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[Artemis Ioannou](#)*, [Lionel Guez](#), [Remi Laxenaire](#), [Sabrina Speich](#)

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Article

Global Assessment of Mesoscale Eddies with TOEddies; Comparison between Multi-Datasets and Colocation with In-Situ Measurements

Artemis Ioannou ^{1*}, Lionel Guez ¹, Remi Laxenaire ^{2,3} and Sabrina Speich ^{1,4}

¹ Ecole Normale Supérieure, Laboratoire de Météorologie Dynamique, LMD-IPSL, Paris, France;

² Laboratoire de l'Atmosphère et des Cyclones (LACy, UMR 8105 CNRS, Université de la Réunion, Météo-France), Université de La Réunion, Saint-Denis de la Réunion, France

³ Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, FL, USA

⁴ Ecole Normale Supérieure ENS-PSL, Paris, France

* Correspondence: artemis.ioannou@lmd.ipsl.fr

Abstract: The present study investigates the general characteristics of mesoscale eddies in the Global Ocean, as identified and tracked by the TOEddies algorithm [1] implemented on a global scale. Applied to satellite observations (AVISO/DUACS) of Absolute Dynamic Topography (ADT), TOEddies provides daily information on eddy dynamical characteristics (e.g., size and intensity) over a 30-year period (1993–2023) and identifies complex eddy-eddy interactions that lead to eddy splitting and merging. By capturing the multiple merging and splitting events that a single eddy can undergo, TOEddies generates a complex network of eddies that challenges the conventional view of a single trajectory associated with a single eddy. Furthermore, it offers an original assessment of interconnected eddy trajectories. A statistical description of the average characteristics of the eddies and their spatial distributions (generation, disappearance and merging/dividing) is first provided. A comparative analysis of existing global eddy datasets is then presented. Among the years of observations, several coherent, long-lived mesoscale eddies with lifetimes exceeding 1.5 years stand out. However, we find that only a small fraction of these eddies is comparable between datasets, while their dynamic properties can differ substantially. Furthermore, the detection of eddies from altimetry is combined with 23 years of Argo profile co-localised measurements (2000–2023), allowing us to further investigate their contribution to the global subsurface ocean.

Keywords: mesoscale eddies; remote sensing; satellite altimetry; eddy tracking methods; subsurface oceanic signal; eddy-eddy interactions; merging-splitting events; coherent eddies; eddy networks

1. Introduction

Mesoscale eddies play a pivotal role in the global transport of water masses and properties [2–4], providing crucial connections and exchanges across varying horizontal and vertical spatial scales [1,5–8]. Their unique ability to remain coherent for extended periods (up to several months or even years) and their capacity to retain properties within their cores [9–11], contribute to the efficient transport and redistribution of heat, salt, mass, and biogeochemical properties as they propagate into the oceanic environment. It has been observed that vertical isopycnal displacements, which are influenced by the polarity and internal structures of these systems, have a notable impact on the biological productivity of the ocean [12–16].

Meanwhile, to date, multi-mission altimeters can only provide sparse coverage of the ocean mesoscale. Obtaining real-time measurements of the large-scale ocean dynamic topography remains an on-going challenge that limits the continuous monitoring of ocean mesoscale eddy dynamics. Nonetheless, gridded data on sea surface height can be generated through a spatio-temporal mapping technique [17] that incorporates satellite measurements within a 10-day time frame. The longer time scale over which mesoscale dynamics evolve, permits such a reconstruction despite inevitable inaccuracies inherent to the mapping process, particularly due to the absence of measurements between satellite tracks. While grid-based ocean surface height reconstruction may not effectively capture small-scale dynamics and rapid changes [18], it can adequately represent mesoscale features. Moreover,

unlike other passive remote sensing techniques (such as optical or infrared sensors), altimetry remains one of the few active observational methods, that is not affected by cloud cover, with the sole exception of synthetic-aperture radar (SAR) imagery [19–21]. Furthermore, the combination of satellite altimetry with in-situ measurements from dedicated oceanographic missions has been demonstrated to be an effective method for the detection and monitoring of mesoscale eddies [22–24].

As demonstrated by Chelton *et al.* [10,25], altimetric maps are a valuable tool for detecting mesoscale eddies (defined as those exceeding a diameter of ~40 km) and creating a comprehensive global eddy census. By employing sea-level anomaly (SLA) maps, they initially delineated the global characteristics of mesoscale eddies. Since that time, mesoscale eddies have been extensively documented in a number of studies, typically at specific locations of dynamical interest, employing a variety of tracking techniques [10,26–33]. Eddy detection algorithms employ a variety of criteria, including physical, geometrical, and hybrid approaches [34] to identify the centers of eddies and extract their horizontal characteristics. Furthermore, the most recent algorithms offer novel methodologies for the identification of dynamical events between eddies, including splitting and merging events [1,29,35,36]. The improvement of eddy identification and tracking techniques enables the comprehensive characterization of the primary eddy dynamical parameters.

Despite the multitude of mesoscale eddy detection and tracking methodologies, only a select few offer publicly accessible datasets that encompass a continuous and global assessment of mesoscale eddies over an extended period of observations [10,27,31,37,38]. While the choice of the tracking method is not expected to a priori affect the characterization of the mesoscale fields, inter-comparisons of globally detected mesoscale eddies from different methods are rare and usually conducted in targeted regional studies [39–44]. Additionally, only a limited number of these studies include the identification of eddy interactions through merging and splitting events at the global scale [1,36]. It is therefore unclear how the detection of mesoscale eddies differs according to the tracking methods used. It would be beneficial to ascertain how geometric and physical criteria influence the detection and tracking of eddies, and to determine the impact of this on the estimation of dynamic phenomena.

The objective of this paper is to conduct a comparative analysis of mesoscale eddy detection and tracking using four distinct global eddy datasets. Our analysis begins with an examination of the updated TOEddies dataset, which has been expanded from the South Atlantic [1] to encompass the global ocean. The TOEddies Atlas furnishes data on the dynamical characteristics of eddies and on the incidence of eddy merging and eddy splitting events. This enables the reconstruction of a complex eddy network by linking the eddy trajectories associated with both the merging of eddies with other eddies and the splitting of eddies into two or more eddies. Moreover, the TOEddies Atlas incorporates available colocalized vertical information from Argo floats with its eddy detection [5,45]. The combination of satellite altimetry with autonomous measurements has been demonstrated to be particularly effective for analyzing the vertical properties of eddies [5,45,46]. Subsequently, the key characteristics of mesoscale eddies as identified and monitored by the TOEddies global database are evaluated against three commonly used global eddy atlases [33,37,38].

The paper is organized as follows. In Section 2 we present the TOEddies algorithm and describe the various datasets used in this study. In Section 3.1, the mean statistical properties and spatial distributions of eddies are presented as derived from the various eddy Atlases. In Section 3.2, we present the dynamical evolution of long-lived and long-propagating eddies, as well as a comparison of the differences and similarities between the main eddy pathways. Subsequently, Section 3.3 presents specific information on merging and splitting events in a new eddy-network view offered by TOEddies. Furthermore, two distinct eddy instances that coincided with Argo float observations are illustrated. Finally, the results are summarized, and the findings are presented in Section 4.

2. Materials and Methods

In this study, we analyze four publicly available eddy Atlases, with the aim of investigating mesoscale eddy structures on a global scale. We initially utilize the TOEddies Atlas, as previously

documented for the South Atlantic [1,5,45] and extend it globally. To date, approximately 20 peer-reviewed publications have employed the TOEddies algorithm [7,15,22–24,47–55]. Furthermore, the TOEddies algorithm has been implemented in numerous scientific missions, including the EUREC4A-0A mission [24,54,56,57] and the Tara Mission (2020) in the Atlantic and Southern oceans [57,58]) demonstrating its robustness and widespread adoption within the scientific community.

TOEddies Atlas employs all-satellite (DT2018, [59]) sea surface height fields of Absolute Dynamic Topography (ADT) generated by SSALTO/DUACS data, spanning the period from 1993 to 2023. Additionally, we include the most recent iteration of the Mesoscale Eddy Trajectory Atlas META(3.2), as described in [33] and distributed by AVISO+ (<http://www.aviso.altimetry.fr/>) with support from CNES. This META version covers 29 years (from Jan 1993- February 2022) of daily eddy detection and is applied also on the ADT fields (Table 1). To enhance the breadth of our analysis, we have also included the eddy detection and tracking outputs provided by Tian *et al.* [37](<http://coadc.ouc.edu.cn/tfl/>), based on the all-sat AVISO dataset of Sea Level Anomaly (SLA) for the years 1993-2016 (hereafter referred to as TIAN). Lastly, we have incorporated the recent GOMEAD dataset [38], which offers an eddy detection and tracking based on SLA fields spanning from January 1993 to December 2019.

2.1. Sea Surface Height Fields and Eddy Atlases

All atlases included in this work are based on daily all-satellite sea surface height fields produced by SSALTO/DUACS and distributed by AVISO. This specific multi-satellite product integrates data from four satellites at a given time and is projected onto a Mercator grid with a resolution of $\frac{1}{4}^{\circ}$ covering the global ocean. In order to assess mesoscale eddies, each dataset uses time-delayed gridded maps of either absolute dynamic topography (ADT) or sea level anomaly (SLA) fields (Table 1). The ADT is defined as the sum of SLA and the Mean Dynamic Topography (MDT), averaged over a 20-year reference period. Although the SLA product is more commonly used for eddy detection (as in TIAN, in earlier versions of META and GOMEAD), the use of ADT (as, for example, in TOEddies and META3.2) helps to avoid misidentifying permanent signatures in the MDT or large meandering features (such as currents or jets) as eddies [1,60]. It is therefore advisable to exercise caution when interpreting SLA fields for the purpose of eddy identification. Furthermore, satellite altimetry maps (SLA and ADT) are typically spatially filtered to remove large-scale variability before any detection and tracking methods are applied. Further details on the filtering processes can be found in [33,37,38]. In contrast, the TOEddies atlas applies its detection method directly to the absolute dynamic topography (ADT) fields without any filtering, ensuring that the entire observed altimetric signal is preserved.

Table 1. Overview of Eddy Detection Datasets.

Dataset	SSH (all-sat)	Threshold	Period
TOEddies	ADT	0.1 cm	Jan 1993 - May 2023
META3.2	ADT	0.4 cm	Jan 1993 - Sep 2022
TIAN	SLA	0.25 cm	Jan 1993 - Dec 2016
GOMEAD	SLA	-	Jan 1993 - Dec 2019

2.2. Eddy Amplitude Criterion

Each Atlas employs different physical and geometric criteria to detect and track eddies. As a result, we have identified a number of key differences between the datasets. For a comprehensive understanding of the TOEddies detection and tracking method, please refer to Appendix A.1.

One notable distinction among the datasets is the tuning of the eddy amplitude threshold, commonly known as the persistence parameter. This directly affects the number of detected eddies and their derived characteristics. Eddies are identified as points of maximum or minimum in the Sea Surface Height (SSH) fields. Cyclonic eddies correspond to local minima of SSH, while anticyclonic eddies correspond to local maxima. In the META3.2 and TIAN datasets, the eddy amplitude criterion

is set to 0.4 cm and 0.25 cm, respectively. Conversely, the TOEddies method employs the lowest amplitude threshold of 1 mm (see Table 1).

Typically, the eddy detection process begins with the identification of maxima and minima across the field, which is then followed by the application of the specified amplitude thresholds. In a different approach, TOEddies incorporates the persistence parameter directly into the detection process. This integrated approach is topologically distinct and has been shown to enhance eddy detection, functioning as a low-pass filter [1]. The latter has been validated against a totally independent dataset of upper-ocean eddies identified by surface drifters and provided by Lumpkin [61]. For each local extreme, TOEddies identifies the outermost contours of ADT that satisfy the specified constraints detailed in Appendix A.1. Once the outermost contour has been established, defining the eddy boundary, a maximum-speed contour is also identified. This contour, defined as the characteristic contour, represents the closed isoline of ADT with the maximum mean azimuthal speed (computed from the gridded field of surface geostrophic velocity derived from the ADT) and encloses the eddy's dynamical core. The outermost and characteristic contours are used to determine the average size of the eddy. This size is defined as the radius of a circle that would cover the area outlined by these contours. Consequently, two distinct average eddy radii are specified, $\langle R_{max} \rangle$ for the maximum radius and $\langle R_{out} \rangle$ for the outer characteristic eddy radius.

An alternative approach is employed by the GOMEAD Atlas, which utilises a vector geometry-based algorithm for the detection of eddies. This methodology identifies eddy centers as local minima of the surface geostrophic velocity magnitude derived from the SLA, and delineates eddy boundaries through the utilization of isolines of the geostrophic stream function.

2.3. Eddy Tracking Parameters

To monitor eddies over time, both META3.2 and TOEddies employ an overlapping criterion between successive time steps, as previously introduced in Pegliasco *et al.* [62]. This criterion guarantees that a defined area of the eddy will remain consistent between consecutive time steps. This approach allows us to identify distinct segments of eddies, rather than isolated occurrences, which is essential for reconstructing eddy trajectories. In TOEddies, a graph method has been implemented to identify eddy segments and build eddy trajectories, enabling the detection of merging and splitting events. This is achieved by integrating a cost function that assigns weights to the graph of segments, taking into account three key similarity parameters: the distance between eddies, their Rossby numbers, and their speed radius. Please refer to Appendix A.2 for further details regarding the TOEddies tracking methodology. Please note that META3.2 does not include the identification of merging and splitting events.

In contrast, the TIAN dataset links trajectories over time by identifying each eddy at the current time step and searching for an eddy in the subsequent time step within a fixed area of radius 0.5° . In the event that an eddy remains unassociated in the subsequent step, a synthetic or "fake" eddy with similar attributes to the last observed eddy is created. The synthetic eddy is then introduced into the fields and propagated in the same direction. This technique, originally proposed by Faghmous *et al.* [27], helps to prevent the premature termination of tracks or large jumps between eddy positions. The maximum number of steps that fake eddies are permitted in TIAN is set at five days, while their propagation distances cannot exceed 1.75 times the distance over which a long baroclinic Rossby wave can propagate in a week. In the event that multiple eddies fall into the same area, a cost function is employed that considers four similarity parameters: distance between eddies, amplitudes, area, and EKE. META3.2 and TOEddies also prevent the disappearance of eddies by extending this search to four (META3.2) or five (TOEddies) time steps if no eddy is found before. Lastly, GOMEAD implements a similar fixed search area approach to track eddies over time. If multiple eddies of the same type are detected within the search area, the eddy track is updated by selecting the center point that is closest to the eddy.

2.4. Eddy Network Reconstruction

TOEddies capability to detect eddy merging and splitting events enables the reconstruction of eddy networks linked to specific eddy origins. This methodology, introduced in Laxenaire *et al.* [1,5,45], allows for continuous monitoring of eddy evolution, capturing interactions that occur throughout an eddy's lifetime. The TOEddies network tracks interactions between oceanic eddies by detecting merging and splitting events, assigning an "order" to each trajectory (see Figure 1 in [45]). A reference eddy trajectory, originating from a specific region, is assigned an order of zero, while eddies that merge with or split from this reference are assigned orders based on the number of interactions separating them from the original trajectory. This network-based approach provides a novel way to trace eddy origins, pathways and cross-basin connectivity [1,7,24]. By accounting for multiple merging or splitting events, the TOEddies network provides a more detailed and dynamic reconstruction of eddy movements compared to conventional methods, which consider eddies as isolated structures.

2.5. Co-Location with Argo data

TOEddies incorporates its daily eddy detection with vertical temperature and salinity data from autonomous Argo float measurements from 2000 to 2023. The total colocalization dataset comprises up to 1,976,124 individual Argo profiles collected by 14,839 different floats. It should be noted that approximately 10% of the Argo floats included in this dataset are Biogeochemical-Argo (BGC-Argo). Argo profiles are separated into two groups based on their detection within or outside of mesoscale eddy last contours at a specific location and date. The latter represent the adjacent environment and are used to construct climatological profiles of temperature (T), salinity (S), and density (σ) in the given area. TOEddies co-localisation provides a "no-eddy" climatology consisting of all profiles located outside of eddies at a radial distance of up to $\leq 1^\circ$ around the selected position and during a period of up to 30 days from the given date (regardless of the year) over the 23 years.

3. Results

3.1. Statistical Description of Mesoscale Eddies

Figure 1 presents a global characterization of mesoscale eddy activity. The figure shows the detection from each atlas accumulated on a $1^\circ \times 1^\circ$ gridded map, with areas of eddy generation and disappearance clearly delineated. The latter were identified as the initial and final detection point of each eddy trajectory that was monitored for a minimum of 4 weeks. The highest concentrations of eddy activity are defined by a high density of eddy generations and disappearances, with a total exceeding $N > 30$ eddies per degree square. It is notable that in all datasets, areas where eddies frequently generate are also areas where eddies disappear from the altimetry maps. It is evident that the eastern boundary areas, including the major eastern upwelling boundary systems in the Canary and Benguela in the South Atlantic, as well as the western boundary near the Confluence Zone between the Malvinas and South Brazil currents, exhibit a higher number of eddy generations. Please refer to Figure S1 of the Supplementary Material for a visual representation of the higher number of eddy disappearances in the western boundary systems.

Figure 2 shows frequency maps of eddy-eddy interactions (merging and splitting events) identified by TOEddies. It is important to note that the spatial distribution of merging and splitting events, as identified by TOEddies, also occurs in similar locations. This reinforces the necessity of considering eddy-eddy interactions for comprehensive understanding of the detected eddies' dynamic evolution. Over the course of the observation period, approximately 3% of the detected eddies were found to be involved in merging and splitting events, with 52% of these classified as cyclonic eddies.

From the numerous mesoscale eddies identified across the global data sets over the various years of observation, we have chosen to focus on individual detections that are part of main eddy trajectories with lifetimes of at least 16 weeks. The TOEddies dynamical dataset detects over 25 million (25,117,786) eddy occurrences (lasting a minimum of 16 weeks) organized in 119,994 eddy trajectories globally. In

terms of the same subset of tracked mesoscale eddies, TOEddies outperforms META3.2 and TIAN in terms of the number of total trajectories, with an increase of almost 2% and 18% (117,035 and 98,375). In comparison with the other datasets, GOMEAD reports a lower number of detected eddies (17,822).

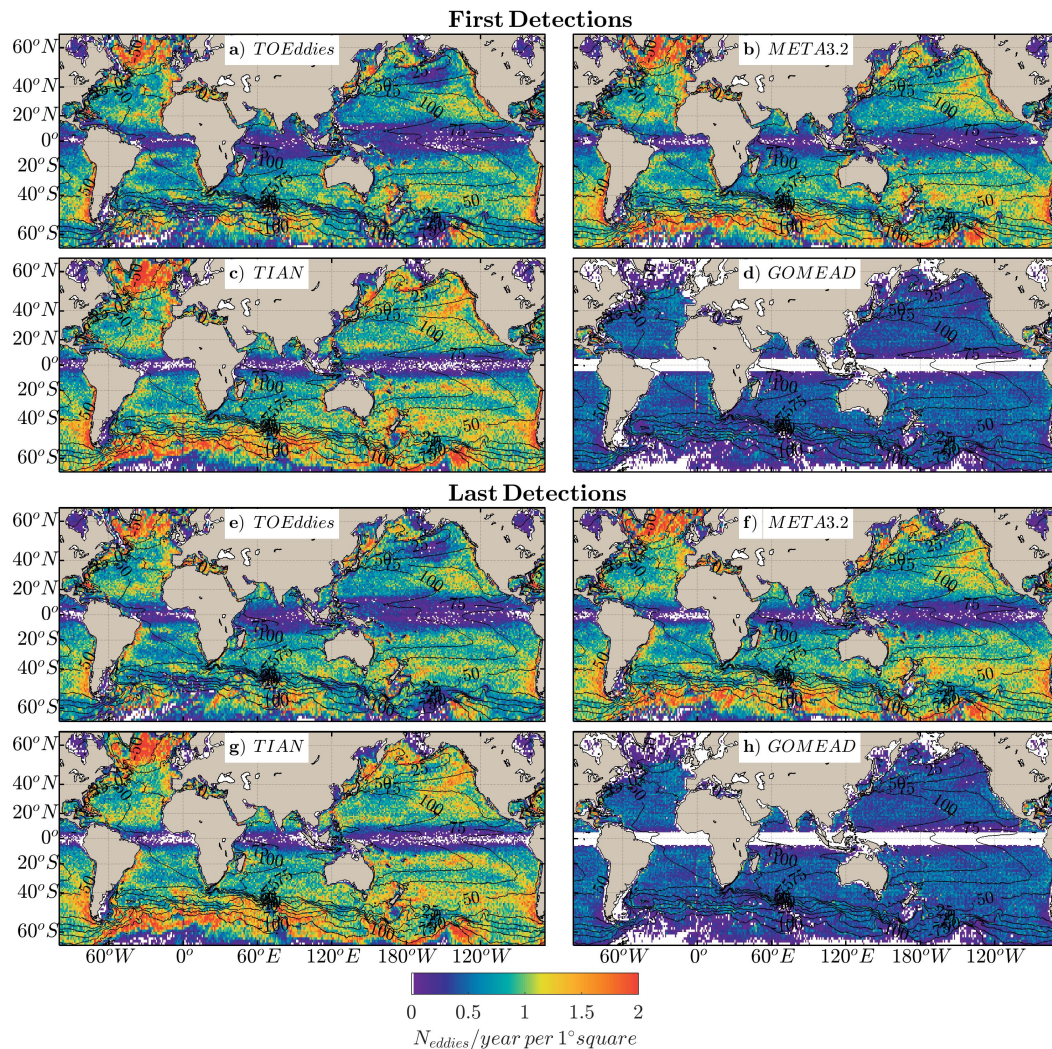


Figure 1. Frequency maps of first (a-d) and last (e-h) detection points of mesoscale eddies per year derived from TOEddies, META3.2, TIAN and GOMEAD datasets, respectively. The data is aggregated into $1^\circ \times 1^\circ$ bins and normalised by the number of observation years for each dataset. The mean dynamic topography (MDT in cm) is shown by black contours.

Figure 3 compares the horizontal eddy characteristics of each Atlas. Histograms, of mesoscale eddy lifetimes, characteristic radii and velocities were plotted separately for cyclonic and anticyclonic eddies. However, when longer lifetimes are considered (more than 26 weeks), the predominance of anticyclonic over cyclonic eddies becomes apparent, as noted in Chelton *et al.* [10].

In the TOEddies and META3.2, the characteristic radii of anticyclonic eddies were estimated at $\langle R_{max} \rangle = 56.25 (\pm 27.3)$ km and $\langle R_{max} \rangle = 62.08 (\pm 27.8)$ km. These values of the equivalent average radius of the anticyclonic eddies in these atlases is 5% and 3% larger, respectively, in comparison to that of the cyclones. In TIAN dataset, anticyclonic eddies sizes are slightly larger, with an average radius of $\langle R_{max} \rangle = 68.86 (\pm 27)$ km while cyclones are 7% smaller in size. However, the relative size of of the eddies in the TIAN atlas remains larger than those identified in META3.2 and TOEddies. In general, the GOMEAD dataset identifies significantly larger structures (with an estimated average

$\langle R_{max} \rangle = 109.5 (\pm 45)$ km). We note that in this atlas, eddy radii smaller than ≤ 30 km were not included to avoid small-scale features that are not accurately captured by altimetry.

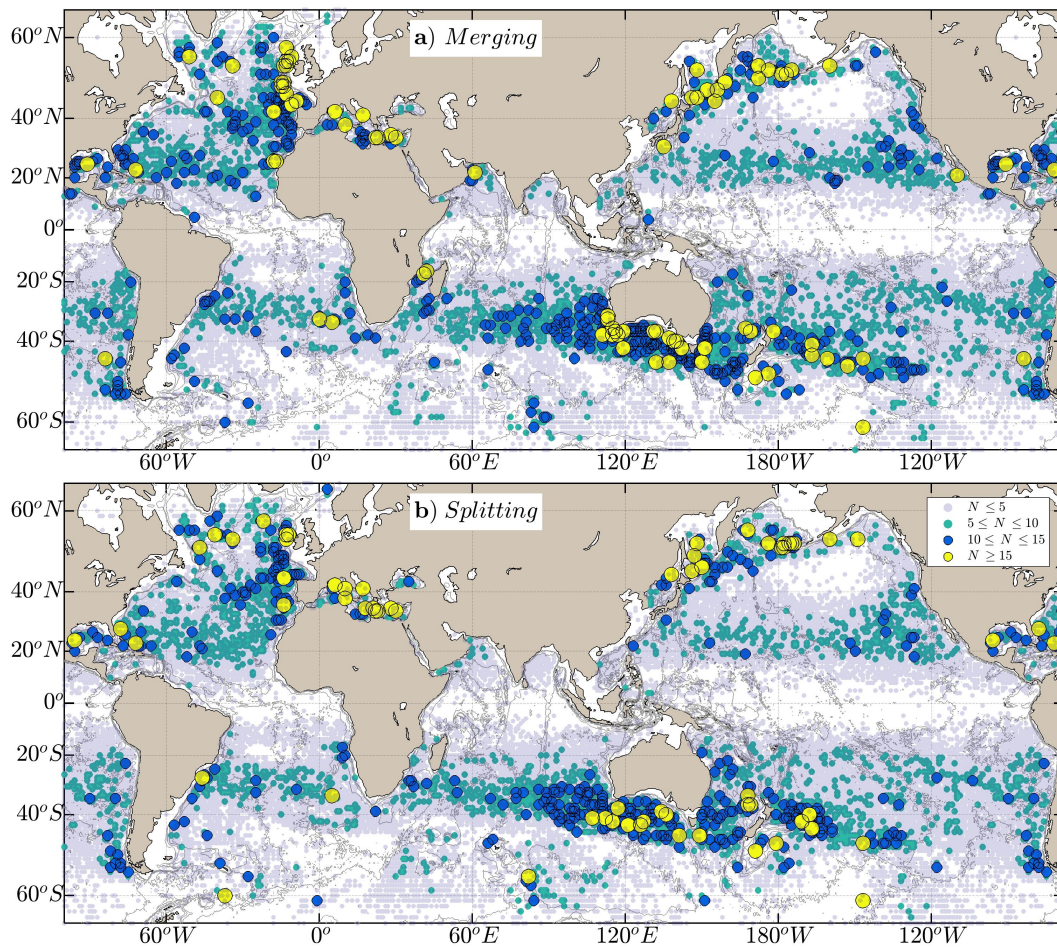


Figure 2. Scatter plot representing the distribution of eddy occurrences for **a)** merging and **b)** splitting events based on TOEddies atlas for eddy with lifetimes longer than 4 weeks in each $1^\circ \times 1^\circ$ region. Bathymetry shallower than 4,000 m is indicated by gray lines.

To identify areas where these differences are noticeable, we present in Figure 4 the geographical distribution of the radii of eddies. These maps were calculated by averaging the R_{max} for each daily detected mesoscale eddy that falls within bins of $1^\circ \times 1^\circ$. For a suitable comparison, zonal averages of the eddy radius are also computed in Figure 4e. In terms of the spatial radius distribution, smaller eddies are detected near the poles while larger ones near the equator. This aligns with the first baroclinic Rossby radius, which varies with latitude [10,63]. However, the absolute values of the eddy radius vary considerably across the datasets. The mean zonal radii from the GOMEAD dataset are higher, estimated at approximately ~ 150 km in the equatorial bandwidth of 10°S to 10°N . In contrast, the TOEddies, META3.2 and TIAN datasets detect lower eddy radii of the order of 100-120 km. At latitudes lower than 40°S higher than 40°N , the TIAN dataset identifies larger structures of approximately 60 km, while the TOEddies and META3.2 estimates indicate smaller structures (~ 40 km).

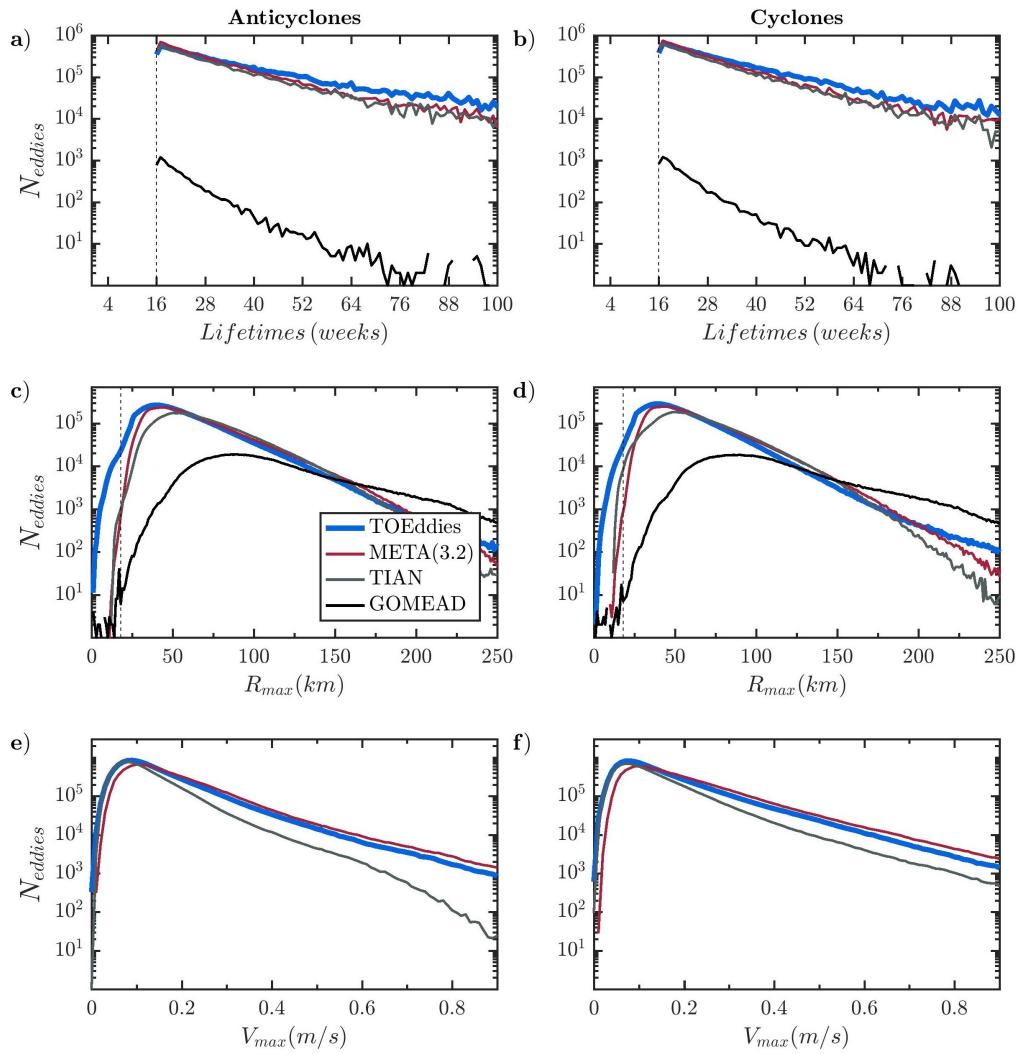


Figure 3. Upper-tail cumulative histograms of eddy lifetimes (weeks) (a-b) and histograms of eddy characteristic radius R_{max} (km) (c-d) and velocity V_{max} (m/s) (e-f) of anticyclonic (first column) and cyclonic eddies (second column) for the TOEddies, META3.2, TIAN and GOMEAD datasets. We consider only mesoscale eddies having lifetimes ≥ 16 weeks as indicated by the dashed lines in panels (a-d) and characteristic radii larger than $R_{max} \geq 30$ km.

In terms of intensity, the mean characteristic velocities in the TOEddies dataset reached almost $\langle V_{max} \rangle = 15 (\pm 12)$ cm/s, while eddies in META3.2 and TIAN indicated slightly higher and lower velocities, $\langle V_{max} \rangle = 19 (\pm 13)$ cm/s and $\langle V_{max} \rangle = 13 (\pm 9)$ cm/s respectively. It is worth noting that there are significant variations in the characteristics of the eddies, indicating that their sizes and intensities could differ significantly between observation periods. Furthermore, a comparison of all datasets reveals that cyclonic eddies display higher standard deviations in intensity than anticyclonic eddies.

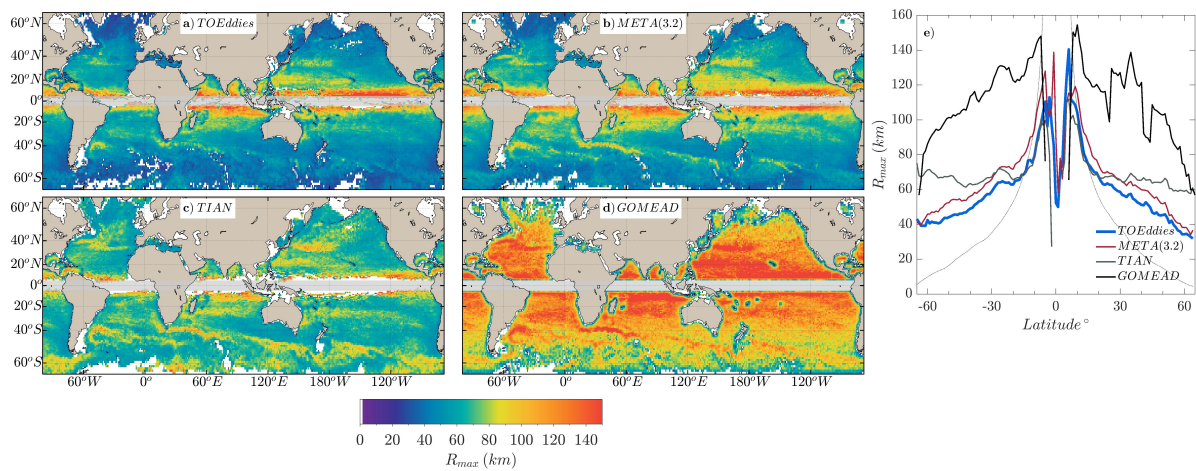


Figure 4. Maps of the speed-based radius scale R_{max} (km) for eddies with lifetimes ≥ 16 weeks for each $1^\circ \times 1^\circ$ region from (a) TOEddies (b) META3.2 (c) TIAN and (d) GOMEAD datasets. Zonal averages of the eddy characteristic radius are illustrated in panel (e). The dashed line indicates the estimated first baroclinic Rossby Radius of deformation R_d (km) [10].

3.2. Characterization of Main Eddy Pathways

Figure 5 depicts eddy trajectories from the TOEddies atlas, based on their estimated lifetimes. The cyclonic and anticyclonic trajectories are presented separately, with blue and red colors, respectively. To facilitate a comparative analysis, we have selected similar thresholds as those chosen in Chelton *et al.* [10] for the eddy lifetimes. This results in lifetimes that exceed 52, 78 and 104 weeks respectively. For instance, the selection of eddy trajectories that live longer than 78 weeks (more than 1.5 year) with TOEddies dataset (Figure 5b) results in 2007 anticyclonic and 1339 cyclonic trajectories. In the North Atlantic, we find an equal eddy mixture of long-lived cyclones and anticyclones. However, in the Indian Ocean, we predominantly observe long-lived cyclones. These cyclones account for 40% of the total long-lived cyclones (for lifetimes ≥ 104 weeks) and are among the longest propagating eddies found in the TOEddies Atlas.

Figure 6 shows the same selection of eddy trajectories (with lifetimes more than 78 weeks) with the META3.2, TIAN, and GOMEAD atlases. While both the META3.2 and TIAN atlases follow a comparable number of persistent trajectories, their total is 53% and 41% lower, respectively, than that of TOEddies. For example, the META3.2 database includes 995 (773) anticyclonic (cyclonic) eddies with a lifetime exceeding 78 weeks, representing 56% (44%) of the total eddies. Similarly, the TIAN dataset contains 810 (564) anticyclonic (cyclonic) eddies, representing 59% (41%) of the total eddies. This discrepancy is primarily attributable to the lack of long-duration trajectories in the North and South Pacific. It is worth noting that the GOMEAD dataset identifies fewer trajectories than the other atlases. In fact, it contains 63 anticyclonic and 20 cyclonic eddies for this selection.

In alignment with Chelton *et al.* [10], all atlases indicate that the majority of long-lived oceanic eddies propagate in a westerly direction, influenced by the β -effect. Only a minority of eddies propagate eastward, particularly in regions dominated by strong eastward currents. This eastward propagation is most notably observed in the Southern Ocean, specifically within the intense Antarctic Circumpolar Current (ACC) [10,64,65]. In addition, a distinct pattern of deflection has been observed, with anticyclonic eddies tending to drift northward and cyclonic eddies southward (see Figure S2 of Supplementary Material). The proportion of eastward-propagating eddies is notably larger in the TIAN dataset. When lifetimes of less than 4 weeks are considered, the distribution of both westward and eastward eddies can reach as high as 50%, indicating an almost equal distribution. However, when eddies persist for at least 16 weeks, this ratio falls significantly to around 35%. TOEddies and (META3.2) contain 20,061 and (30,440) eastward eddies, accounting for only 20% (35%) of the total eddies in the datasets.

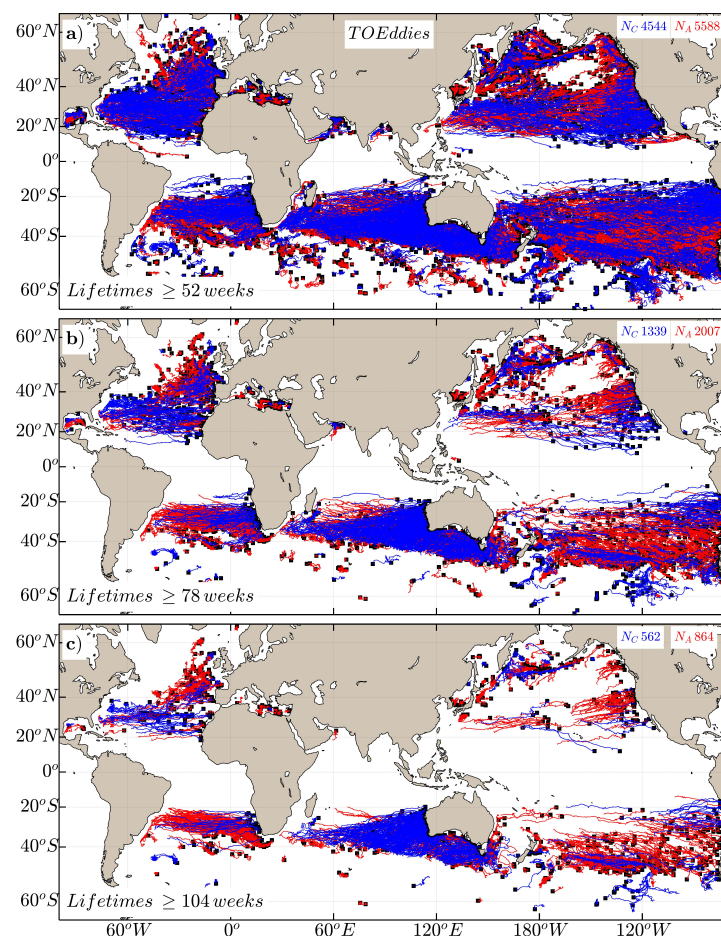


Figure 5. Cyclonic (blue) and anticyclonic (red) eddy trajectories as detected from TOEddies algorithm having lifetimes of at least (a) ≥ 52 weeks (b) ≥ 78 weeks and (c) ≥ 104 weeks. The numbers of detected eddies are labeled at the top of each panel for each polarity.

It is also worth noting that there are differences in the behaviour of long-distance propagating eddies between the eddy datasets. Figure 7 illustrates the trajectories of eddies from each dataset that were tracked for over 26 weeks and have propagated over 1,100 km. The distance was calculated for each eddy trajectory as the centroid distance between their initial and final positions, measured in kilometers. Long-lived, far-propagating eddies are of considerable interest to many studies due to their significant role in trapping and transporting water masses, along with heat, carbon, and oxygen. This process, in turn, influences global climate, marine connectivity, and ecosystem functioning [1,7,45,66]. The reliability of such estimates hinges on the precision with which mesoscale eddy temporal evolution and their en route interactions can be characterized. For example, the long-propagating Agulhas Rings leave a visible surface signature in the South Atlantic, which is reflected in all datasets. However, there are slight differences in the overview of the main eddy pathways depicted in each atlas, with some cases showing significant discrepancies. Such examples are visible mostly in the Pacific Ocean, where TOEddies detects more long-propagating eddies in the North Pacific, while only a portion of them is found in the TIAN dataset and META3.2 dataset (~11% and 46% fewer long-propagating trajectories, respectively). Large variations can also be observed in the South Pacific and North Atlantic.

To investigate in greater detail the similarities between long-lived eddies, we have focused our investigation on eddies with lifetimes of at least 26 weeks. We have then specifically targeted only those eddies that exhibited a consistent spatiotemporal evolution across all datasets. Given that the TOEddies dataset tracks a greater number of long-lived and long-propagating eddies, it was selected as the reference atlas. We then assessed the degree of similarity between the trajectories from the

various datasets and the reference one. Eddies were classified as "similar" if, during the same temporal range, the average distance between their barycenters did not exceed a specified threshold, that we defined as $\geq 0.5^\circ$. Our analysis revealed that the proportion of common eddy trajectories between TOEddies and the various datasets was approximately 72% for META3.2, 60% for TIAN and only 25% for GOMEAD.

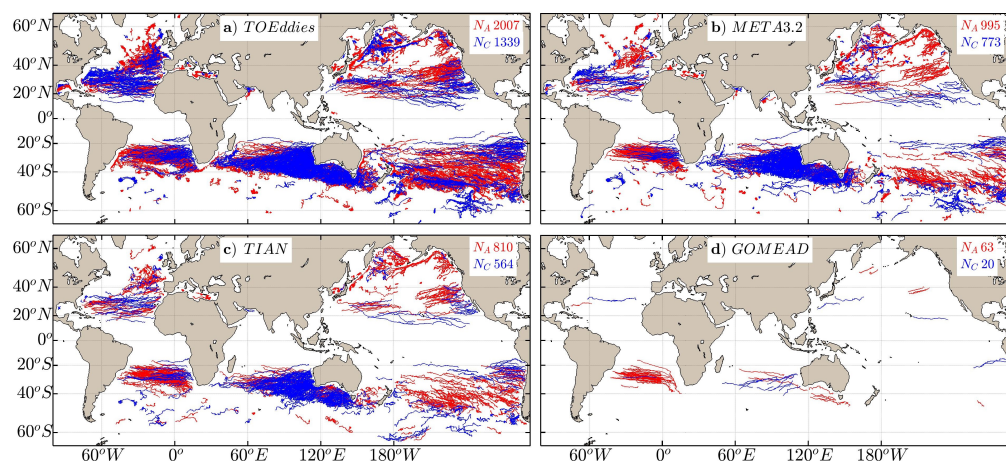


Figure 6. Trajectories of long lived (≥ 78 weeks) cyclonic (blue) and anticyclonic (red) eddies from (a) TOEddies (b) META3.2 (c) TIAN and (d) GOMEAD datasets. The numbers of eddies are labeled at the top of each panel for each polarity.

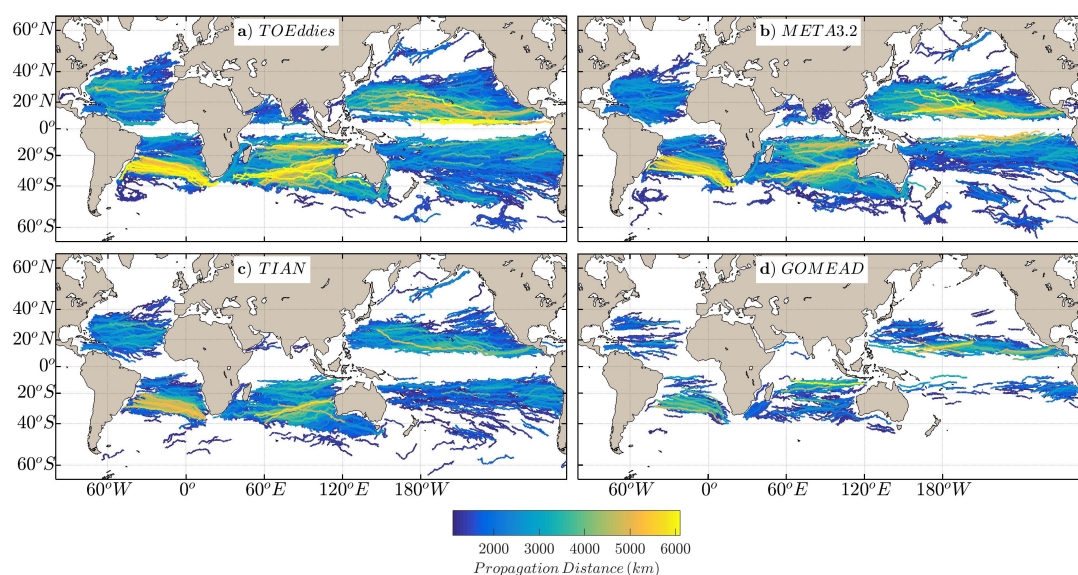


Figure 7. Trajectories of long-propagating (≥ 1100 km) eddies of both types from (a) TOEddies (b) META3.2 (c) TIAN and (d) GOMEAD datasets tracked for more than ≥ 26 weeks.

3.3. Characterization of Main Eddy Interactions

It is crucial for any dataset aiming to represent mesoscale variability to have the capability to accurately track the temporal evolution of mesoscale eddies. It should be noted, however, that these large-scale mesoscale eddies are not isolated in the turbulent oceanic fields. Both anticyclonic and cyclonic eddies may undergo complex interactions along their dynamical evolution and can experience multiple merging or splitting events during their propagation. Such events modify the primary eddy pathways and are purported to be associated with substantial water transfers. It is, therefore, essential

that merging and splitting events of both eddy types be identified so that the evolution of eddies can be understood.

The ability of TOEddies to determine the occurrence of eddy merging and splitting events enables the construction of unique eddy networks associated with specific eddy origins. In accordance with the methodology detailed in Laxenaire *et al.* [1,5,45], Figure 8 illustrates three eddy-network reconstructions as a case study. These are associated with the Agulhas Rings corridor, eddies originating from the North Pacific upwelling system, and eddies from the Australian western boundary. The trajectories in black, which originated from the area delineated by the dashed line, serve as the reference trajectories and are defined as order zero in the network (see [1]). The order number is increased with each additional interaction required to trace a reference trajectory in either direction. Consequently, these networks comprise all eddy trajectories that have encountered at least one merging or splitting event during their lifetime and, depending on their order, have connections to eddies of specific origins. The reconstruction of eddy networks indicates that long-lived and long-propagating eddies frequently interact with each other and have the potential to transport water from various regions of generation further away. To investigate the discrepancies among the different eddy atlases in tracking throughout the lifespan of eddies, an exhaustive analysis of two distinct long-lived eddies has been conducted. The TOEddies algorithm incorporates the co-location of the eddies identified from the altimetry gridded field with available in-situ measurements, thereby providing a valuable resource for in-depth studies of tracked eddies. To gain deeper insight into the vertical characteristics of these eddies and how they evolve over time, we have identified individual eddy trajectories that were sufficiently sampled by Argo floats across the years of observation. In particular, we have selected one anticyclonic eddy (A0) originating from the Agulhas leakage and one cyclonic eddy (C0) originating from the Australian western boundary, which were present in all datasets (Figure 9).

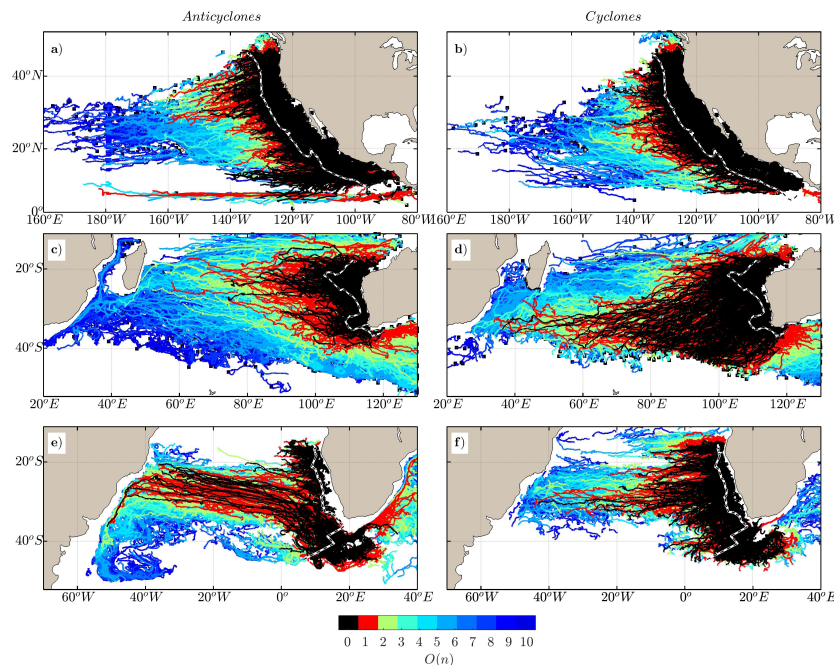


Figure 8. Eddy network example of anticyclonic (first column) and cyclonic (second column) trajectories for the (a-b) California Upwelling System (c-d) western Australian boundary and (e-f) extended South Benguela System. Each eddy trajectory is colored according to their assigned order.

In Figure 9a,c, we present the specific trajectory network reconstruction of A0, which includes all eddies that have merged with and split from A0 during the three years of its lifespan. Based on the TOEddies dataset, it can be concluded that A0 is the result of a splitting event that occurred in the Cape

Basin on September 11, 2010 at (6.92°E, 32.88°S). Figure 10a) shows that A0 originated from another anticyclone (A1) that was tracked back in the Agulhas retroflection as early as on November 19, 2009 (15.17°E, 37.40°S). During the period between October 2011 and January 2012, a number of complex interactions were observed in the Cape Basin, as illustrated in Figure 10b–d. After March 2011, A0 was observed crossing the Walvis Ridge and entering the South Atlantic, continuing westward at a consistent pace over 169 weeks (more than three years), reaching 7 December 2013.

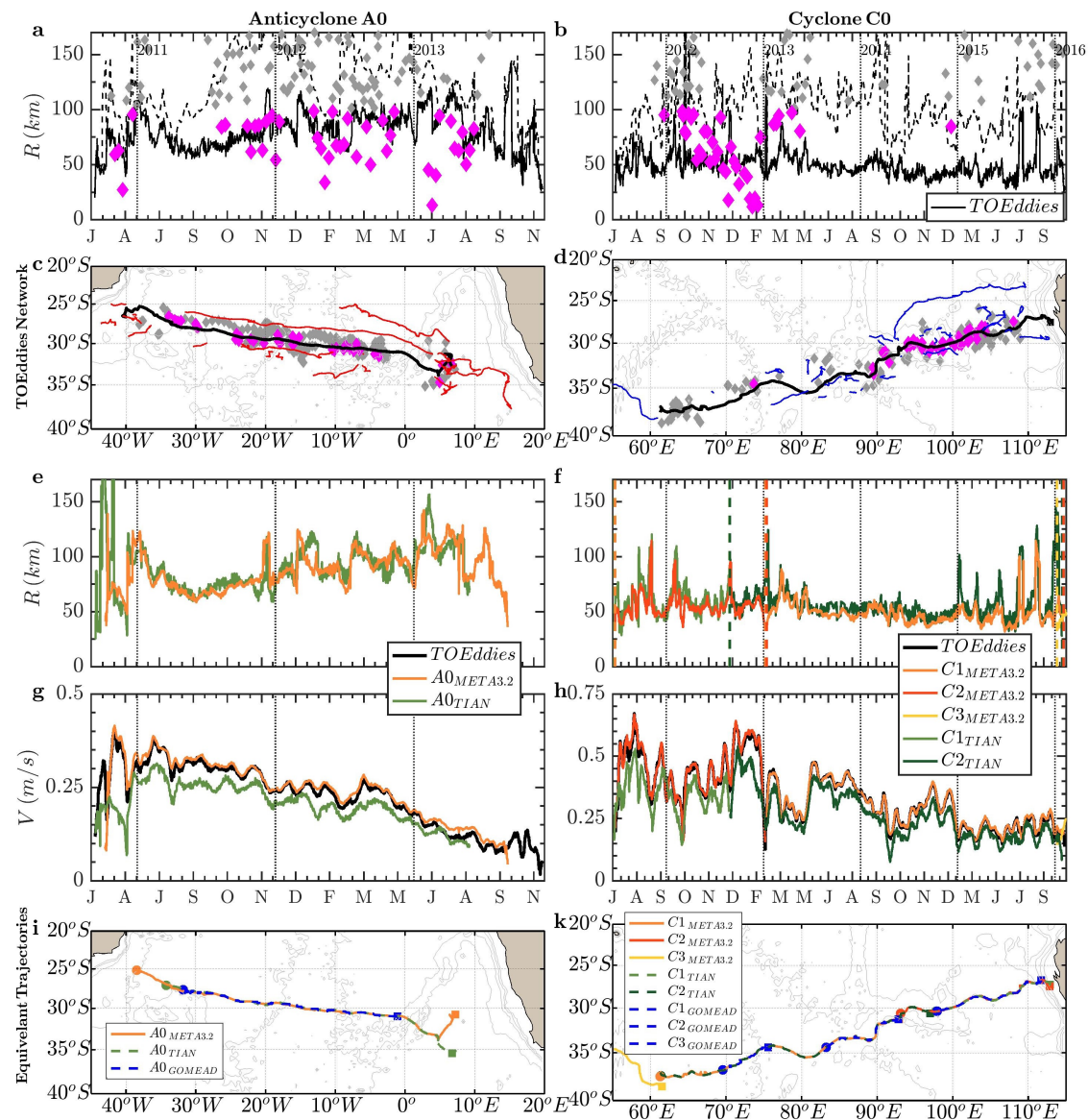


Figure 9. Temporal evolution of dynamical characteristics of anticyclone A0 and cyclone C0, as tracked by all considered datasets. The evolution of the eddy characteristic radius R_{max} (km), outermost radius R_{out} (km) as tracked by TOEddies is shown in panel a and b for the A0 and C0 respectively. The TOEddies network reconstruction comprised by all detected merging and splitting events is shown in panels c and d. The evolution of the eddy radii and characteristic velocity V_{max} (m/s) from the different datasets are shown in panels e–h. Panels i and k depict the equivalent A0, C0 trajectories as tracked from META3.2, TIAN and GOMEAD datasets. Bathymetry shallower than 4,000 m is indicated by gray lines.

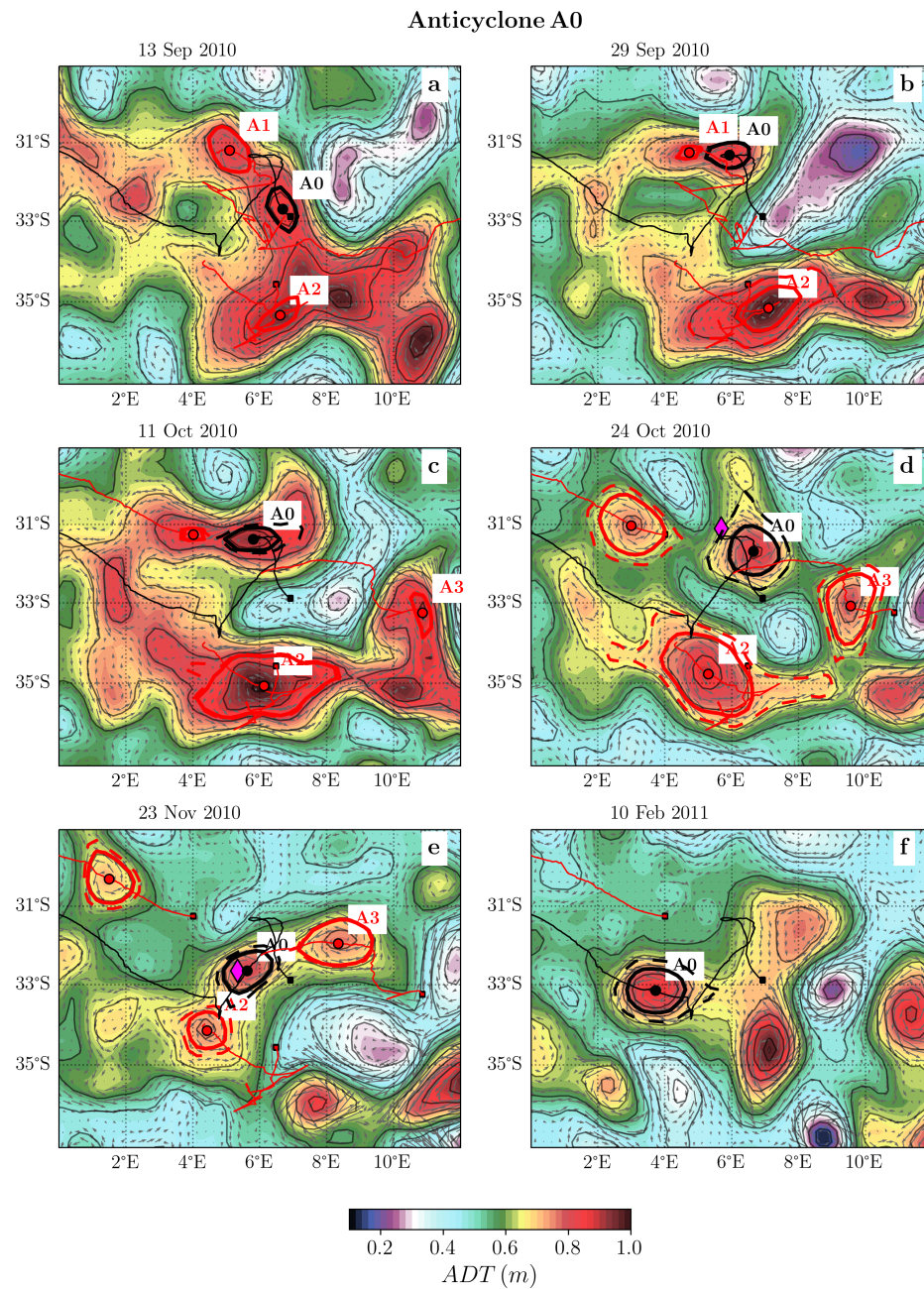


Figure 10. Snapshots along the temporal evolution of anticyclone A0 (panels a-f) propagating westward in the Southern Ocean. The background colors correspond to the ADT (m) fields while the gray arrows correspond to surface geostrophic velocities. The characteristic and outer contours as detected by TOEddies are shown in the blue solid and black dashed lines. The Argo trapped in the eddies are shown with the magenta diamond points. The bathymetry that is shallower than 4,000 m is illustrated with the gray shading.

From October 2010 to September 2013, 20 Argo floats collected data of A0 at different radial distances from the core of the eddy. Figure 9a illustrates the temporal evolution of the A0 characteristic radii as computed by TOEddies applied to the ADT maps. In addition, the estimated distances of the Argo floats from the eddy core (magenta points, Figure 9a,b) are provided. The eddy defined by the R_{max} contour remains relatively constant, with a median value of 80 km and a standard deviation (STD), of 18.1 km. However, the outermost contour defining the eddy, R_{out} , shows important variations, ranging from 26 to 202 km and an STD of 34.3 km. Both META3.2 and TIAN identified the presence of

eddy A0, as illustrated in Figure 9i. There is a noticeable overlap in the description of the main eddy pathway across all datasets. However, the TIAN algorithm identified a section of the eddy before its interaction with anticyclone A1, whereas the META3.2 dataset incorporated a portion of eddy A2 into the main trajectory.

Figure 9e,g shows the temporal evolution of the anticyclone's characteristic radii and velocity across the various datasets. The temporal evolution of the eddy radius demonstrates a high level of similarity across the datasets, with mean differences with TOEddies of less than 6 km in META3.2 and 8 km in TIAN. Furthermore, the eddy V_{max} shows a consistent decline over time, a trend evident in all datasets. We observe a systematic decrease (in average 0.05 m/s), in the mean eddy intensity, as measured by TIAN, which is likely attributable to the use of SLA fields. However, while the decay of surface properties in the eddy indicates a distinct dissipation process, only the TOEddies atlas provides direct access to this information by integrating available hydrographic properties from Argo floats.

Figure 12a presents the temporal evolution of the density anomaly of the eddy A0 from Argo floats trapped within its core from 24 October, 2010 to 08 June, 2013. Only profiles situated within the eddy outermost radius of the eddy from its center were selected (Figure 9a). The integration of Argo vertical profiles with the eddy detection based on satellite altimetry suggests that A0 is not undergoing dissipation. Instead, the data suggests that the eddy is experiencing a progressive deepening of its vertical structure and a clear separation from the ocean surface. Dynamical topography results from the vertical integration of the thermohaline properties of the water column. A reduction in eddy intensity may be linked to alterations in the thermohaline properties of the upper water column through eddy cooling as observed by [67] or eddy subsidence at depth (as in this case). The latter case was initially documented for another Agulhas ring in [5,45] showing that the eddy subducted to become an intensified subsurface eddy. Therefore, when the eddy signal disappears from altimetry maps, it is possible that it has not simply dissipated. Instead, it may indicate that the eddy has penetrated more deeply and become disconnected from the surface.

Meanwhile, the Cyclone C0 was initially identified by TOEddies on June 24, 2011, off the western coast of Australia (112.9°E, 27.57°S) and was subsequently tracked as it propagated southwestward into the Indian Ocean for a period exceeding four years. The reconstruction of the TOEddies network also revealed multiple instances of merging and splitting along this cyclonic eddy trajectory. A few months after its formation, on February 25, 2012, a merging event (Figure 11b) was detected with a short-lived cyclone (less than a month). On January 9, 2013 (Figure 9c), C0 merged with another cyclonic eddy that originated from the western border of Australia and propagated westward. By June 14, 2014, C0 had already drifted 2,226 km, while being sampled by 22 different Argo floats, providing 138 vertical profiles at varying radial distances from the center of the eddy (magenta dots in Figure 9b). On February 7, 2016, the eddy reached 61.28°E, 37.58°S and merged with another cyclone, which continued its westward propagation till February 26, 2018, reaching 33.82°E, 33.93°S.

To facilitate comparison between datasets, we located Cyclone C0 in the META3.2, TIAN, and GOMEAD atlases. META3.2 dataset has identified three separate cyclones (instead of one) that appear to be following a similar westward trajectory, as illustrated in Figure 9b. The second cyclone in the META3.2 dataset was identified just a few days after the last detection of the first cyclone in the same dataset. The TOEddies identified this interaction as a merging of two cyclones. Similarly, Cyclone C0 in the TIAN dataset was identified as two distinct cyclonic eddies with no prior connection between them. The TIAN atlas was unable to link the two trajectories due to a significant variation in eddy size during the period in question (25 August 2012). Furthermore, the eddy velocity was found to be slightly lower (0.12 m/s) in intensity compared to that of TOEddies. GOMEAD also classified these cyclones as two distinct eddies, though with shorter trajectories.

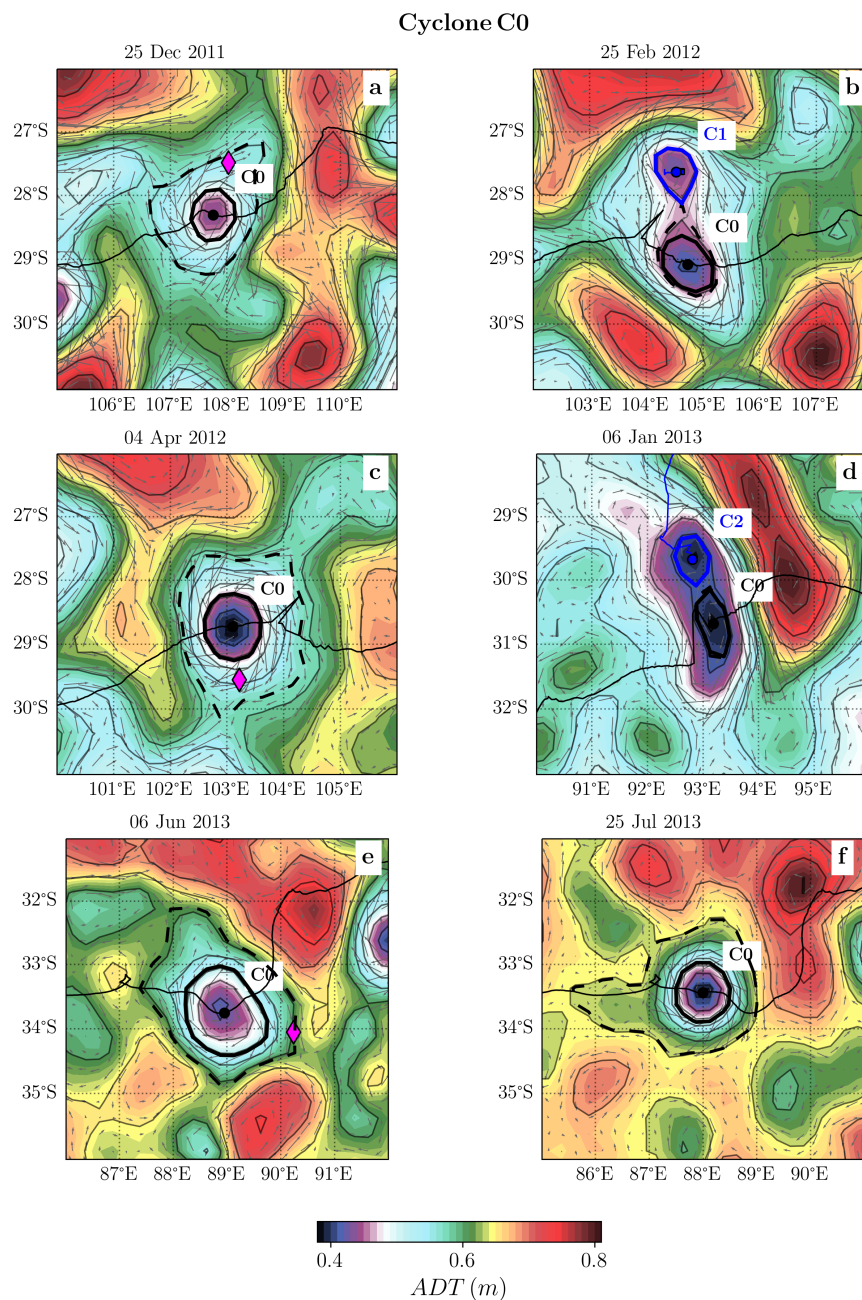


Figure 11. Snapshots along the temporal evolution of cyclone C0 (panels a-f) propagating westward in the Indian Ocean. The background colors correspond to the ADT (m) fields while the gray arrows correspond to surface geostrophic velocities. The characteristic and outer contours as detected by TOEddies are shown in the blue solid and black dashed lines. The Argo trapped in the eddies are shown with magenta diamond points. The bathymetry that is shallower than 4,000 m is illustrated with the gray shading.

Figure 12 provides an illustration of the value of integrating satellite altimetry data with the eddy subsurface properties derived from the extensive Argo vertical profiles. This approach offers a more comprehensive understanding of the dynamics and evolution of eddies. The figure illustrates the presence of a pronounced inverted temperature anomaly signal in the upper layers for C0. Furthermore, the analyzed data indicate that the core of A0 is situated between 200 and 1,000 m, exhibiting consistent and markedly distinct properties that are largely independent of seasonal variations in the mixing layer. The presented evidence suggests that these eddies are subsurface intensified. These findings

are consistent with those of previous studies that employed the TOEddies atlas to examine a range of Atlantic eddies [5,7,45]. These examples demonstrate the necessity of this integrated approach to fully grasp the complex vertical and horizontal structure of mesoscale eddies, particularly when considering their role in large-scale oceanic exchanges. Future work will aim to explore these vertical structures in more detail to gain a deeper understanding of their dynamical behavior throughout their lifecycle.

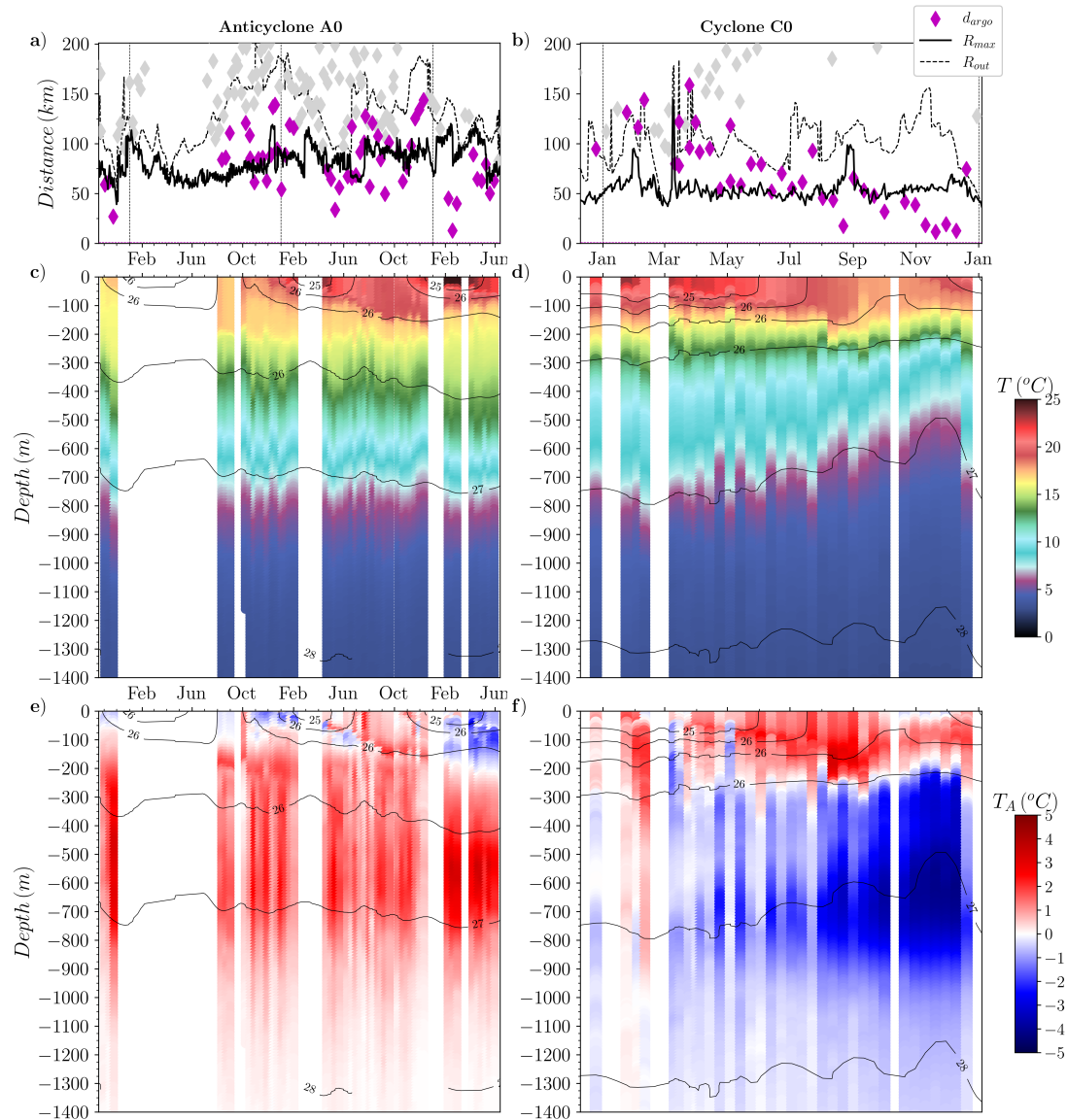


Figure 12. Temporal evolution of anticyclone A0 and cyclone C0 vertical structure as obtained by Argo floats trapped inside the eddy core ($d_{ARGO} \leq R_{max}$) (shown as magenta points in panels a and b). Vertical profiles of temperature T ($^{\circ}\text{C}$) and temperature anomalies T_A ($^{\circ}\text{C}$) are shown in panels c-f.

4. Conclusions

In this study, we examined and evaluated key characteristics and pathways of mesoscale eddies for the global ocean using four different global datasets [1,33,37,38]. We have specifically employed and used an enhanced version of the TOEddies algorithm, originally designed for the South Atlantic and expanded here to the world ocean. We then compare our findings with those of three other established global eddy datasets. Each of the datasets employs a different approach to processing and tracking eddies using global satellite altimetric data from AVISO/DUACS. This includes daily sea

surface height anomalies, as well as absolute dynamic topography, and it covers a two-decade period. The TOEddies atlas offers a more comprehensive description of ocean dynamics than other datasets. It considers interactions between eddies and integrates in-situ Argo float measurements, providing additional details on eddy vertical structures.

The results consistently showed certain characteristics of mesoscale eddies across all datasets. In line with previous findings [10], the majority of these eddies (>80%) exhibited a westward propagation in the Global Ocean, predominantly driven by the beta effect. Additionally, a notable northward deflection of anticyclonic eddies and southward deflection of cyclonic eddies was observed consistent with prior research [10,46,68,69]. On the other hand, a comparison of the eddy properties extracted from the four global atlases revealed variations in both the number of eddies and their average characteristics. This is to be expected, given the distinct methodologies employed. In particular, when examining a consistent set of eddies detected by the various algorithms, the average differences remained in the order of 17 km in eddy radius and 2 cm/s in eddy intensity. Furthermore, the use of SLA versus ADT demonstrated a consistent tendency to underestimate eddy intensities. This was demonstrated by two randomly selected examples of eddies, one anticyclonic and one cyclonic. Moreover, an analysis of long-lived eddies from multiple atlases revealed that the majority of these long-lived trajectories are more commonly associated with anticyclonic rather than cyclonic eddies. This finding is in line with the results of previous studies [70–72], which observed a global anticyclone/cyclone asymmetry. This suggests that anticyclones maintain a more stable and coherent structure compared to cyclones, which are often smaller. However, this may also indicate that anticyclones, due to their larger size, remain visible in satellite altimetry maps for extended periods, even if subsiding or subducting in the ocean's subsurface, in comparison to cyclones.

In this regard, TOEddies offers a distinctive advantage in that it integrates eddy surface detection with available vertical measurements, thus providing a unique solution to the problem of inferring the eddy dynamics and its evolution from surface observations. This demonstrates that inferring the eddy dynamics and its evolution from surface (satellite) observations is an inadequate approach. In Section 3.3, two examples of individual eddies in the TOEddies dataset are presented. These eddies were co-localized with Argo floats along their en route propagation. These examples demonstrate notable discrepancies in the evolution of hydrological properties between the upper and lower layers. The observed attenuation of anomalies in the upper layers and the persistence of larger anomalies in the deeper layers indicate that the attenuation of the altimetry signal in eddies, their eventual disappearance, and the observed asymmetry of cyclonic and anticyclonic eddy trajectories with time may not be solely attributed to dissipation processes. An additional possibility is that subduction processes may be involved, resulting in an effective disappearance from satellite data due to a reduction in the signal in satellite altimeter fields. As previously noted, this behavior has been observed, in particular, in the case of the Agulhas Rings [1,5,45]. Recent studies have also demonstrated that cyclones are frequently prone to subduction into deeper layers [2–4,7,22,73]. Consequently, the limitations of satellite altimetry in resolving mesoscale eddies could also introduce an observational bias, resulting in an overall underrepresentation of the dynamics of anticyclones and particularly of cyclonic features. It is not possible to infer the evolution of eddies based on observations of the ocean surface alone. Nevertheless, the integration of satellite data with in situ measurements can markedly enhance our comprehension of ocean eddies and their influence on oceanic processes.

It is evident that the selection of distinct parameters for the detection and tracking of eddies can result in enhanced datasets that more accurately reflect the characteristics of eddies in the ocean. Despite the high degree of similarity observed between eddy trajectories across the various datasets, only a limited subset of them constituted the comprehensive eddy network presented by TOEddies. The specific information on merging and splitting events provided by TOEddies calls into question the conventional view of a single eddy and its associated trajectory. In contrast, mesoscale eddies are not isolated within the turbulent oceanic fields. Successive eddy interactions have the potential to alter the main eddy pathways, which in turn affects the reconstruction of eddy trajectories and their estimated

lifetimes. Such interactions can result in the exchange of a significant portion of the water mass, which in turn affects the estimated water mass transport associated with the eddies.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on [Preprints.org](https://preprints.org).

Author Contributions: AI and SS designed the study and contributed to the writing. AI performed the data analysis while RL and LG provided TOEddies dataset and automatic eddy detection for the study area. All authors contributed to the article and approved the submitted version.

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Data Availability Statement: The Ssalto/Duacs altimeter products were produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS) (<https://marine.copernicus.eu/>). The Argo data were collected and made freely available by the International Argo Program and the national programs that contribute to it (<https://coriolis.eu.org>). The TOEddies global Atlas data used for this paper will be made available at a publicly available repository after the completion of the review process. Data from other Atlases were obtained by accessing the corresponding publication links, as provided by the respective papers.

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Conflicts of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Appendix A

Appendix A.1 : TOEddies Eddy Detection

TOEddies identifies the outermost contours of ADT around extrema of ADT. These contours are approximated as polygons with vertices of the polygons aligned with the grid lines of the ADT field. An outermost contour C around a given extremum E is thus defined by the following properties:

- C is a closed isoline of ADT.
- C contains extremum E .
- C does not contain any extremum of opposite sign.
- C has a minimum area of $\pi(25 \text{ km})^2$.
- The absolute value of the difference between the ADT level of C and the ADT of E is greater than 1 mm. This threshold difference is called the persistence parameter.
- C does not contain any extremum other than E with same sign as E and with an associated outermost contour ;
- No isoline exterior to C has the above properties.

This definition is recursive in its fifth point so it is not complete. We complete the definition by adding that the minima of ADT are examined in descending order of ADT and the maxima in ascending order. If TOEddies finds an outermost contour around an extremum E then it also looks for a maximum-speed contour. The maximum-speed contour is the closed iso-line of ADT containing E and inside the outermost contour, with maximum mean azimuthal speed. The azimuthal speed at a point of a contour is computed as:

$$V_{\theta} = \frac{xv - yu}{\sqrt{x^2 + y^2}}$$

where:

$$x = \cos \phi_E (\lambda - \lambda_E)$$

$$y = \phi - \phi_E$$

(u, v) is the geostrophic speed at the point (λ, ϕ) on the contour, and (λ_E, ϕ_E) is the position of the extremum.

Appendix A.2 : TOEddies Eddy Tracking

In TOEddies, the overlapping criterion is applied firstly to the maximum-speed contours and then to the outer-most contours. Two instantaneous eddies overlap if they are between one and 5 days apart and if the area of the intersection of their maximum-speed or outermost contours is greater than 50% of the minimum of the areas of the contours. An eddy can overlap with more than one other eddy.

A given eddy can even have several successors (overlapping eddies at subsequent dates) at different dates or several predecessors (overlapping eddies at previous dates) at different dates. However, if an eddy has a successor at time distance δ then we restrict the search for successors at time distances greater than δ : an eddy at distance $\delta' > \delta$ can only be a successor if it has no predecessor at distance $< \delta'$.

Thus, TOEddies creates, for each polarity (anticyclones and cyclones) an abstract graph in which each node is an instantaneous eddy and there is an edge between two nodes if the instantaneous eddies overlap. The edges have the time direction so the graph is directed acyclic. Splitting of eddies appear in the graph as nodes with an out-degree ≥ 2 and merging of eddies appear as nodes with an in-degree ≥ 2 . For each polarity, the graph has about 3×10^7 nodes and 3×10^7 edges.

TOEddies proceeds by collapsing the graph of instantaneous eddies into a "graph of segments". A segment is a sequence of nodes in the graph of instantaneous eddies, without splitting except maybe at the last node of the segment, and without merging except maybe at the first node of the segment. In the graph of segments, each node is a segment and edges correspond to splitting or merging events.

For each edge in the graph of segments, TOEddies computes a cost:

$$C = \sqrt{\left(\frac{d - \bar{d}}{\sigma_d}\right)^2 + \left(\frac{\Delta N - \overline{\Delta N}}{\sigma_{\Delta N}}\right)^2 + \left(\frac{\Delta r - \overline{\Delta r}}{\sigma_{\Delta r}}\right)^2}$$

where d is the distance between the extremum of the last eddy in the head segment of the edge and the extremum of the first eddy in the tail segment of the edge,

$$\Delta N = N_{\text{Ro,first}}(\text{tail segment}) - N_{\text{Ro,last}}(\text{head segment})$$

$$\Delta r = r_{\text{first}}(\text{tail segment}) - r_{\text{last}}(\text{head segment})$$

$N_{\text{Ro,first}}(\text{segment})$ is the mean on the first seven days of the segment of the Rossby number associated to the maximum-speed contour. $r_{\text{first}}(\text{segment})$ is the mean on the first seven days of the segment of the radius of the maximum-speed contour (that is, the radius of the equal-area disk). Similarly, $N_{\text{Ro,last}}(\text{segment})$ and $r_{\text{last}}(\text{segment})$ are mean values on the last seven days of the segment.

From the graph of segments weighted by cost values, TOEddies computes eddy trajectories. A trajectory is a path in the graph of segments. Each non-root node in the graph has a closest predecessor: head of the in-edge with the lowest cost. Each non-leaf node in the graph has a closest successor: tail of the out-edge with the lowest cost. In order to construct trajectories, TOEddies processes the nodes in topological order. For each node, TOEddies looks whether the node is the closest successor of its closest predecessor. If so, then this node is placed in the same trajectory as its closest predecessor. Else this node begins a new trajectory. Because of "phantom instantaneous eddies", detected from the Aviso dataset, but not real, there are in the graph of segments patterns where a splitting is immediately followed by a merging. We do not want to let those phantom patterns interrupt trajectories so we detect those patterns in the graph: if the merging is 6 days or less after the splitting, then the trajectory continues through the pattern, going through the shortest (that is, with smallest cost) branch of the splitting-merging.

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