure (a). A constant radius contradicts expectations based on the Rossby radius of deformation, which is not commented on in the text. Figure 16 also gives the impression that the minimum radius for the BHEs was 20km, whereas the RCLVs was around 25km. If that is the case, it is an issue for comparing BHE and RCLVs if the size minimum for detection differed between the datasets.*

Response: We are very grateful to you for this extremely detailed and insightful feedback, which has helped us to fundamentally improve our analysis and discussion of Figure 16. We have addressed each of the points raised.

Regarding the visualization: To facilitate a clear and direct comparison, we have completely revised Figure 16 (now in Figure 20). We now plot both the BHE and RCLV radius statistics on a single panel with a shared y-axis, using different colors to distinguish them. (Please see Line 696-700)

- Original Figure:

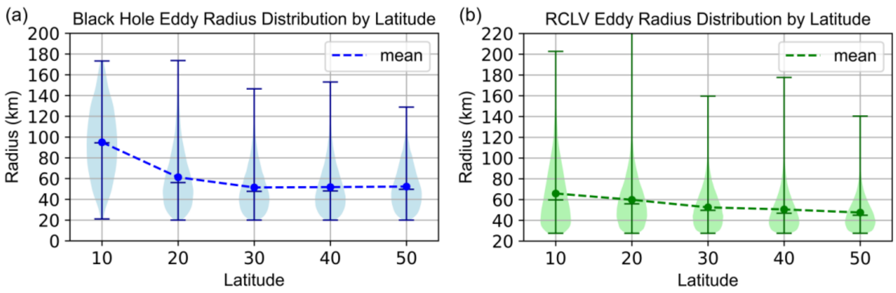

Figure 1. Statistics of radius for BHE and RCLVs. The box plot shows statistics of all eddies in 10° bins. The box and the whisker span the min value to the max of the distribution. The line in the box indicates the median. The means of all eddies in a bin are shown using dashed lines, blue for BHE and green for RCLVs.

- Revised Figure:

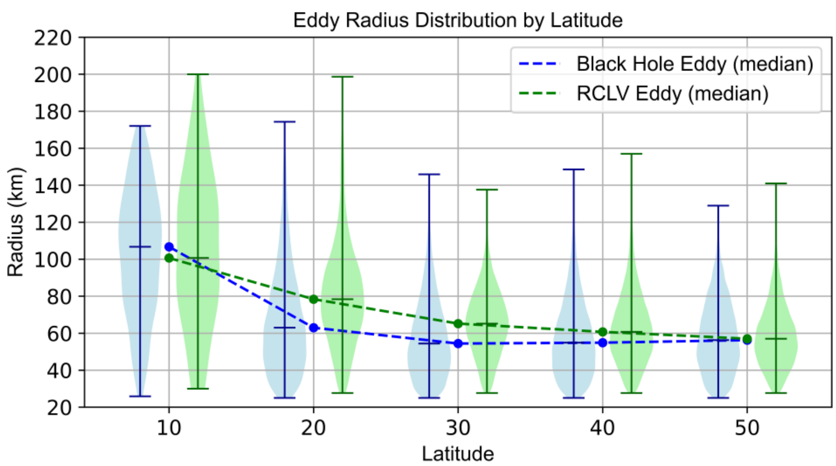

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Figure 18. Latitudinal distribution of eddy radius for BHEs and RCLVs, presented in 10° bins. The violin plots show the probability density of the radius, with the vertical lines indicating the min-max range. The dashed lines connect the median values for bins each bin.

1. **Regarding the scientific interpretation:** We agree that our original conclusion was confusing and did not accurately reflect the data, and we thank the reviewer for pointing out the important connection to the Rossby radius of deformation. We have thoroughly rewritten our interpretation in the text. The revised text now correctly states that the RCLV radius decreases with latitude, as expected, while the BHE radius remains surprisingly constant at latitudes above 20°N. Furthermore, we have added sentences acknowledging that the constant radius of BHEs is an unexpected result that deviates from theoretical expectations based on the Rossby radius, highlighting this as a topic for future study.

- Original paragraph:

"Figure 16 illustrates the distribution of eddy radius across different latitude zones. In Figure 16a, the mean eddy radius (dashed line) exhibits a clear decreasing trend from low to high latitudes, particularly at latitudes of 40° and above, where the eddy radius becomes notably smaller and more concentrated. In contrast, the eddy radius of the RCLVs, shown in Figure 16b, varies within a relatively small range and does not display a clear monotonic trend, indicating that it is weakly influenced by latitude. The BHE demonstrates larger and more dispersed radius at lower latitudes, which progressively decrease and become more consistent as latitude increases. These latitudinal differences in the BHE radius may be linked to variations in geostrophic balance and Coriolis force (Chelton et al., 2011b)(Chelton et al., 2011b). At low latitudes, where the Coriolis force is weaker, eddies are more likely to develop larger radius, while at higher latitudes, the strengthening Coriolis force leads to smaller and more constrained eddy radius."

- Revised paragraph:

"Figure 20 presents a statistical comparison of the radius of BHEs and RCLVs across different latitude zones using a uniform 25 km minimum radius threshold. The median radius of RCLVs (green dashed line) exhibits a clear decreasing trend with increasing latitude, falling from approximately 100 km at 10°N to under 60 km at 50°N. This pattern is consistent with the theoretical decrease in the first baroclinic Rossby radius of deformation at higher latitudes (Chelton et al., 2011b).

In contrast, the median radius of BHEs (blue dashed line) behaves differently. While it also decreases from low to mid-latitudes, it remains surprisingly constant at approximately 55-60 km for all latitudes above 20°N, which is different from the expected trend based on the Rossby radius. It suggests that the strict rules used to define BHEs might be finding a special group of eddies whose size is controlled by different physical forces." (Please see Line 687-695)

Reference:

Chelton, D. B., Schlax, M. G., and Samelson, R. M.: Global observations of nonlinear mesoscale eddies, Progress in Oceanography, 91, 167-216, https://doi.org/10.1016/j.pocean.2011.01.00210.1016/j.pocean.2011.01.002, 2011b.

2. **Regarding the minimum radius threshold:** Our original comparison was indeed unfair because we had inadvertently used different minimum size thresholds for the BHE and RCLV datasets.

To correct this fundamental flaw, we have returned to our data processing stage and re-run the entire analysis. We have now applied a uniform minimum radius threshold of 25 km to both the BHE and RCLV datasets. Consequently, related statistical results have been recalculated, and Figure 16 (now in Figure 20), have been updated based on this consistent and fair comparison. The manuscript text has been revised accordingly to reflect the new results and methodology.

Minor Comments:

Comment 1: *Line 24: "And" at the beginning of the sentence is likely a typo*

Response: We thank you for the careful reading. This was indeed a typo, and the word "And" has been removed. The sentence has been revised to: "Transport analysis shows that BHEs induce westward transport of about 1.5 Sv, three times weaker than RCLVs, suggesting that they may offer a more accurate estimate of oceanic transport than RCLVs.". (Please see Line 25)

Comment 2: *Lines 25: How does weaker transport by the RCLVs suggest that BHE offer a "more accurate estimate of transport"? Aren't they both contributing to transport considering the significant overlap?*

Response: We sincerely thank you for this insightful question. This is a crucial point that was not sufficiently explained in our original manuscript. You are correct that both structures contribute to transport, but our use of "more accurate" refers specifically to the estimate of coherent, non-leaky transport, rather than the total volume of water in motion.

We have clarified this distinction in the revised manuscript. The key difference is:

RCLVs identify the larger rotating structure, and their associated transport value is high. However, these structures can be "leaky" (Jones-Kellett and Follows, 2024), meaning water parcels on their periphery are often exchanged with the surrounding ocean. Therefore, the RCLV transport value tends to overestimate the actual mass of water that is coherently transported over long distances.

BHEs, by their strict definition, identify the materially coherent, non-leaky core within an eddy (Haller and Beron-Vera, 2013). The water trapped inside a BHE is guaranteed to be transported with it. Although its transport value is smaller, it is a more faithful and precise measure of the water mass that is effectively isolated and carried across the ocean.Therefore, while BHEs transport less water in total, the value of 1.5 Sv is a "more accurate estimate" of the truly effective, long-distance transport of properties.

To make this clear to the reader, we have revised the sentence as follows:

- Original sentence:

"And Transport analysis shows that BHEs induce westward transport about 1.5 Sv, three times weaker than RCLVs, suggesting that they may offer a more accurate estimate of oceanic transport than RCLVs."

- Revised sentence:

"Transport analysis shows that BHEs induce a westward transport of about 1.5 Sv, three times weaker than the transport attributed to the broader RCLVs, suggesting it likely represents a more accurate estimate of the coherent, non-leaky component of oceanic transport, as BHEs isolate the materially coherent core of the eddies." (Please see Line 25-29)

Reference:

Haller, G. and Beron-Vera, F. J.: Coherent Lagrangian vortices: the black holes of turbulence, Journal of Fluid Mechanics, 731, https://doi.org/10.1017/jfm.2013.39110.1017/jfm.2013.391, 2013.

Jones-Kellett, A. E. and Follows, M. J.: A Lagrangian coherent eddy atlas for biogeochemical applications in the North Pacific Subtropical Gyre, Earth System Science Data, 16, 1475-1501, https://doi.org/10.5194/essd-16-1475-2024, 2024.

Comment 3: *Lines 29 & 31: Contains repeated information, e.g. "Mesoscale eddies, one of the most prominent processes in the ocean," and "Mesoscale eddies are ubiquitous in the ocean"*

Response: Thank you for this valuable suggestion. We agree that the original phrasing was repetitive. We have revised and combined these two sentences to improve conciseness and flow. The revised sentence now reads:

- Original sentence:

"Mesoscale eddies, one of the most prominent processes in the ocean, typically range from several tens to hundreds of kilometers in spatial scale and can persist for periods of a few weeks to several years (Chelton et al., 2011a; Chaigneau et al.,2008). Mesoscale eddies are ubiquitous in the ocean and play a crucial role in the transport of heat, salinity, and other various variables, further influencing on the marine material cycle, large-scale water body transport, and biological activities (Chen et al., 2012; Chen et al., 2021; Faghmous et al., 2015; Dong et al., 2014)."

- Revised sentence:

"Mesoscale eddies, one of the most prominent processes in the ocean, typically range from several tens to hundreds of kilometers in spatial scale and can persist for periods of a few weeks to several years (Chelton et al., 2011a; Chaigneau et al., 2008). In the North Pacific, mesoscale eddies generally persist for about 4 weeks to one year, with longer-lived structures occasionally exceeding this range, particularly in energetic regions such as the Kuroshio Extension (Chelton et al., 2011a; Chen and Han, 2019). These eddies play a crucial role in the transport of heat, salinity, and other various variables, further influencing on the marine material cycle, large-scale water body transport, and biological activities (Chen et al., 2012; Chen et al., 2021; Faghmous et al., 2015; Dong et al., 2014). " (Please see Line 33-39)

Reference:

Chaigneau, A., Gizolme, A., and Grados, C.: Mesoscale eddies off Peru in altimeter records: Identification algorithms and eddy spatio-temporal patterns, Progress in Oceanography, 79, 106-119, https://doi.org/10.1016/j.pocean.2008.10.013, 2008.

Chelton, D. B., Gaube, P., Schlax, M. G., Early, J. J., and Samelson, R. M.: The Influence of Nonlinear Mesoscale Eddies on Near-Surface Oceanic Chlorophyll, Science, 334, 328-332, https://doi.org/10.1126/science.1208897, 2011a.

Chen, G. X., Gan, J. P., Xie, Q., Chu, X. Q., Wang, D. X., and Hou, Y. J.: Eddy heat and salt transports in the South China Sea and their seasonal modulations, Journal of Geophysical Research-Oceans, 117, https://doi.org/10.1029/2011JC007724, 2012.

Chen, G., and Han, G.: Contrasting short-lived with long-lived mesoscale eddies in the global ocean, Journal of Geophysical Research: Oceans, 124, 3149–3167, https://doi.org/10.1029/2019JC014983, 2019.

Chen, G., Yang, J., and Han, G. Y.: Eddy morphology: Egg-like shape, overall spinning, and oceanographic implications, Remote Sensing of Environment, 257, https://doi.org/10.1016/j.rse.2021.112348, 2021.

Dong, C. M., McWilliams, J. C., Liu, Y., and Chen, D. K.: Global heat and salt transports by eddy movement, Nature Communications, 5, https://doi.org/10.1038/ncomms4294, 2014.

Faghmous, J. H., Frenger, I., Yao, Y. S., Warmka, R., Lindell, A., and Kumar, V.: A daily global mesoscale ocean eddy dataset from satellite altimetry, Scientific Data, 2, https://doi.org/10.1038/sdata.2015.28, 2015.

Comment 4: *Lines 74-75: "This approach demonstrates greater efficiency compared to previous Lagrangian eddy identification methods and enhances the objectivity of eddy boundary identification." This seems to be the major assumption driving this analysis, however, citations for this conclusion are not provided, and the other Lagrangian methods have not yet been introduced in the introduction at this point (lines 102-125).*

Response: We sincerely thank you for this insightful and crucial comment. You are absolutely correct that our statement in lines 74-75 was misleading and, in fact, contradictory to our main thesis. Our intention was to highlight that while the geodesic-based methods (the "approach" we referred to) provide a more objective and theoretically rigorous framework compared to earlier heuristic Lagrangian methods (such as FTLE/FSLE, mentioned in lines 53-54), they are not more computationally efficient.

The high computational cost of these methods is the primary limitation that prevents the generation of long-term, large-scale Black Hole Eddy (BHE) datasets, which is the central motivation for our study. The later section (lines 102-125) discusses the evolution of Lagrangian data availability, which further emphasizes why such a BHE dataset does not yet exist despite advances in data collection.

To correct this critical error and clarify our logic, we have completely rewritten the sentence in question. The revised sentence now reads:

- Original sentence:

"This approach demonstrates greater efficiency compared to previous Lagrangian eddy identification methods and enhances the objectivity of eddy boundary identification. Therefore, the process of solving BHE is complex (Karrasch and Schilling, 2020), but they still maintain superior coherence in the long-term transportation of flow fields. But due to the inherent complexity of the algorithm designed for detecting BHE, an efficient detection algorithm for such eddies has yet to be developed."

- Revised sentence:

"This enhances the objectivity of eddy boundary identification, representing a significant theoretical advance over previous heuristic Lagrangian methods. And the process of solving BHE is complex (Karrasch and Schilling, 2020), but they still maintain superior coherence in the long-term transportation of flow fields. However, the practical implementation of these algorithms remains computationally intensive." (Please see Line 88-92)

Reference:

Karrasch, D. and Schilling, N.: Fast and robust computation of coherent Lagrangian vortices on very large two-dimensional domains %J The SMAI Journal of computational mathematics, 6, 101-124, https://doi.org/10.5802/smai-jcm.63, 2020.

Comment 5: *Lines 107: "Lagrangian-averaged vorticity deviation (LAVD) method"; I suggest adding a citation to the original study, Haller et al. 2016 (https://doi.org/10.1017/jfm.2016.151)*

Response: Thank you for this very helpful suggestion and for providing the reference. The reviewer is correct that we should cite the original paper that introduced the LAVD method. We have now added the citation for Haller et al. (2016) at the appropriate location. (Please see Line 125)

Reference:

Haller, G., Hadjighasem, A., Farazmand, M., and Huhn, F.: Defining coherent vortices objectively from the vorticity, Journal of Fluid Mechanics, 795, 136-173, https://doi.org/10.1017/jfm.2016.151, 2016.

Comment 6: *Figure 3: Why are yellow particles drawn outside of the contours in the second and third* *timesteps, which gives the impression of eddy leakiness rather than coherence?*

Response: Thank you for this important observation. You are absolutely correct that our original Figure 3 was misleading. By showing particles outside the eddy boundary at later times, it incorrectly gave the impression of eddy leakiness, which contradicts the fundamental definition of a Black Hole Eddy.

Our true intention with this figure was not to illustrate the physical coherence of a single eddy, but rather to provide a schematic for the tracking algorithm detailed in the main text, which links a sequence of independently identified BHEs over time. We realize now that our original visualization was deeply flawed and confusing.

To address this fundamental issue, we have completely redesigned Figure 3 and rewritten its caption. The revised figure now correctly illustrates the tracking process without the misleading visual of escaping particles. The new caption explicitly states that the algorithm links a BHE identified at one time step with a new candidate BHE at the next, clarifying the logic of our methodology. (Please see Line 434-435)

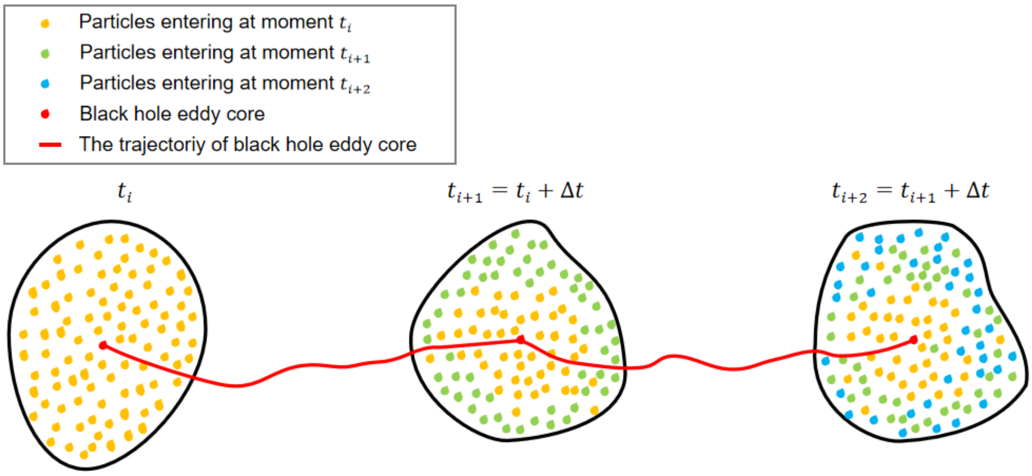

Figure 3. Schematic of the BHEs tracking algorithm.

Comment 7: *Figure 6: Are these the boundaries of eddies at age 30-day or with total 30-day lifetimes?*

Response: Thank you for this excellent question, which highlights an ambiguity in our original figure caption. To be precise, the boundaries shown are neither for eddies of 'age 30-day' nor for those with 'total 30-day lifetimes'. They represent the coherent material boundaries identified on a specific start date (4 June 2021) that remain isolated from their surroundings over a subsequent 30-day forward integration period.

To eliminate this confusion, we have revised the caption for Figure 6 to be more explicit. The revised caption now reads: "Figure 8. Comparison between identified Black Hole Eddies (BHEs) and Rotationally

Coherent Lagrangian Vortices (RCLVs) from Liu et al. (2022) over the North Pacific on 1 March 2019, over a detection time interval T = 30 days with the Finite-Time Lyapunov Exponent (FTLE) field superimposed. (a) Anticyclonic BHEs are outlined in red, cyclonic BHEs in blue, and RCLVs in black. (b, c) Zoomed-in views of two representative regions.”. (Please see Line 504-508)

Comment 8: *Figs 11 & 12: I am confused about how the features relate to each other in these panels. Are the authors arguing this is an evolution of a single eddy or two different eddies in each row? I can't tell which color corresponds to which feature due to how small the figure caption labels are.*

Response: Thankyou for pointing out the significant lack of clarity in our presentation of these case studies. You are correct that the original figure layout was confusing. Our intention was to present separate examples for anticyclonic and cyclonic Naked BHEs, and we realize that our original presentation was flawed and insufficient.

To resolve this, and to provide more comprehensive and unambiguous evidence, we have completely redesigned our presentation and expanded it into four separate figures. We now dedicate two figures to the anticyclonic case study and two figures to the cyclonic case study.

This new format allows us to clearly demonstrate the coherence of these 'Naked' BHEs and to explicitly show that they are not enclosed by corresponding contours in either the Eulerian (ADT) or the RCLV (LAVD) fields. Specifically:

New Figure 11 shows the evolution of the anticyclonic NBHE overlaid on ADT contours, demonstrating its absence in the Eulerian field.

New Figure 12 shows the same anticyclonic NBHE, but overlaid on LAVD contours, demonstrating its absence in the RCLV field.

New Figures 13 and 14 repeat this same detailed analysis for the cyclonic case study.

We have also enlarged the legends in all new figures to ensure they are clear and readable. Here are the revised figures and corresponding captions. (Please see Line 600-610)

- Orignal Figure:

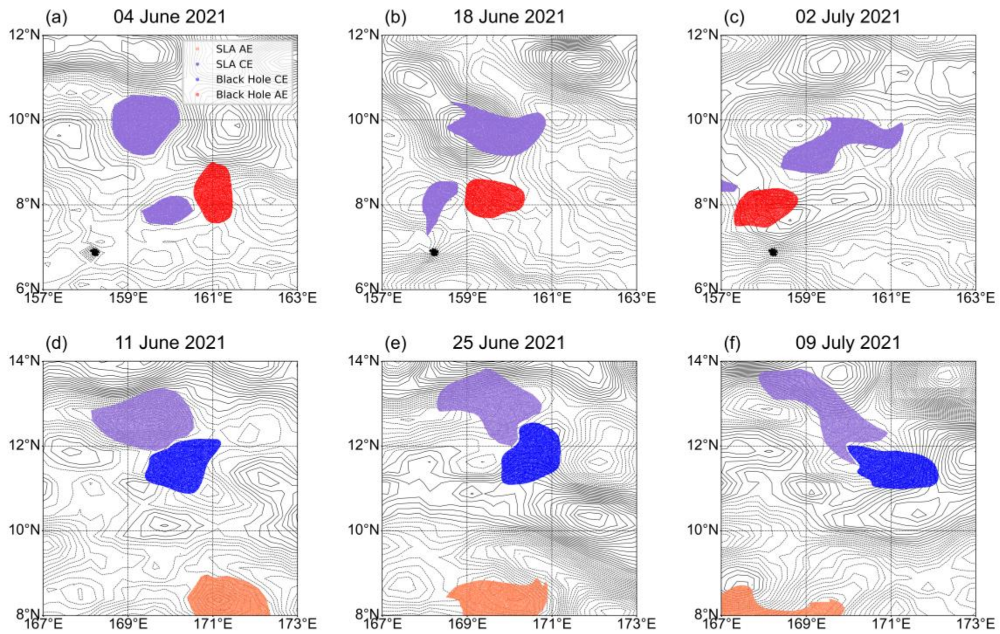

Figure 2. Positions of particles (colored dots) inside the BHE boundary and the SLA eddy boudary every 14 days. The ADT fields are overlaid using black contours with solid lines for positive values and dashed lines for negative values.

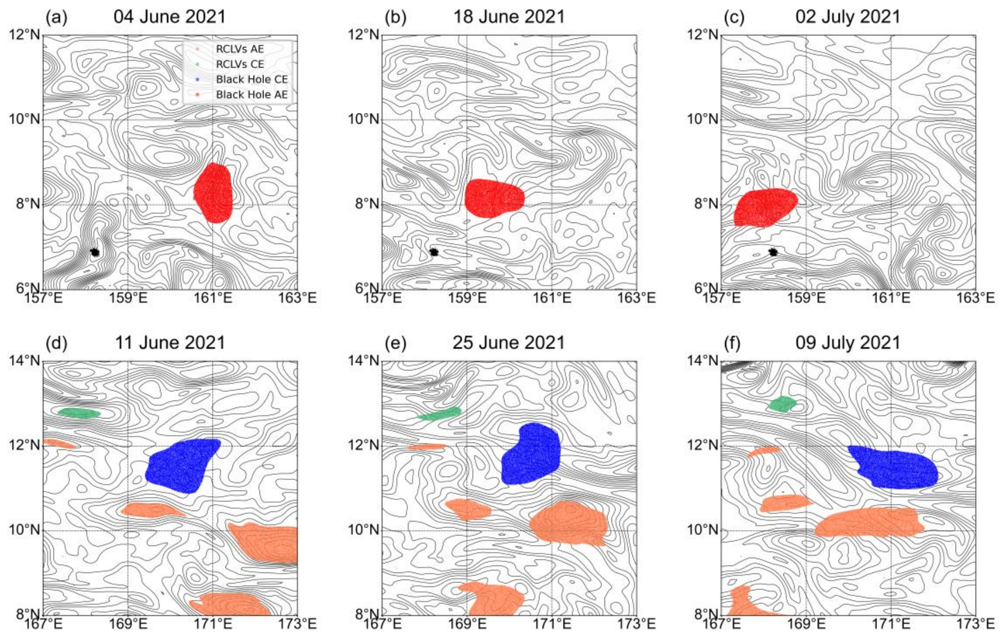

Figure 3. Positions of particles (colored dots) inside the BHE boundary and the RCLVs boudary every 14 days. The background is the LAVD fields.

- Revised Figure:

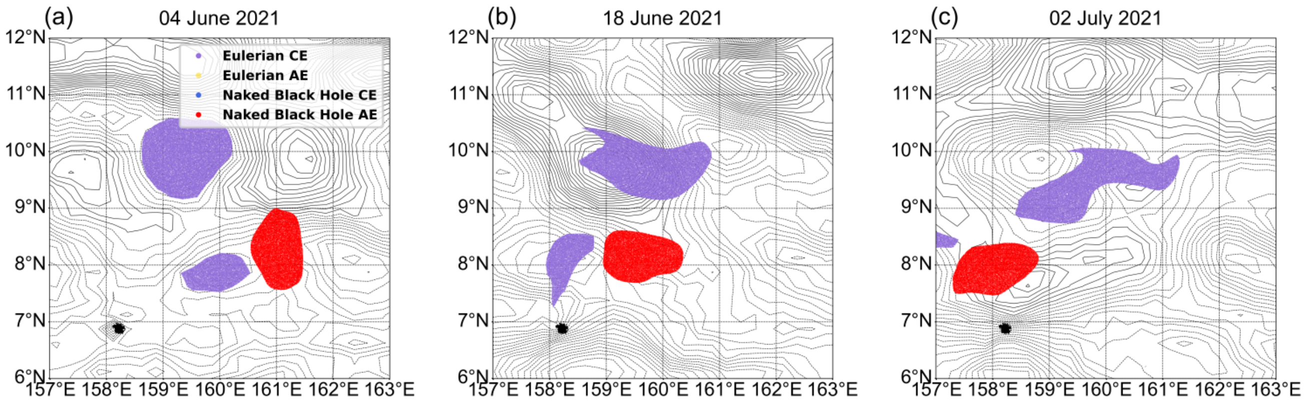

Figure 13. Evolution of an anticyclonic Naked Black Hole Eddy (red particles). The background contours show the Absolute Dynamic Topography (ADT) field.

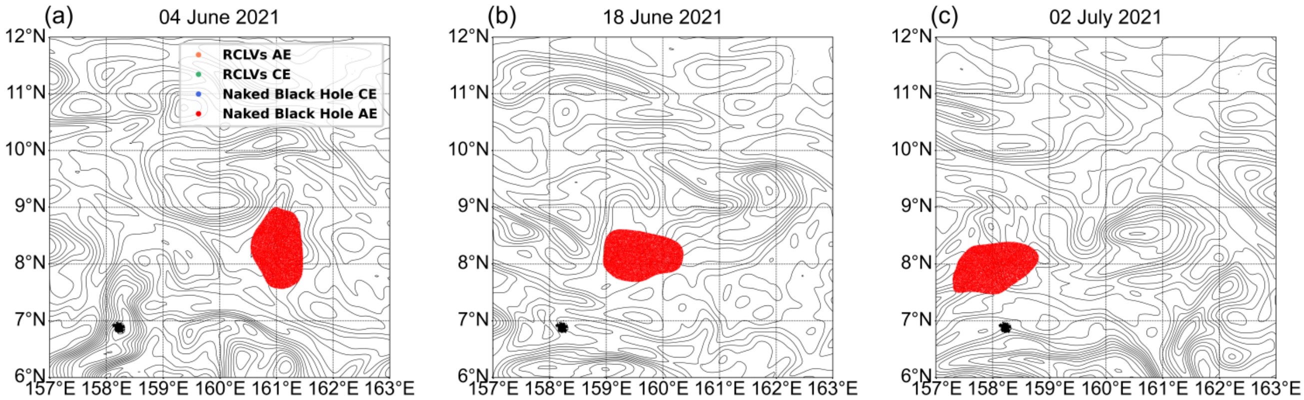

Figure 14. The same anticyclonic Naked Black Hole Eddy from Figure 11, here overlaid on Lagrangian Averaged Vorticity Deviation (LAVD) contours.

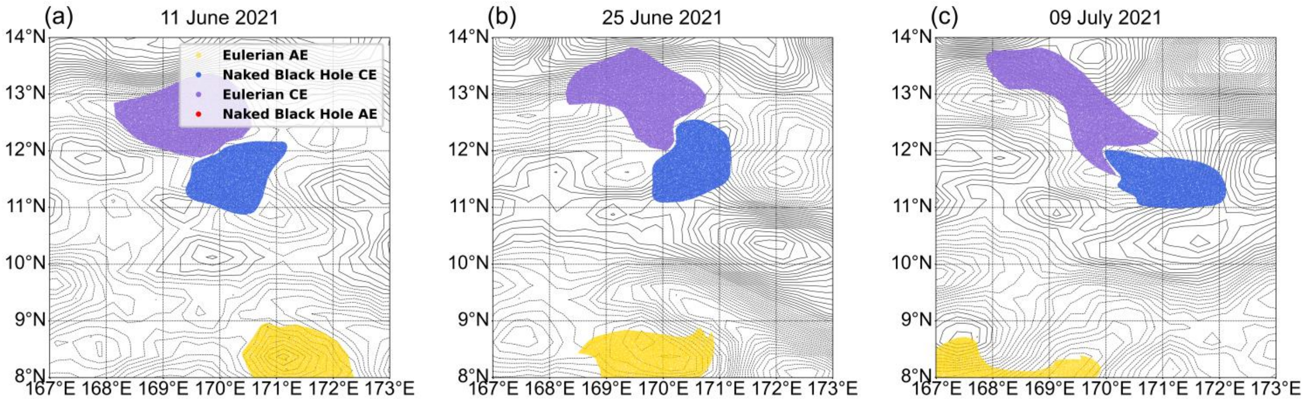

Figure 15. Evolution of a cyclonic Naked Black Hole Eddy (blue particles), overlaid on ADT contours.

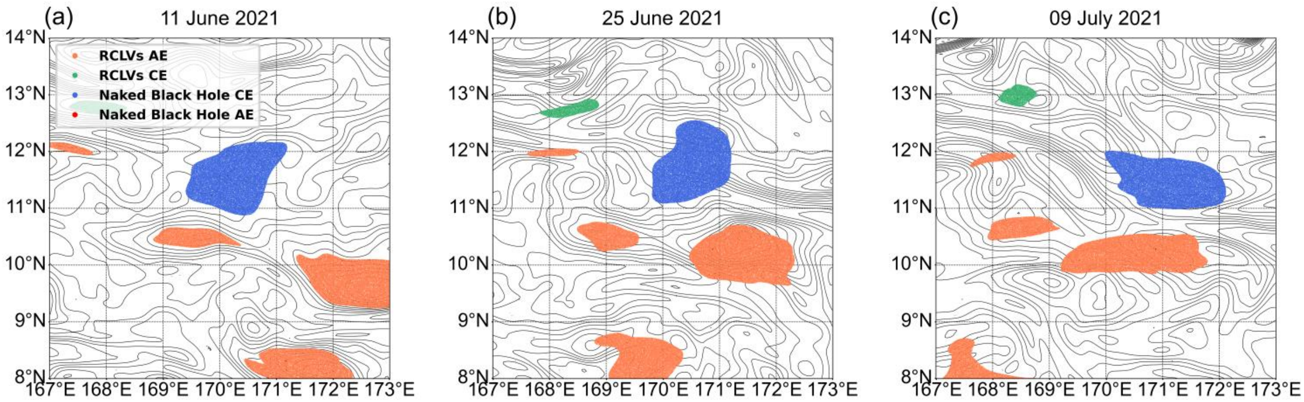

Figure 16. The same cyclonic Naked Black Hole Eddy from Figure 13, here overlaid on LAVD contours.

Comment 9: *Line 525: Double citation typo*

Response: Thank you for pointing out this typo. We have corrected the repeated citation in Line 525. (Please see Line 691)

Comment 10: *Lines 551-552: The assumptions made here of constant size with depth do not align with the structures previously reported for Lagrangian eddies (see Deogharia et al. 2024; https://doi.org/10.1038/s41598-024-61744-6), which should at least be discussed.*

Response: Thank you for this very important and constructive comment, and for bringing the recent Deogharia et al. (2024) paper to our attention. You are correct that our volume calculation is based on a simplified model that assumes a constant vertical structure, which does not capture the complex 3D nature of Lagrangian eddies reported in recent literature.

To address this, we have added sentences that explicitly acknowledges the limitations of our approach. We state that our formula is a first-order approximation, cite the work of Deogharia et al. (2024) as an example of studies showing more complex structures, and provide the rationale for using the simplified method in the context of our large-scale, altimetry-based study. We believe this addition makes the limitations of our method transparent to the reader and properly situates our findings within the evolving understanding of Lagrangian eddy structures.

The newly added sentences now read:

"We note that our volume calculation is a simplified parameterization. Recent study (Deogharia et al., 2024) has revealed the complex 3D structure of Lagrangian eddies, which our surface altimetry-based analysis cannot resolve. Therefore, we use this established method to provide a first-order volume estimate, sufficient for the climatological scope of our study." (Please see Line 729-733)

Reference:

Deogharia, R., Gupta, H., Sil, S. et al.: On the evidence of helico-spiralling recirculation within coherent cores of eddies using Lagrangian approach. Scientific Report, 14, 11014, https://doi.org/10.1038/s41598-024-61744-6, 2024.

Comment 11: *Figure 18: The caption has a typo, "distribution distributions"*

Response: Thank you for pointing out this typo. We have corrected the repeated word in the caption for Figure 18 (now in Figure. 22). (Please see Line 758)

Comment 12: *Line 617: "Unlike Eulerian eddies and RCLVs, which experience significant boundary deformation and mixing with the surrounding water during motion": it is misleading to couple Eulerian eddies with RCLVs in this way, considering that the BHEs are only marginally different than RCLVs, but both RCLVs and BHEs are substantially more coherent than Eulerian eddies.*

Response: We sincerely thank you for this important point. The reviewer is absolutely correct that it was misleading to group Eulerian eddies and RCLVs together. We recognize that both RCLVs and BHEs are advanced Lagrangian concepts representing materially coherent vortices, and they stand in contrast to the less coherent, flow-through nature of Eulerian eddies.To correct this logical flaw, we have completely restructured the sentence. The goal of the new phrasing is to first contrast Eulerian eddies with the family of coherent Lagrangian vortices (which includes both RCLVs and BHEs), and then to highlight the specific features of BHEs that are central to our analysis.

The revised sentence now reads:

- Original sentence:

"Unlike Eulerian eddies and RCLVs, which experience significant boundary deformation and mixing with the surrounding water during motion, BHE maintains a well-defined boundary and preserves their structure without significant filamentation or mixing with surrounding waters that effectively encloses and transports the water mass within."

- Revised sentence:

"Unlike traditional Eulerian eddies, whose boundaries are not material and allow for significant exchange with surrounding waters, Lagrangian vortices such as RCLVs and BHEs are defined by materially coherent boundaries that effectively trap the water mass within. Among these Lagrangian structures, BHEs are characterized by exceptionally stable boundaries that preserve their structure without significant filamentation or mixing during their motion." (Please see Line 806-810)