

Reviewer: Igor M. Belkin

Dear Reviewers,

We sincerely thank you for taking your time to review our manuscript and for providing such insightful and constructive comments. Your thorough and professional feedback has been invaluable in helping us improve the clarity, accuracy, and overall quality of our work.

We have carefully considered each of your suggestions and have revised the manuscript accordingly. Below, we provide a point-by-point response to your specific comments, detailing the changes made in response to each one. The text in blue represents the original comments.

Major issues:

Frontal pattern of the SO:

Line 49: “In the SO, the transition from the warm subtropical waters to the cold Antarctic waters is not smooth but concentrated along a series of fronts (Deacon, 1937).”

Comments: Deacon (1933, 1937) missed the Subantarctic Front (SAF) largely due to the poor spatial resolution of oceanographic observations during RV Discovery cruises, with most stations placed three degrees of latitude apart. The SAF was discovered much later. The first definitive report of SAF was published by R.W. Burling in 1961. Thus, regarding the large-scale frontal pattern of the SO, Deacon’s works of 1933 and 1937 are outdated. The first modern circumpolar surveys of the SO fronts were published by Orsi et al. (1995) and Belkin and Gordon (1996).

**Response:** Thank you for this precise and instructive comment regarding the historical context of Southern Ocean frontal research. Now, in the revised version, the reference to Deacon (1937) has been removed. The updated text now correctly cites the foundational modern studies as “In the SO, the transition from the warm subtropical waters to the cold Antarctic waters is not smooth but concentrated along a series of circumpolar fronts (Orsi et al., 1995; Belkin and Gordon, 1996).” in **Line 51**.

ACC’s northern boundary (NB):

The authors use the northern boundary (NB) of ACC, which was introduced by Park et al. (2019, pp. 4515-4516): “The streamlines corresponding to the above five circumpolar fronts are determined as follows. First, the ACC northern and southern boundaries are unambiguously defined as those circumpolar streamlines passing through the northernmost and southernmost latitudes of Drake Passage, coinciding with the MDT contour of 0.30 m for the NB and –1.11 m for the SB. There is no great alternative for defining these boundaries because their streamlines are constrained by continental slopes at Drake Passage... ..the definition of the NB from altimetry seems new. Note however that our NB runs close to the northern branch of the SAF (SAF-N) in Sokolov and Rintoul (2009) and Barré et al. (2011). Indeed, it is shown in the following subsection that the newly defined NB from altimetry matches well with the SAF-N identified from hydrography in the study area. Therefore, the altimetry derived NB and the hydrography-derived SAF-N are used interchangeably in this study.”

Also, L123: “Park et al. (2019) produced the most updated mapping of the ACC fronts. As shown in Figure 1, from north to south, the key fronts include the northern boundary of ACC (NB), the Subantarctic Front (SAF), the Polar Front (PF), the Southern Antarctic Circumpolar Current Front (SACCF), and the southern boundary of the ACC (SB).”

Comments: Fronts are commonly defined as narrow high-gradient zones. The ACC’s northern boundary (NB) defined by Park et al. (2019) is a streamline, not a front. Therefore, the authors should not use NB in their analysis. Traditionally, the northern boundary of ACC is the Subantarctic Front (SAF).

**Response:** Thank you for your insightful comment regarding the definition of Antarctic Circumpolar Current (ACC) fronts and our use of the term “Northern Boundary (NB)”. We fully agree with you that the Subtropical Front (STF) is traditionally used as the northern boundary of the ACC (Orsi et al., 1995).

Our reference to the “NB” stems from our reliance on the consistent frontal dataset of Park et al. (2019). In that work, the authors provided an operational, circumpolar definition of ACC boundaries using satellite altimetry, defining the NB as the specific Mean Dynamic Topography (MDT) contour of 0.30 m that passes through the northernmost latitude of Drake Passage.

Crucially, Park et al. (2019) explicitly state that this altimetry-derived NB coincides with the hydrographically identified northern branch of the Subantarctic Front (SAF-N), which was identified as the northernmost jet along P16S (Figure 6 in their paper). To quote directly from their manuscript (Page 6): “...the newly defined NB from altimetry matches well with the SAF-N identified from hydrography in the study area. Therefore, the altimetry-derived NB and the hydrography-derived SAF-N are used interchangeably in this study.” Furthermore, about the streamlines, they explained explicitly as “The choice of these streamlines is not arbitrary but is constrained by well-defined frontal positions from both altimetry and hydrography.” Therefore, our use of “NB” was intended to precisely adopt this objective, altimetry-based boundary definition from Park et al. (2019), ensuring methodological consistency for spatial comparisons.

We recognize that our initial wording did not sufficiently clarify the distinction between this operationally defined boundary streamline and the canonical dynamical definition of a front, which may have caused confusion. To fully address your concern and align with the traditional frontal concept, we have revised the full paragraph in **Lines 119-126** as: “The geographical positions of the ACC’s fronts and boundaries used in this study are from the synthesis of Park et al. (2019). This dataset provides the most updated mapping of the ACC frontal system and its associated boundaries, derived from satellite altimetry and independently validated against extensive subsurface observations, including Argo float profiles (2001–2017) and dedicated CTD surveys (2016–2017). As shown in Figure 1, the dataset defines five major streamlines from north to south: the Northern Boundary (NB), the Subantarctic Front (SAF), the Polar Front (PF), the Southern ACC Front (SACCF), and the Southern Boundary (SB). Specifically, the NB represents the northern dynamical limit of the ACC and coincides with the northern expression of the Subantarctic Front system (SAF-N) in this region. The SAF, PF, and SACCF correspond to the core frontal jets.”

#### Eddy tracking:

L150: “SLA data with 0.25° spatial resolution were first linearly interpolated to 0.125° for better performance in eddy detection.”

Comments: The interpolation does not mitigate the poor spatial resolution (28 km) of SLA data. Such data is inadequate for studies of mesoscale eddies, whose diameters can be as small as 40-50 km.

**Response:** Thank you for your valuable comments on the spatial resolution of SLA data, which was 0.25° in the original manuscript. We totally agree with your concern that approximately 28 km resolution is not sufficient to resolve the mesoscale eddies in the Southern Ocean. Now, we have changed to using a new product with a spatial resolution of 0.125° × 0.125° (approximately 14 km) from the CMEMS all-satellite L4 SLA product (SEALEVEL\_GLO\_PHY\_L4\_MY\_008\_047). This dataset provides a more appropriate foundation for mesoscale analysis. Further, we acknowledge that even a 0.125° grid may not effectively resolve the smallest eddies in the Southern Ocean. To ensure the robustness of our findings, our methodology incorporates stringent post-detection criteria that focus the analysis on well-resolved, significant eddies:

- (1) **Lifespan > 14 days** (ensuring temporal coherence beyond synoptic noise).
- (2) **Amplitude > 5 cm** (selecting energetically meaningful signals).
- (3) **Radius > 30 km** (resolving structures well above the native grid scale).

The minimum radius criterion of 30 km guarantees that the eddies analyzed for our core scientific conclusions have a minimum physical diameter of 60 km, which covers approximately 4 grids. This filter systematically excludes smaller, marginally resolved features, ensuring that our statistical results on cross-frontal eddy characteristics are derived from a high-confidence dataset of eddies that are, by design, well above the effective resolution limit of the input data.

In summary, we have addressed the concern about data resolution by (i) employing a higher-resolution (0.125°) altimetry product throughout our analysis; (ii) implementing a conservative size filter (radius > 30 km) that restricts our study to eddies large enough to be reliably resolved by the data grid. We believe these methodological choices ensure the rigor and validity of our study. Thank you again for your insightful comment, which has helped us improve the clarity of our methodology.

L152: “For eddy tracking, the algorithm identifies eddies at time  $t+1$  that meet the following criteria relative to time  $t$ : (1) minimal centroid distance, (2) identical polarity (i.e., rotation direction), and (3) the minimum radius variation.”

Comments: Traditionally, ocean eddies are tracked using their thermohaline (TS) signatures. This is a standard approach successfully utilized in hundreds of field campaigns and data analyses. The authors’ ignorance of TS signatures of individual eddies is a major flaw of this study.

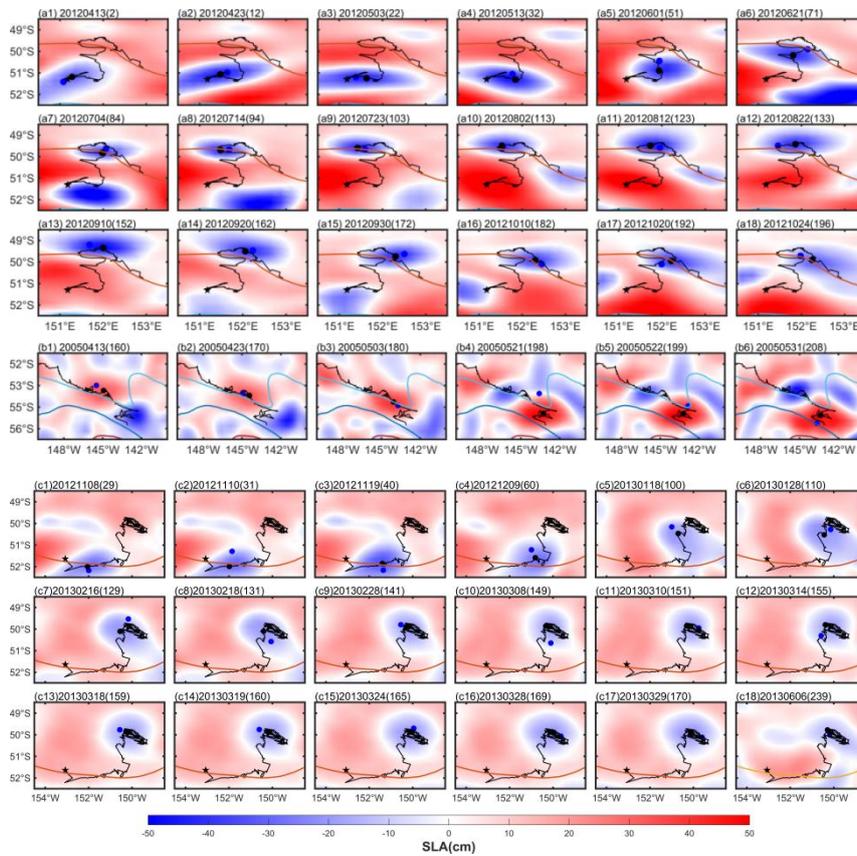
**Response:** Thank you for raising this important point regarding the methodology for eddy tracking and characterization. We agree with you that thermohaline (TS) signatures are a fundamental and powerful tool for identifying and tracking coherent water masses in eddies.

We respectfully wish to clarify that our study employs a complementary and equally established methodology, which is then robustly validated using TS signatures. Our approach is designed to address a different scale of scientific question: conducting a statistically robust, basin-scale census of mesoscale eddies and their interactions with frontal systems over multiple years, for which satellite altimetry provides the requisite synoptic coverage and temporal continuity.

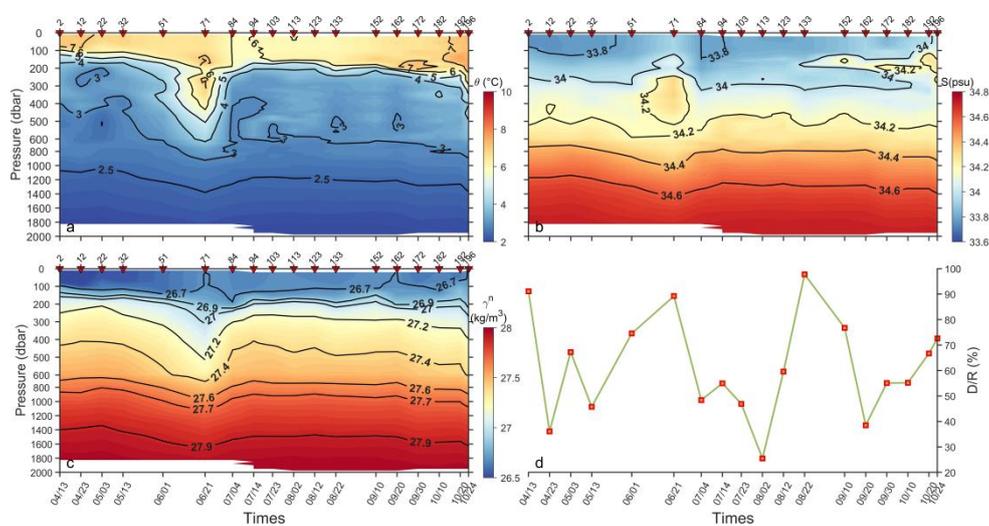
Crucially, we do not ignore TS signatures. To confirm that the eddies tracked by our satellite-based algorithm represent physically coherent, water-mass transporting eddies (and not mere artifacts of the tracking scheme), we performed a rigorous validation using independent Argo float data. **3.3 section in the manuscript provides a comprehensive comparison of the internal thermohaline structures between anticyclonic eddies (AEs) and cyclonic eddies (CEs)**, with Figure 8 showing individual thermohaline characteristics detected in AEs and CEs and Figure 9 exhibiting normalized sectional distributions. **Furthermore, we also identified several long-lived eddies that entrapped Argo profiling floats for extended periods (up to 194 days)**. Throughout these multi-month, cross-frontal journeys, the Argo floats provided continuous TS profiles in the eddy interior (as shown in the following Figures R1 to R4). These TS characteristics remained coherent throughout the eddies’ lifespans, even as they crossed sharp frontal boundaries, demonstrating the eddies’ material coherence and our algorithm’s ability to correctly track them.

Therefore, our methodology integrates the strengths of both approaches, which satellite altimetry provides the large-scale, statistical framework necessary for our study’s objectives, and independent Argo float data provides the physical validation. We believe this combined approach, large-scale objective tracking validated by direct

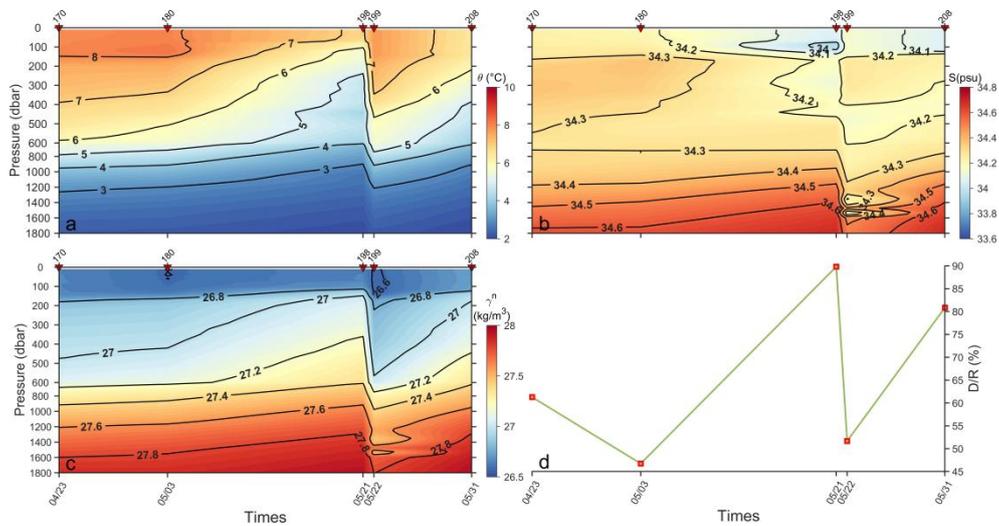
physical observations, is a strength of our work, not a flaw. It allows us to draw statistically significant conclusions about Southern Ocean eddy-front interactions while being firmly grounded in observational physics.



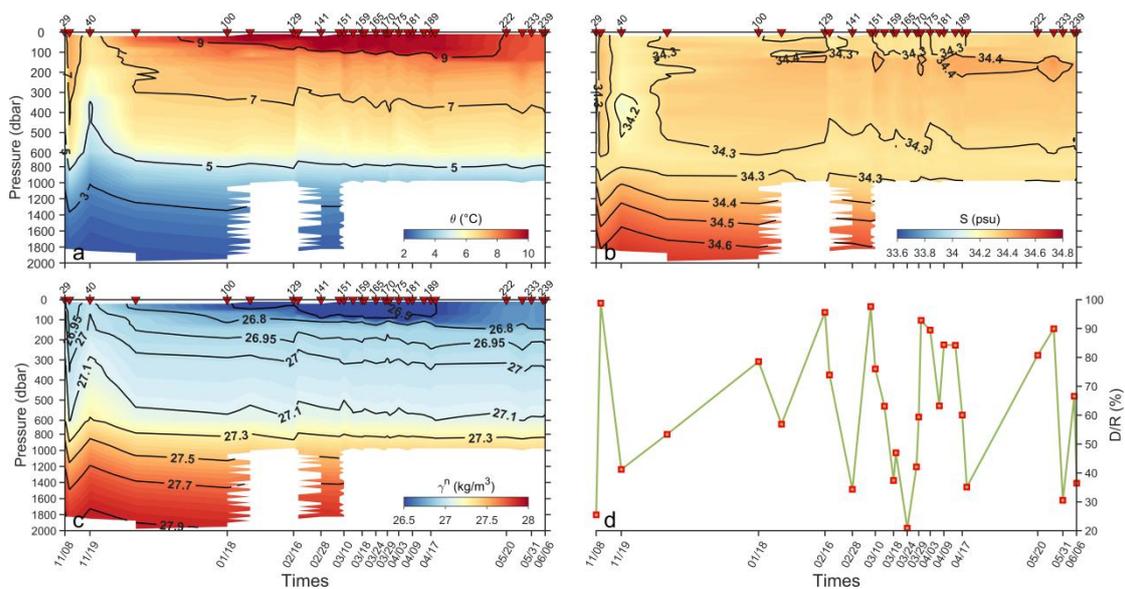
**Figure R1. Spatiotemporal evolution of the three cross-frontal eddies (CFEs) and associated Argo float positions. a1–a18: First cyclonic eddy (CE); b1–b6: Second anticyclonic eddy (AE); c1–c18: Third CE. Black and blue dots denote real-time positions of eddy centers and Argo profiles, respectively. Stars represent the eddy genesis points. Black lines are complete propagation trajectory over the eddy’s lifespan. Red and blue lines indicate the Subantarctic Front (SAF) and the Polar Front (PF), respectively. Dates are marked above each subplot, and the number in parentheses represents the number of days since it was generated.**



**Figure R2. Sectional distributions within the first detected CE in a1-a18 of Figure R1. (a) potential temperature, (b) salinity, (c) neutral density; (d) Time series of normalized distance (Argo distance from eddy center divided by eddy radius).**



**Figure R3. The same as Figure R2, but for the detected AE in b1-b6 of Figure R1.**



**Figure R4. The same as Figure R2, but for the detected CE in c1-c18 of Figure R1.**

L156: “Based on eddy identification and tracking results, this study focuses on eddies with lifespans exceeding 7 days and amplitudes greater than 2 cm.”

Comments: Mesoscale eddies have a typical lifespan ranging from several weeks up to a few years (rings of major currents). Their typical SSHA amplitudes range widely. In the Southern Ocean, the mean SSHA is 12 cm (Frenger et al., 2015, JGR). In the North Pacific, the SSHA ranges from 10 cm to 30 cm and higher (Ebuchi and Hanawa, 2001, Journal of Oceanography, Fig. 2 and Fig. 3). Rings spawned by major currents have SSHA > 40 cm in the Gulf Stream area (Belkin et al., 2020, JPO, Fig. 11), 35-50 cm in young Agulhas rings (van Aken et al., 2003, DSR2; Schmid et al., 2003, DSR2; Wang et al., 2016, JGR) and up to 60 cm in the South Atlantic (Souza et al., 2011, Ocean Science, Table 2). Thus, the 7-day, 2-cm SSH anomalies are hardly qualified as mesoscale eddies.

Such anomalies should be considered noise, especially given the accuracy of satellite altimetry of about 1-2 cm.

**Response:** Thank you for this exceptionally insightful and critical comment. Our originally stated criteria (lifespan > 7 days, amplitude > 2 cm) were indeed far too permissive and would include signals comparable to altimetric noise or sub-mesoscale variability, rather than robust mesoscale eddies.

In direct response to this pivotal point, we have performed a fundamental revision of our core methodology. All eddy detection, tracking, and subsequent statistical analyses in the revised manuscript are now based on a rigorously filtered dataset of “significant eddies”. The revised Methods section now explicitly states the following conservative criteria:

(1) **Lifespan > 14 days.** This ensures temporal coherence well beyond synoptic-scale noise and short-lived features.

(2) **Amplitude > 5 cm.** This selects for energetically meaningful signals above the typical altimetric error (1-2 cm). It effectively filters out the “noise” rightly cautioned by the reviewer. **Here, we respectfully wish to clarify that the eddy amplitude is the absolute sea level anomaly (SLA) difference between the center and along the contour (Lines 154-155) rather than the SSHA relative to the entire background sea level height.**

(3) **Radius > 30 km.** This guarantees that the analyzed structures are well-resolved spatially, with a diameter (>60 km) that clearly qualifies as mesoscale.

This change is among the most significant improvements to our work. By applying these strict, physics-based filters, we ensure that all reported statistics are derived exclusively from a high-confidence population of true, coherent mesoscale eddies, not algorithmic artifacts or noise.

Frontal zones:

L165: “While climatological fronts define the ACC’s mean structure (Park et al., 2019), their positions exhibit meridional variability influenced by both bathymetry and eddy activity (Kim and Orsi, 2014; Thompson et al., 2010): Fronts stabilize over major bathymetric features (e.g., the Pacific-Antarctic Ridge) but show maximum variability in flat basins, with widened frontal zones developing downstream of obstacles like the Campbell Plateau. To account for topographically induced frontal displacements, we defined frontal zones as a strap  $\pm 15$  km expanded in the normal directions from each climatological front, consistent with observed SO frontal oscillation area (Kim and Orsi, 2014).”

Comments: The 15 km threshold grossly underestimates the real observed shifts of SO fronts. Frontal meanders lead to frontal shifts of up to  $\sim 100$  km in either direction. When a frontal meander pinches off and forms a ring, the ring diameter is typically on the order of 100 km. The 30-km-wide frontal zone definition thus makes little sense.

L433: “...this study defines each frontal zone as a 30 km-wide strip-shaped area but does not account for potential interannual or seasonal variations that may extend beyond this range. Similarly, all qualified Argo profiles from 2000 to 2022 were used without considering interannual or seasonal variability in hydrographic properties. These limitations inevitably introduce certain uncertainties.”

Comments: In addition to seasonal and interannual shifts of individual fronts, these fronts experience so-called synoptic (or intra-seasonal) variability caused by meanders. Such meanders effectively lead to shifts of individual fronts on the order of 100 km in cross-frontal directions.

**Response:** Thank you for your insightful comments regarding the definition of the frontal zone width. We fully agree with your core concern: the synoptic/intra-seasonal meandering of Southern Ocean fronts can indeed reach amplitudes on the order of  $\sim 100$  km due to a meandering structure, and our original definition of a fixed  $\pm 15$  km

half-width (30 km total) zone did not adequately represent this observed variability, potentially calling into question the representativeness of our method.

Your critique prompted a fundamental re-evaluation and strengthening of our methodology. Below, we detail the substantive improvements implemented to address this concern and the rationale behind our final methodological choices.

### **1. Core Enhancement: Introducing a Radius-Dependent Physical Criterion to Define the “Effective Crossing Scale”**

To ensure that the statistically identified “crossing” events correspond to genuine physical interactions matching the observed scales, we introduced a strict geometric criterion based on each eddy’s instantaneous radius ( $R$ ) as an eddy was considered to have entered (exited) the frontal zone once its boundary first touched (last detached from) the frontal zone boundary (Lines 177-184), which means that an eddy is recorded as having “completely crossed” a frontal zone only when its entire circular contour has moved completely outside the  $\pm 15$  km band centered on the climatological frontal position. Under this criterion, a recorded “complete crossing” requires the eddy center to cross a distance greater than  $(15 \text{ km} + 2R + 15 \text{ km})$ . For an eddy with a typical radius  $R = 40$  km, the required center propagation at least reaches 110 km during frontal crossing. In contrast, an eddy with the same radius is regarded as partially or transiently crossing fronts when its center propagates less than 110 km.

This criterion ensures non-contamination of the frontal meanders, as you mentioned. If this meander evolves to an eddy, according to its further behavior, our method will detect it as a frontal-generated or transient eddy. Otherwise, there is no eddy at the meandering place. This addresses the concern about “width underestimation” at the level of event definition physics.

### **2. Rationale for the Width Selection: Based on Robustness Verification and Physical Constraints of a Multi-Front System**

Building upon the above criterion, our decision to retain the  $\pm 15$  km half-width in the main text is based on the following validated, multi-faceted reasoning:

#### **a) Verified Robustness of Conclusions (Appendix Analysis):**

To test the sensitivity of our conclusions to the width choice, we performed, as you suggested, a systematic test in the Supplementary Materials by expanding the half-width to  $\pm 25$  km (applying the same radius criterion). The results confirm that all core conclusions (e.g., the polarity/direction asymmetry of CFEs, their energy budgets) remain fully robust. This demonstrates that our key findings are not an artifact of the specific 15 km value.

#### **b) Physical Constraint of Avoiding Multi-Front Overlap (A Decisive Factor):**

This study analyzes multiple ACC fronts (e.g., SAF, PF) that are often in close proximity. Adopting a wider half-width (e.g.,  $\pm 30$  km or more) would cause severe overlap of the “interaction zones” of adjacent fronts. This would make it statistically impossible to distinguish with which specific front an eddy interacted, thereby fundamentally undermining the study’s goal of revealing potential front-specific eddy dynamics. The  $\pm 15$  km half-width represents a necessary trade-off between adequately characterizing the physical process and maintaining the analytical resolvability of the multi-front system structure.

#### **c) Supporting Regional Context (Revised for Accuracy):**

Our use of climatological mean frontal positions as a baseline is also informed by the specific oceanographic context of our study region. Kim and Orsi (2014), in their analysis of the southeast Pacific sector ( $150^\circ$ – $90^\circ$ W), which encompasses our core study area, concluded that ACC frontal displacements there exhibit “no apparent seasonal cycles” in their altimetry record. They attribute the observed large year-to-year meridional fluctuations primarily to interannual climate forcing (e.g., ENSO) rather than a dominant seasonal signal. This absence of a strong, repeating seasonal migration supports the use of a climatological mean position as a stable reference frame for investigating the higher-frequency, synoptic-scale eddy-front interactions that are the focus of our work.

### 3. Summary of Textual Revisions

We have revised the manuscript to ensure methodological transparency as follows:

**a) Main Text “Data and Methods” Section:** Clearly describes the new radius-dependent geometric criterion and explicitly states that the choice of a  $\pm 15$  km half-width is based on careful considerations, representing a balance between physical realism, statistical robustness, and system complexity. (Lines 171-184)

**b) Supplementary Materials (Appendix):** A new dedicated section provides a complete report on the “Sensitivity Analysis Based on a  $\pm 25$  km Half-Width”, serving as key evidence for the robustness of our conclusions.

We believe the revised manuscript now handles this issue with greater rigor and transparency. Thank you again for your insightful review.

Cross-frontal eddies:

L193: “CFE occurrence peaks downstream of prominent topographic features, particularly near the Campbell Plateau ( $150^{\circ}\text{E}$ – $180^{\circ}\text{E}$ ; 39% of total CFEs) and downstream of the Udintsev Fracture Zone ( $125^{\circ}\text{W}$ – $160^{\circ}\text{W}$ ; 38%), where multiple fronts converge (Figure 2a). Eddies may cross multiple fronts sequentially at these frontal convergent regions. The majority of eddies cross a single front (Figure 2c). Double-frontal crossings (total 434) occur preferentially at southern fronts (SACCF/SB;  $> 50\%$  of cases; Figure 2d). Triple-frontal crossings are rare and primarily limited to the PF/SACCF/ SB system (Figure 2e), and no instances of quadruple-frontal crossings were observed.”

Comments: The cross-frontal transport by rings spawned by fronts is well known. However, the cross-frontal transport by other types of mesoscale eddies is a totally different phenomenon, which is exceedingly rare and not well documented from in situ observations. Dufour et al. (2015, JPO) wrote: “However, meridional transport in the Southern Ocean requires crossing multiple intense jets that form the ACC fronts and act as natural barriers to tracer transport. Both observational and experimental studies have demonstrated that mixing across the core of jets is strongly inhibited due to the speed of the jet being higher than the propagation speed of eddies, hence reducing the time during which eddies can stir tracers (e.g., Bower et al. 1985; Lozier et al. 1997; Sommeria et al. 1989; Ferrari and Nikurashin 2010). Nonetheless, strong perturbations, such as rings detaching from the front, might provide a way for tracers to cross the jet cores (Samelson 1992; Wiggins 2005).” – Comments: The above excerpt from Dufour et al. (2015, JPO) makes clear that the cross-frontal eddy transport is likely effectuated by rings, while the cross-frontal transport by other types of mesoscale eddies is exceedingly small except for the cross-frontal transport by subsurface (intrathermocline) lenses at depth (e.g., Bower et al., 2013, DSR2). Thus, the probability of the same eddy crossing multiple fronts is infinitesimally small. Nonetheless, the authors claim that their algorithm detected numerous cases of multiple frontal crossings by the same eddies, with 434 cases of double-frontal crossings, and several cases of triple-frontal crossings (lines 197-198 and Figure 2e). It seems that these numbers are artifacts that resulted from a faulty eddy tracking algorithm.

**Response:** Thank you for this essential critique concerning the physical plausibility of multi-frontal eddy crossings and the integrity of our tracking algorithm. We address the two core concerns (1) the perceived contradiction with the classical paradigm and (2) the potential for algorithmic artifacts.

#### 1. Contextualizing Our Findings Within the Classical Paradigm

We agree with the reviewer and with Dufour et al. (2015) that, for a canonical, isolated frontal jet, cross-jet transport is dominated by rings, presenting a high barrier for other eddies. **However, our findings do not contradict this but instead identify an important exception within the specific dynamical setting of ACC frontal convergence zones** (e.g., downstream of the Udintsev Fracture Zone). In these regions, multiple fronts (SAF, PF, SACCF) are compressed into a narrow meridional band ( $\sim 100$ – $200$  km). This configuration

fundamentally alters the dynamical environment, increasing the probability that a single, robust eddy may interact sequentially with more than one frontal jet during its lifetime.

## 2. Algorithmic Rigor and In Situ Validation Against Artifacts

The assertion that our detection is algorithmic artifacts is countered by our method's conservative design and, decisively, by independent observational validation.

**a)Conservative Methodology:** Our analysis is restricted to strong, coherent eddies by strict post-detection filters (lifespan >14 days, amplitude >5 cm, radius >30 km). The crossing detection requires an eddy's complete contour to move across a defined frontal zone, preventing false positives from meanders.

**b)Definitive Lagrangian Proof:** The most direct validation comes from in situ Argo float trajectories. We identified cases where long-lived eddies, tracked by our algorithm, entrapped floats for months. One exemplary eddy (shown as b1-b6 in Figure R1, Figure R3) **transported a float completely across the Subantarctic Front (SAF) and subsequently to the immediate vicinity of the Polar Front (PF)**, maintaining a coherent thermohaline signature throughout. This proves our algorithm tracks **real, materially coherent eddies** capable of sustained cross-frontal propagation and interaction with multiple frontal systems, the precise physical prerequisites for the sequential interactions we report statistically.

In summary, the multi-front crossing events we report are a credible feature of ACC frontal convergence zones. They involve robust eddies (a population that includes rings, **Lines 191-192**) within a unique dynamical geometry and are validated by direct Lagrangian evidence.

Minor edits:

L55: "Practically" – Delete.

**Response:** Thank you for the suggestion. The word "Practically" has been deleted (**Line 57**).

L73: "Electrona calserbgi" should be "Electrona carlsbergi"

**Response:** Thank you for spotting this typographical error. The species name has been corrected to "Electrona carlsbergi" (**Line 74**).

L84: "mitigating the eastward flow in the ACC" – "Mitigating" is not the best term in the given context.

**Response:** Thank you for your suggestion. Now "mitigating" has been revised to "acting to moderate" in **Line 85**.

L108: "the Campbell Plateau, Pacific-Antarctic Ridge, and Udintsev Fracture Zone (Figure 1)." – Add the Eltanin Fracture Zone to the text and to the maps in Figure 1 and elsewhere.

**Response:** Thank you for this suggestion. As advised, the **Eltanin Fracture Zone** has been added to Figure 1, the list of prominent topographic features (**Line 109**).

L112: "during 2000 and 2022" should be "during 2000-2022"

**Response:** Thank you. It has been revised following your suggestion (**Line 115**).

L216: "and mitigate thermohaline gradients across frontal zones." – Comments: Replace "mitigate" with a more appropriate term."

**Response:** Thank you. Now, we have revised "mitigate" to "reduce" in **Line 231**.

L239: “display marked longer lifespans” should be “display markedly longer lifespans”

**Response:** Thank you. This sentence has been revised into “completely transported CFEs exhibit markedly different dynamical characteristics...” in [Line 251](#).

L284: “Note the x-axis in a–b are not equidistant at higher values.” – Rewrite.

**Response:** Thank you. This sentence has been rewritten into “The x-axes in (a) and (b) are compressed at higher values” in [Line 325](#).

L334: “Argo  $\theta$ -S profiles (Figure 8) demonstrate that marked meridional thermohaline gradients exist between eddy intervals in different interfrontal zones, with colder and fresher water properties poleward. In the same zones, CEs consistently exhibit colder, fresher properties with shallower isopycnals (upper 1000 dbar), while AEs contain warmer, saltier waters with deeper isopycnals, reflecting their respective meridional origins.” – Comments: This is a trivial observation: From north to south, the SO temperature and salinity generally decrease across all fronts and interfrontal zones. This general ocean-wide trend has been known for a century.

**Response:** Thank you for this critical comment. To sharpen the focus, we have revised the opening of this paragraph to immediately highlight our key observational finding: the systematic hydrographic differences between CEs and AEs within the same interfrontal zones, which directly reflects their contrasting meridional origins and trapping capabilities. The revised text now reads: “Argo  $\theta$ -S profiles (Figure 8) reveal that within the same interfrontal zones, cyclonic eddies (CEs) and anticyclonic eddies (AEs) exhibit distinct, polarity-dependent hydrographic signatures. CEs consistently show colder, fresher properties with shallower isopycnals (upper 1000 dbar), whereas AEs contain warmer, saltier waters with deeper isopycnals.” in [Lines 377-380](#).

L423: “CFEs mitigate cross-frontal water mass property gradients” – Comments: Avoid using “mitigate” regarding gradients.

**Response:** Thank you. We have replaced “mitigate” with the more objective term “reduce” in [Line 484](#).

L456: “This process directly mitigates the sharp meridional gradients.” – Comments: Avoid using “mitigate” regarding gradients.

**Response:** Thank you. This sentence has been deleted in the new version.

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Response to Reviewer 2:

### Major issues:

#### Altimetry Dataset and Eddy Detection and Tracking (EDT)

**Comments:** The manuscript uses the C3S DUACS two-satellite L4 SLA product. While a fixed two-altimeter constellation can improve long-term stability/homogeneity (important for climate metrics), the C3S QUID

explicitly states that the all-satellite CMEMS products provide better spatial sampling and reduced mesoscale errors and “should be preferred for oceanic mesoscale applications,” whereas the C3S two-satellite products are intended for climate applications. The authors should justify this choice in the context of eddy detection/tracking, and ideally add a short sensitivity test (e.g., a representative sub-period) comparing C3S vs CMEMS all-satellite to show that eddy counts/sizes/intensities and the main conclusions are not materially affected.

**Response:** Thank you for this insightful and critical comment regarding the suitability of the altimetry dataset for eddy detection studies. We fully agree with the reviewer’s assessment.

In direct response, we have replaced the previously used C3S DUACS two-satellite L4 SLA product with recommended and more appropriate CMEMS all-satellite L4 product (SEALEVEL\_GLO\_PHY\_L4\_MY\_008\_047). As explicitly stated in the official Product User Manual (Pujol and Grassi, 2025), the all-satellite products provide superior spatial sampling and lower mesoscale errors, and “should be preferred for oceanic mesoscale applications” (Section 2.i), whereas two-satellite products are intended for climate-scale studies prioritizing long-term stability.

Given that we have now adopted the dataset specifically recommended for mesoscale analysis, which represents the current best practice for studies like ours, we believe a direct comparison with the less suitable previous dataset is not necessary. The new analysis, therefore, is based on the most robust and appropriate data foundation from the outset. All eddy detection, tracking, and subsequent analyses in the revised manuscript have been performed using the superior CMEMS all-satellite product.

**Comments:** Several recent eddy atlases and methodologies increasingly rely on ADT rather than SLA for eddy detection/tracking, as SLA removes the mean dynamic topography and may therefore suppress quasi-permanent features associated with standing meanders, jets, or long-lived structures (e.g., Laxenaire et al., 2018; Pegliasco et al., 2022). Please justify the use of SLA here and clarify whether using ADT would affect eddy detection and the inferred eddy–front relationships.

**Response:** Thank you for raising this important point regarding the use of SLA versus ADT. We acknowledge that ADT is indeed valuable for capturing quasi-permanent features like frontal jets. However, for the specific objectives of our study, focusing on the properties and cross-frontal behavior of propagating mesoscale eddies, the use of SLA is not only standard but methodologically more appropriate for the following reasons:

First, the core dynamic variable for analyzing propagating eddies is the geostrophic velocity anomaly ( $u',v'$ ), from which Eddy Kinetic Energy ( $EKE$ ) is derived ( $EKE=(u'^2+v'^2)/2$ ). These velocity anomalies are calculated directly from the gradients of the SLA field via the geostrophic relationship. Therefore, the SLA field is effectively the streamfunction for the anomalous flow associated with eddies. Defining eddy boundaries using closed SLA contours is a well-established and physically robust method, as employed in foundational global datasets (e.g., Chelton et al., 2011) and the specific algorithm we adopted (Saraceno and Provost, 2012). Using ADT, which represents the absolute flow including the large-scale background, would inherently suppress the signal of eddies embedded within strong frontal jets.

Second, to quantitatively address your concern, we performed a comparative eddy detection analysis using both ADT and SLA in an energetic region (the Brazil/Malvinas Confluence and the Brazil Current retroflexion system; see Figure R1). The results confirm the expected trade-off: (1) As noted, ADT excellently captures the major jets and large meanders, which are absent in the SLA field. (2) Crucially, however, the SLA-based method detected a larger number of smaller, propagating eddies, particularly at the peripheries of the energetic region. Eddy parameters (radius, amplitude) derived from SLA were also more representative of the mesoscale signal. This demonstrates that while ADT is superior for studying the mean flow, SLA is more sensitive to the transient

mesoscale eddies that are the focus of our study.

Third, we wish to clarify that the climatological positions of the ACC fronts used in our study (from Park et al., 2019) were themselves derived from a mean dynamic topography product (MDT, specifically CNES-CLS18), which is the time-averaged component of the ADT. Therefore, the frontal zones against which we measure eddy interactions are already defined using the “absolute” field recommended for identifying quasi-permanent features. Our methodology thus appropriately uses SLA (for the transient eddies) in conjunction with an MDT-based product (for the semi-permanent fronts).

In conclusion, our choice of SLA is grounded in the fundamental physics of eddy dynamics and is the standard for this type of analysis. The comparative test confirms that it optimizes the detection of the propagating mesoscale eddies central to our research questions. We are confident that this approach is the most suitable for investigating cross-frontal eddy transport.

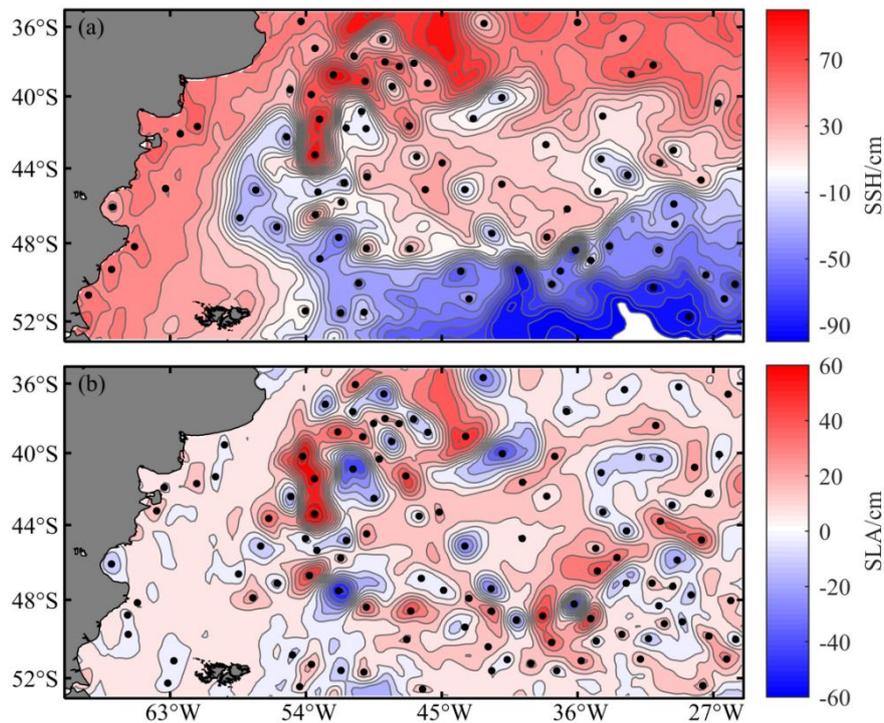


Figure R1. Comparison of eddy detection results based on SSH (or ADT, a) and SLA (b), respectively on Jan. 1<sup>st</sup>, 2019. Black dots are eddy centers. Contour intervals both for ADT and SLA are 8 cm.

145-147: “A threshold  $W = -0.2\sigma_w$  was often chosen to identify the outer boundary of an eddy, with  $\sigma_w$  being the standard deviation of  $W$  over the entire region (e.g., Henson and Thomas, 2008; Isern-Fontanet et al., 2006).”

**Comments:** The definition of  $\sigma_w$  is unclear. Is it the standard deviation of  $W$  computed over the full spatial domain for each day separately, or over the full domain and the entire study period? Please clarify. In addition, the choice of the threshold needs stronger justification for the Southern Ocean/ACC context. The cited studies (e.g., Isern-Fontanet et al., 2006) applied this criterion in different dynamical regimes and data products, and such a fixed fraction of  $\sigma_w$  may be product and region dependent. A brief sensitivity analysis (e.g., varying the coefficient around 0.2) would help demonstrate that the results are robust.

**Response:** Thank you for raising these critical methodological points, which have allowed us to improve the clarity of our manuscript. We apologize for any lack of clarity in the original text.

First, this study used the outermost closed SLA contour to delineate eddy boundaries, not a fixed  $W = -0.2\sigma_w$  threshold. As validated in previous studies cited, this geometric approach is specifically chosen to define coherent structures.

Second, we concur with your underlying point. As noted in our revised text (and by scholars like Matsuoka et al., 2016, and Saraceno and Provost, 2012), a fixed  $W$  threshold can lead to biases such as underestimated eddy areas or the misidentification of meanders as eddies in energetic regions. The outermost closed SLA contour provides an eddy-specific geometric definition that avoids these issues. In direct response, we have revised the methodology section (Lines 145-155) to clearly state our approach, acknowledge the alternative method, and justify our choice, thereby preventing any future misunderstanding.

Since our core methodology is fundamentally based on the geometric SLA contour method, a well-established technique whose parameters are derived from the physical shape of each eddy, a sensitivity test on an unused  $W$  threshold coefficient would not yield relevant insights for our specific analysis. The robustness of our approach is inherent in its design and prior validation. We are confident that the revised manuscript now presents a clear, robust, and well-justified methodology.

150-151: “SLA data with  $0.25^\circ$  spatial resolution were first linearly interpolated to  $0.125^\circ$  for better performance in eddy detection.”

**Comments:** I am concerned this is not appropriate, sampling to a finer grid does not add information and may introduce interpolation artefacts (artificial noise/small-scale structure) that can bias eddy detection and tracking. I recommend performing the analysis on the native-resolution SLA.

**Response:** We thank the reviewer for this important methodological insight. We fully agree that interpolating to a finer grid does not add information and may introduce artifacts. In response, the entire eddy detection, tracking, and all subsequent analyses have been revised using a SLA dataset with native-resolution of  $0.125^\circ \times 0.125^\circ$  from the Copernicus Marine Service (the CMEMS all-satellite L4 SLA product SEALEVEL\_GLO\_PHY\_L4\_MY\_008\_047), without any interpolation. The data source has been described in Lines 110-114.

152-156: “For eddy tracking, the algorithm identifies eddies at time  $t+1$  that meet the following criteria relative to time  $t$ : (1) minimal centroid distance, (2) identical polarity (i.e., rotation direction), and (3) the minimum radius variation. If no eddy at  $t+1$  satisfies these proximity thresholds for a given eddy at  $t$ , the eddy is considered dissipated. Conversely, if an eddy detected at  $t+1$  does not match any eddy at  $t$ , it is classified as a newly generated eddy. Based on eddy identification and tracking results, this study focuses on eddies with lifespans exceeding 7 days and amplitudes greater than 2 cm.”

**Comments:** The proposed eddy detection/tracking workflow (OW thresholding combined with outermost closed SLA contours and a local nearest-neighbour tracking based on centroid distance/polarity/radius change) appears insufficiently robust, especially for the Southern Ocean, where strong jets, crowding and deformation make eddy identification and track continuity challenging. Such simplified schemes are prone to track switching, fragmentation and sensitivity to thresholds. In addition, the adopted selection criteria (lifetime  $> 7$  days; amplitude  $> 2$  cm) require justification. I recommend either adopting a validated state-of-the-art EDT framework (e.g., Chelton/Schlax-type contour methods, META3.1exp/TOEddies) or providing thorough validation and sensitivity analyses (including reasonable variations of tracking parameters and thresholds) demonstrating that eddy statistics and the derived CFE conclusions are not materially affected by the chosen assumptions.

**Response:** Thank you for this insightful comment regarding the potential for track fragmentation and spurious detection in eddy tracking algorithms. We agree that this is a critical issue for ensuring the reliability of any eddy dataset. In direct and comprehensive response to this comment, we have taken a multi-pronged, conservative approach to rigorously address this concern:

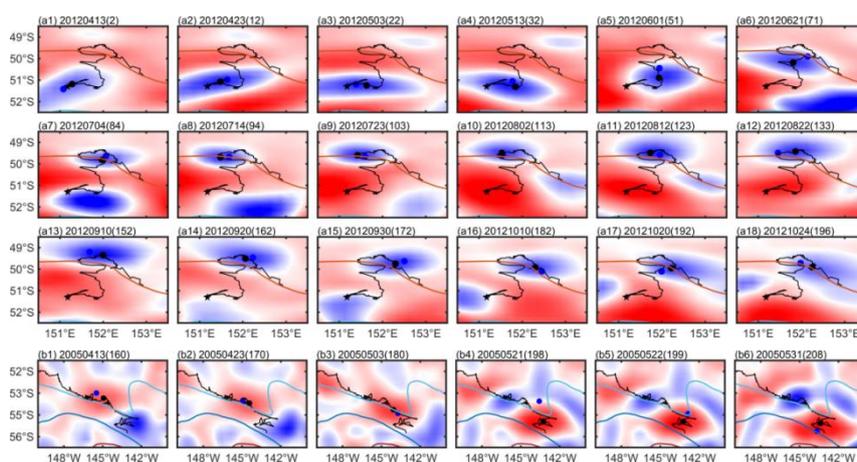
First, to systematically exclude short-lived, weak, or marginally resolved features that are most susceptible to the tracking artifacts noted by the reviewer, we have implemented substantially more stringent selection criteria. Our analysis now focuses exclusively on eddies that meet all of the following thresholds:

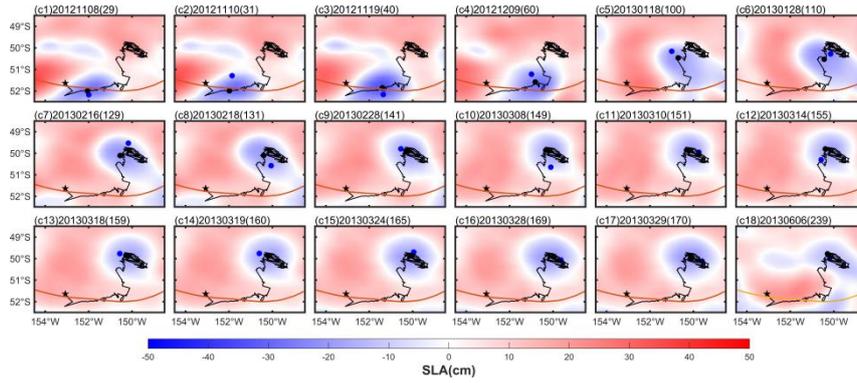
- (1) **radius > 30 km**, to guarantee the eddy structure is sufficiently larger than the ~14 km native grid scale;
- (2) **amplitude > 5 cm**, to select energetically strong mesoscale signals;
- (3) **lifespan > 14 days**, to ensure temporal coherence beyond synoptic noise.

The eddy statistics and the derived CFE conclusions were obtained exclusively from these significant eddies. These thresholds (14 days, 5 cm, 30 km) are substantially more conservative than the initial, more permissive parameters used in the original manuscript. They are designed to **systematically exclude short-lived, weak, or marginally resolved features that are most susceptible to the tracking errors (fragmentation, switching)** noted by the reviewer.

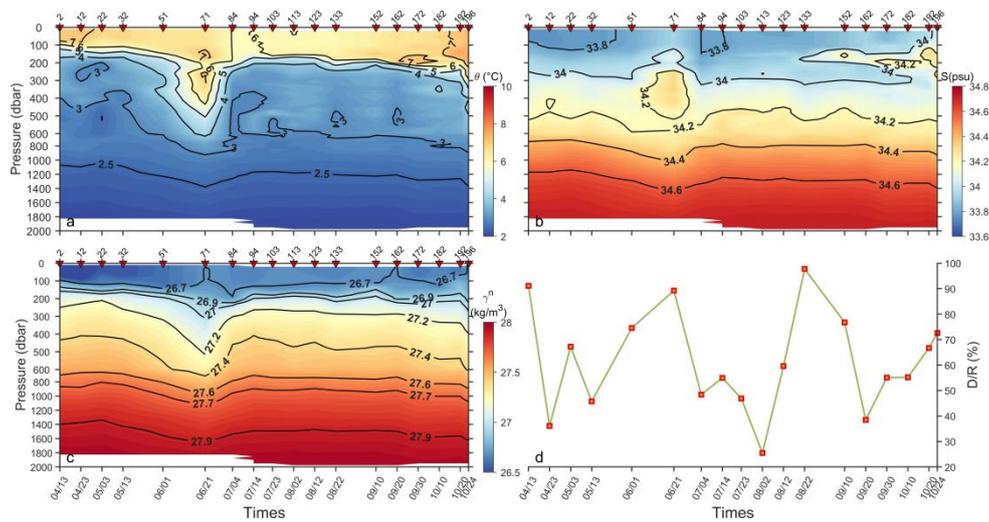
Second, the most decisive validation of our tracking algorithm’s reliability comes from independent Lagrangian observations. We identified several long-lived CFEs (with lifespans of 206, 219, and 307 days) in which Argo profiling floats were continuously entrapped for extended periods (e.g., up to 194 days). As shown in Figures R2-R5, the floats remained within the eddy interiors as defined by our algorithm, recording persistent thermohaline anomalies throughout their entrainment. This prolonged, continuous entrainment provides unambiguous evidence that the eddies we track are physically coherent water bodies capable of trapping and transporting water masses over long distances and timescales. It conclusively demonstrates that our tracks represent genuine, material-coherent eddies, not artifacts of algorithmic fragmentation or switching.

We are confident that the combination of (a) conservative data filtering and (b) direct observational validation robustly addresses the reviewer’s concern and underscores the reliability of our eddy dataset and the conclusions drawn from it.





**Figure R2.** Spatiotemporal evolution of the three cross-frontal eddies (CFEs) and associated Argo float positions. a1–a18: First cyclonic eddy (CE); b1–b6: Second anticyclonic eddy (AE); c1–c18: Third CE. Black and blue dots denote real-time positions of eddy centers and Argo profiles, respectively. Stars represent the eddy genesis points. Black lines are complete propagation trajectory over the eddy’s lifespan. Red and blue lines indicate the Subantarctic Front (SAF) and the Polar Front (PF), respectively. Dates are marked above each subplot, and the number in parentheses represents the number of days since it was generated.



**Figure R3.** Sectional distributions within the first detected CE in a1–a18 of Figure R2. (a) potential temperature, (b) salinity, (c) neutral density; (d) Time series of normalized distance (Argo distance from eddy center divided by eddy radius).

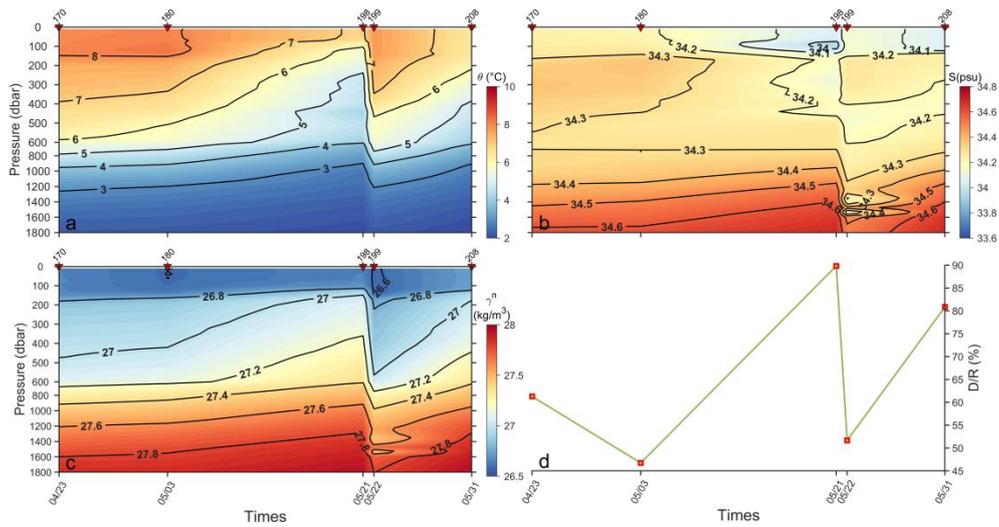


Figure R4. The same as Figure R3, but for the detected AE in b1-b6 of Figure R2.

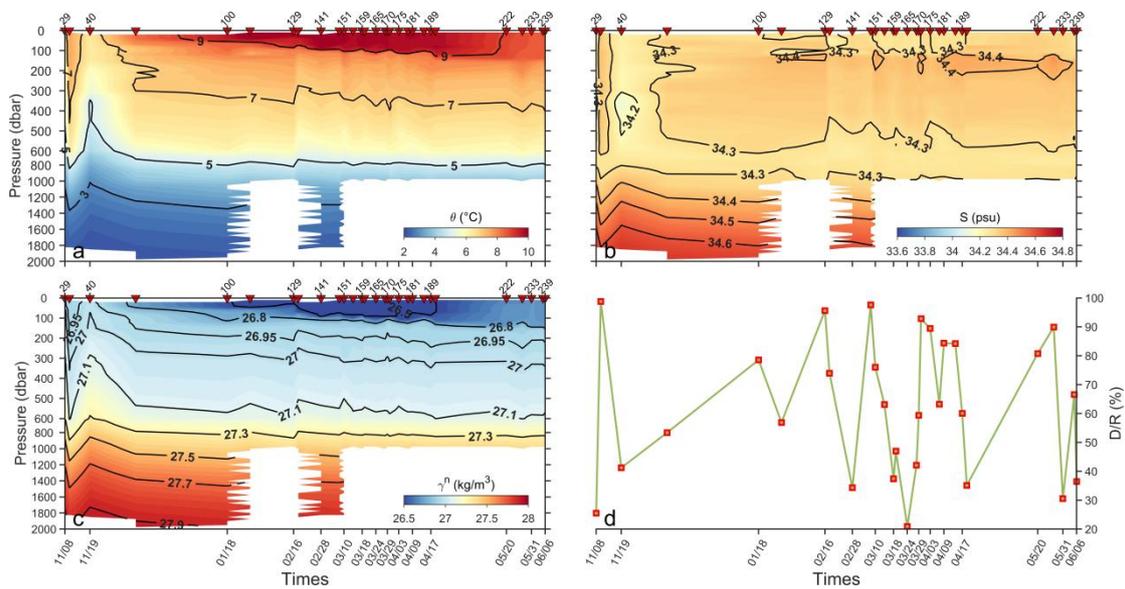


Figure R5. The same as Figure R3, but for the detected CE in c1-c18 of Figure R2.

### ACC frontal zone definition

169-170: “To account for topographically induced frontal displacements, we defined frontal zones as a strap  $\pm 15$  km expanded in the normal directions from each climatological front, consistent with observed SO frontal oscillation area (Kim and Orsi, 2014).”

**Comments:** It is not clear how the  $\pm 15$  km band is justified from Kim and Orsi (2014). In that paper, the reported meridional drift of the ACC fronts between 1993 and 2010 is on the order of  $\sim 28$ – $46$  km (their Fig. 8), and the estimated total drifts assuming a linear trend show sector-dependent values, with the Pacific sector spanning roughly  $-100$  to  $+20$  km depending on the front (their Fig. 9). This suggests that frontal variability/displacement can exceed the adopted 15 km half-width. Because this threshold likely influences eddy-front collocation statistics and therefore the main conclusions, it should be clarified and explicitly justified. A more defensible approach could be to define frontal zones based on the observed latitudinal variability of each front in the study sector (e.g., mean  $\pm 1$  standard deviation of front latitude), rather than using a fixed  $\pm 15$  km value. Therefore, this definition should be

revisited.

**Response:** Thank you for this insightful comment. The point you raised concerning the justification of the fixed bandwidth ( $\pm 15$  km) is of great importance, as it directly influences the statistics of eddy-front collocation events and the study's main conclusions. We fully agree that this threshold requires clear and explicit justification.

Based on your suggestions, we have revisited our methodology and conducted additional analyses. Below, we provide a detailed explanation of the rationale behind our approach and outline the corresponding revisions made in the manuscript.

### **1. Interpretation of Kim and Orsi (2014) and Focus of Our Study**

As you noted that, Figure 9 in Kim and Orsi (2014) shows considerable cumulative frontal displacement around the Campbell Plateau and its downstream in the Pacific sector ( $> 30$  km southward,  $150^{\circ}\text{E}$ - $170^{\circ}\text{W}$ ), with the largest total drift being approximately 80 km southward at  $150^{\circ}\text{E}$ , while much less total displacement eastward ( $< 30$  km). Figure 10 in this paper also indicates that most of the annual cycles in the Pacific sector are less than 30 km, with “most of the circumpolar regions the amplitude of seasonality is less than 10 km”. Thus, the the  $\pm 15$  km half-width (resulting in a 30 km total strap) is intended to be consistent with the typical long-term displacement and annual cycle for most regions other than the Campbell Plateau. About this critical region, this paper also stated that eddy activity can be a main determining factor for meridional frontal locations downstream of prominent topographic obstacles, such as Campbell Plateau, and raised that the spatial distribution of a streamline becomes greater due to the production of mesoscale eddies through eddy-mean flow interaction processes. These statements suggest that eddy-front interactions should be accounted for during frontal zone determination in this region.

### **2. Justification for the $\pm 15$ km Bandwidth, Physical Criteria, and Robustness Check**

Our method does not rely on a fixed  $\pm 15$  km zone for identifying eddy-front interactions. As described in the subsequent sentences (Lines 171-184), we defined an eddy-front interaction dynamically based on the eddy's instantaneous radius ( $R$ ). An interaction was recorded only when the eddy's boundary first touches the  $\pm 15$  km zone. Given that all analyzed eddies have  $R > 30$  km, this created an effective interaction zone with a minimum half-width of  $(15+30) = 45$  km. This 90 km total width is larger than the  $\sim 80$  km maximum meridional drift near the Campbell Plateau, ensuring robust capture of interactions near the variable fronts.

Following your suggestion, we performed a comprehensive sensitivity analysis by expanding the baseline frontal zone to  $\pm 25$  km. The results confirm that the main conclusions of our study, such as the differences between cross-frontal and non-cross-frontal eddies and the overall characteristics of eddy-front energy exchange, remain unchanged. This demonstrates that our core findings are not sensitive to the exact bandwidth within a reasonable range (15–25 km).

### **3. Consideration of the Suggested “Standard Deviation-Based” Definition**

We greatly appreciate your suggestion to define frontal zones based on the observed latitudinal variability (e.g., mean  $\pm 1$  standard deviation) of each front. While this approach is excellent for climate-scale analyses, for our weather-scale process-oriented study, using a fixed width combined with the geometric criterion offers the following advantages: (a) it avoids incorporating long-term trend and interannual signals into the detection of instantaneous interactions; (b) it provides a consistent and comparable baseline for interaction across all fronts and time periods; and (c) it aligns methodologically with our eddy identification scheme based on instantaneous flow fields.

Once again, we sincerely thank you for your constructive comments, which have significantly helped us improve the clarity and rigor of our work.

Minor issues:

40: Please briefly clarify in the text the distinction between front and jet

**Response:** Thank you for this suggestion. We have added the description of front and jet in [Lines 39-42](#) as “The ACC comprises multiple zonal fronts, where oceanic jets exit. Here, a front refers to a boundary between distinct water masses, characterized by strong horizontal density gradients, while a jet denotes the narrow, swift current that flows along the axis of such a front. Together, they form the dynamic core of the ACC.”

70-73: Sentence is too articulated. I suggest simplifying it, by splitting it into two shorter sentences to improve clarity and flow.

**Response:** We fully agree with your suggestion. The long sentence has been split into two shorter, more logically structured sentences to improve readability. The revised text is in [Lines 71-74](#) as : “He et al. (2023) demonstrated that nearly half of the subsurface temperature extremes in the Southern Ocean occur within eddies, with cross-frontal eddies (CFEs) generating extremely high-temperature events on the cold side of the ACC and extremely low-temperature events on the warm side. These extremes eventually impact marine organisms and ecosystems.”

111: Please provide the DOI of the Copernicus Marine product used, and report the date of access/download

**Response:** Thank you for the reminder. We have supplemented the description of the dataset in the “Data and Methods” section with the DOI link and the specific access date for the SEALEVEL\_GLO\_PHY\_L4\_MY\_008\_047 product. The revised text states: “The data were accessed/downloaded on 18 December 2025 from the Copernicus Marine Service Information (DOI: <https://doi.org/10.48670/moi-00148>).” in [Lines 112-114](#).

114-117: Since the horizontal velocities are provided directly by Copernicus, I suggest removing the detailed description of how they are computed. As written, it may imply you derived the velocities yourself. Readers interested in the processing can refer to the product documentation.

**Response:** Thank you for your suggestion. The detailed formula and description for calculating geostrophic velocities have been removed following your advice. The text now directly states that the velocity anomalies are provided within the dataset and refers readers to the product documentation for processing details. The revised text is: “The SLA represents the sea surface height anomaly... The corresponding geostrophic velocity anomalies ( $u'$ ,  $v'$ ) are provided within the same dataset... For detailed processing algorithms, users may refer to the product documentation (Pujol and Grassi, 2025).” ([Lines 115-118](#))

118-126: This paragraph could be shortened for readability. Also, it may help to more clearly separate what is taken from Park et al. versus what is done in this study. For instance, you could briefly state that you used the ACC front positions from Park et al. (altimetry-based), which were validated against available subsurface observations (e.g., Argo over the relevant period and CTD data in 2016–2017).

**Response:** Thank you for your suggestion. This paragraph has been significantly shortened and rewritten to clearly state that we are using the published, validated synthesis product from Park et al., rather than performing frontal

identification ourselves. The revised text reads: “The geographical positions of the ACC’s fronts and boundaries used in this study are from the synthesis of Park et al. (2019). This dataset provides the most updated mapping of the ACC frontal system and its associated boundaries, derived from satellite altimetry and independently validated against extensive subsurface observations, including Argo float profiles (2001–2017) and dedicated CTD surveys (2016–2017). As shown in Figure 1, the dataset defines five major streamlines from north to south: the Northern Boundary (NB), the Subantarctic Front (SAF), the Polar Front (PF), the Southern ACC Front (SACCF), and the Southern Boundary (SB). Specifically, the NB represents the northern dynamical limit of the ACC and coincides with the northern expression of the Subantarctic Front system (SAF-N) in this region, while the SAF, PF, and SACCF correspond to the core frontal jets.” in **Lines 119-126**.

167: Replace “:” with “.”

**Response:** Thank you. The colon “:” in the original sentence has been replaced with a period “.”.

217-219: Please clarify the percentage values mentioned in the text, as they are not directly reported in the table. As I understand it, they are obtained by summing the corresponding AE and CE percentages for that category and specific front, please state this explicitly.

**Response:** Thank you for highlighting this point. We have revised the paragraph thoroughly and avoided mentioning the percentages, which are explicitly provided in Table 1. By doing this, the revised version is more focused on the description and is logically smooth for easy understanding. The revised paragraph is in **Lines 258-267** as: “Quantitative analysis of CFE types reveals distinct frontal-zone behaviors (Table 1). Transient eddies (Type 3) account for the largest proportion overall (> 40% by summing the transient AEs and CEs at each front), particularly at the two weaker southern fronts (SACCF and SB). Their proportions are lower at the SAF and PF, indicating that these two major fronts host more eddies that interact with areas outside the frontal zone during their lifecycle. For partially front-generated eddies (Type 1), both AEs and CEs exhibit relatively high proportions at the SAF and PF. At the southern SACCF and SB, however, the proportion of AEs drops markedly, whereas CEs show no such reduction. Among partially front-dissipated eddies (Type 2), the three northern fronts consistently show a higher proportion of CEs than AEs. At the two southern fronts, the pattern reverses, CE proportions decline sharply, leading to a higher proportion of AEs. This suggests that in the southern fronts, local cross-frontal CEs are more readily generated and propagated outward, while being relatively resistant to dissipation.”

251: “, p=0.08)” replace with “(p=0.08)”

**Response:** Thank you. We have checked and corrected the parenthesis format for p-values at this location and elsewhere in the text to ensure consistency with the “(p=0.08)” format.

272-273: Consider replacing “Total number of CFEs, divided into types of equatorward and poleward directions;” with “Total number of CFEs, divided into types of equatorward and poleward directions, shown as a function of the different ACC fronts;”

**Response:** Thank you. Following your suggestion, the caption for Figure 2(b) has been revised to: “(b) Total number of CFEs, divided into types of equatorward and poleward directions, shown as a function of the different ACC fronts;”

379: Do the water-mass core values reported in Table 3 have circumpolar validity for the Southern Ocean? Please clarify the geographic representativeness of the cited values. Since this work focuses on the Pacific sector, you may also consider or discuss Pacific-sector estimates of SAMW and AAIW core properties (e.g., Bostock et al., 2013; Li et al., 2021, 2022).

**Response:** Thank you for this important comment. We fully agree that the core properties of water masses in the Southern Ocean, such as potential temperature, salinity, and density, are not circumpolarly uniform. Significant sub-regional and inter-basin variability exists across different frontal zones and sectors (Pacific, Atlantic, Indian).

The water mass criteria summarized in Table 3, particularly for Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW), are intended to be representative and primarily applicable to the Pacific sector. To clarify this point and enhance the geographical context of our analysis, we have made the following clarifications and additions to the manuscript: (1) A note has been added to Table 3 stating: “ Note: The ranges listed, particularly for SAMW and AAIW, are primarily representative of the Pacific sector of the Southern Ocean.”. (2) A description about the water masses has been added in **Lines 387-394** for better stating the spatial patterns of core water masses as: “Core water masses, especially Subantarctic Mode Water (SAMW) and Antarctic Intermediate Water (AAIW), are not circumpolarly uniform but exhibit substantial regional variability (Bostock et al., 2013; Li et al., 2022). For instance, within the Pacific sector, the salinity minimum of AAIW ranges from ~34.2 in the southeast Pacific formation region to greater than 34.5 in the Tasman Sea after mixing (Bostock et al., 2013); Similarly, SAMW exhibits distinct spatial patterns in its formation and properties (Li et al., 2021). Accordingly, the ranges in Table 3 are intended as a practical guide for identifying water masses within the specific Pacific sectoral context of this study.” .

383: I suggest using a different colour bar for salinity rather than reusing the same colour bar as potential temperature, to avoid confusion and improve readability.

**Response:** Thank you for this suggestion. Figure 9 has been redrawn following your suggestion by using different color bars for potential temperature and salinity.

465-469: Please provide the DOI of the Copernicus Marine product used and report the date of access/download. Also, the Argo data link does not work, please check and update it.

**Response:** Thank you for your carefulness. Now, The DOI of the Copernicus Marine product and Argo data link have been updated. The date of access/download has also been added in the Data availability part.