



Below the Surface: Detecting Mesoscale Eddies from Argo Density Profiles in the South Atlantic

Beatrice Altamura¹, Artemis Ioannou¹, and Sabrina Speich¹

¹Laboratoire de Météorologie Dynamique (LMD), ENS, Université Paris Sciences et Lettres, 24 rue Lhomond, Paris 75005, France

Correspondence: Beatrice Altamura (beatrice.altamura@lmd.ipsl.fr)

Abstract. Mesoscale eddies play a major role in the distribution of heat, salt and tracers in the ocean, yet satellite observations alone cannot fully characterise their three-dimensional structure. Here we develop a method that detects and characterises mesoscale eddies directly from Argo vertical profiles of potential density anomaly in the South Atlantic. Eddies identified from the TOEddies altimetry atlas are used to colocate Argo profiles and to calibrate region-dependent detection thresholds over the period 2000-2025; altimetry thus serves as a reference and calibration benchmark rather than as an input to the detection itself. We evaluate the method against an independent dataset from two field campaigns, in which mesoscale eddies were located independently from ADCP velocities, comprising 12 anticyclonic and 14 cyclonic eddies. Applying the method to the full dataset reveals distinct spatial distributions of surface- and subsurface-intensified eddies, with cyclones showing a stronger tendency toward subsurface intensification. Surface-intensified eddies are more prevalent in tropical regions and the Cape Basin, while both cyclonic and anticyclonic eddies show evidence of subduction in the Cape Basin, transitioning from surface to subsurface intensification along their trajectories, a transition supported by individual eddy trajectories sampled by Argo floats. The vertical structure of eddies is also closely linked to mixed-layer dynamics and its seasonal variability, with winter associated with more surface-intensified eddies and deeper mixed layers, and summer with more subsurface-intensified eddies and shallower mixed layers. Because the detection thresholds are calibrated on altimetry-detectable eddies, the fraction of eddies found without a surface altimetric signature represents a lower bound on what altimetry misses. By resolving the vertical structure that altimetry cannot see, our approach reveals that a large fraction of South Atlantic eddies are subsurface-intensified, and that eddies detected at the surface in the Cape Basin systematically subduct into the ocean interior along their trajectories. Recovering eddies at depth after they lose their surface signature demonstrates that they have not dissipated but continue to propagate, transporting their trapped water masses and properties far from their generation site. This surface-to-subsurface transition, invisible to satellite altimetry, has direct implications for the subsurface redistribution of heat, salt and tracers across the South Atlantic.

1 Introduction

Mesoscale eddies are ubiquitous features in the ocean and one of the major sources of ocean variability (Stammer, 1997; Wunsch, 1999). With characteristic spatial scales of $O(100\text{km})$ (Chelton et al., 2011) and lifetimes ranging from several months



25 to several years (Ioannou et al., 2022, 2024; Laxenaire et al., 2018), they influence multiple components of the ocean system, including the transport of energy, heat, salt, mass, and biogeochemical tracers across large horizontal and vertical scales (Baudena et al., 2025; Bryden and Brady, 1989; Chaigneau et al., 2011; Jayne and Marotzke, 2002; Laxenaire et al., 2018, 2019; McWilliams, 1985; Zhang et al., 2014).

By trapping water masses and transporting them across long distances while largely preserving their characteristics, mesoscale eddies contribute to the redistribution of heat, salt, and biogeochemical tracers and help regulate ocean circulation. The persistence of distinct thermohaline characteristics within eddies relative to the surrounding waters generates pronounced horizontal gradients and fronts (Martin et al., 2002; Pinot et al., 1995). By advecting tracers like chlorophyll, mesoscale eddies are crucial to the geographical distribution of components vital to biological activities and productivity (Arhan et al., 1999; Cornec et al., 2021; Dilmahamod et al., 2018; Dufois et al., 2016; Ioannou et al., 2022; McGillicuddy et al., 2007; Villar et al., 2015).

35 Mesoscale eddies also influence ocean-atmosphere interactions and air-sea fluxes (Chen and Yu, 2024; Frenger et al., 2013; Moreton et al., 2021; Villas Bôas et al., 2015), ventilation of the ocean interior (Sallée et al., 2010) and large-scale ocean circulation (Lozier, 1997; Morrow et al., 1994).

Satellite altimetry has become the primary tool for observing mesoscale eddies at global scale. Because many eddies have a distinct sea-surface height (SSH) signature, altimetry provides a synoptic view of upper-ocean mesoscale variability and enables the detection and tracking of eddies over multiple decades (Chaigneau et al., 2011; Chelton et al., 2007, 2011; Ioannou et al., 2024; Laxenaire et al., 2018). However, only eddies associated with a sufficiently strong SSH anomaly can be reliably detected from altimetry.

While various eddy-tracking algorithms have been developed for surface fields (Chelton et al., 2007, 2011; Doglioli et al., 2007; Faghmous et al., 2015; Mason et al., 2014; Mkhinini et al., 2014; Nencioli et al., 2010), including recent ones that account for merging and splitting events (Cui et al., 2019; Ioannou et al., 2024; Laxenaire et al., 2018; Le Vu et al., 2018), the detection of subsurface structures remains more challenging because their surface signatures are often weak or even absent from surface altimetric fields. Their full characterization therefore requires complementary analyses based on Argo float observations, by examining whether floats sampled the detected features and, when available, using the corresponding vertical profiles to characterize their subsurface structure (Johnson and McTaggart, 2010; Li et al., 2017; McCoy et al., 2020; Pegliasco et al., 2015; Zhang et al., 2015). Furthermore, geostrophic velocities derived from sea-surface height do not always accurately represent the velocity structure within the eddy core (Bashmachnikov and Carton, 2012; Ienna et al., 2022; Laxenaire et al., 2019; Subirade et al., 2023).

Analysis of vertical profiles has shown that mesoscale eddies exhibit a wide range of vertical structures that are not necessarily surface intensified. While some eddies reach their maximum amplitude near the surface, others are subsurface intensified, with their core located hundreds of meters below the surface. A defining feature of subsurface anticyclones (cyclones) is the doming (bowing) of isopycnals in the shallower layers, and a bowing (doming) of isopycnals in the deeper layers, around a weakly stratified, gradient-wind balanced water mass. Despite their subsurface core, these structures can displace isopycnals sufficiently to generate detectable sea-surface height anomalies, allowing many of them to be identified from satellite altimetry (Dilmahamod et al., 2018; Laxenaire et al., 2019, 2020). In some cases, the surface signature reflects the underlying subsurface



60 structure and can be used to distinguish surface- from subsurface-intensified eddies (Assassi et al., 2016). While subsurface eddies have been observed in many basins, their systematic detection from vertical profiles remains challenging. Several studies have used combined altimetry and Argo observations, where Argo profiles are co-located with altimetry-detected eddies to characterize their subsurface structure. Examples include Pegliasco et al. (2015) and Ioannou et al. (2022) for subsurface eddies in the four eastern boundary upwelling systems (EBUS), Dilmahamod et al. (2018) for South Indian Ocean eddies (SIDDIES),
 65 Chaigneau et al. (2011) for eddies in the eastern South Pacific Ocean, Laxenaire et al. (2019) for Agulhas Rings. McCoy et al. (2020) target global anticyclonic submesoscale coherent vortices (SCV) using the Argo database and three diagnostics: spiciness as a measure of thermohaline variability, buoyancy frequency as an estimate of stratification, and the dynamic height anomaly indicative of the horizontal pressure gradient forces. Zhang et al. (2017) identifies subsurface eddies through “lens-like” density structures, characterized by upward doming isopycnals above the core and downward bowing below, associated
 70 with a potential vorticity minimum.

Other global eddy detection methods, such as Chen et al. (2021), combine Argo-based detection with altimetry to enhance global tracking of subsurface eddies. This approach relates surface signatures to interior ocean properties, partially compensating for altimetric limitations, particularly in low-latitude areas where traditional sea level anomaly signal is weaker and less effective. In this context, we develop a method to detect mesoscale eddies directly from vertical Argo profiles of potential density anomaly, using TOEddies atlas, a 25-year dataset combining co-located Argo float observations and satellite altimetry. We first calibrate region-specific thresholds explicitly accounting for regional variability in stratification and dynamical conditions. We then apply the resulting detection method to individual Argo profiles to identify eddy signatures in the vertical structure of potential density anomaly. The second objective is to characterize the vertical structure of the detected eddies and to distinguish between surface- and subsurface-intensified structures. This analysis enables a systematic assessment of the spatial distribution
 80 and prevalence of different eddy types across the study region.

2 Data and Methods

2.1 The TOEddies atlas

We use the TOEddies atlas as a reference dataset to calibrate the algorithm that allows the detection of eddies from vertical profiles of potential density. TOEddies provides a 30-year global record (Jan 1993 - May 2025) of mesoscale eddies derived
 85 from unfiltered absolute dynamic topography (ADT) fields gridded at $1/8^\circ$, including their polarity, trajectories and key geometrical properties (such as velocity, radii etc). We restrict our analysis to the years 2000-2025 to be consistent with the Argo dataset. The altimetric fields are derived from daily, multi-satellite sea surface height fields produced by Copernicus Marine Service (<https://marine.copernicus.eu/>). Eddies are identified as points of extremum in the SSH (Sea Surface Height) fields (cyclonic eddies correspond to local minima of SSH, while anticyclones correspond to local maxima). TOEddies identifies the
 90 eddy trajectories using an algorithm based on the overlapping of eddy contours at consecutive time steps, taking into account merging and splitting of eddies. Two characteristic contours are identified for each eddy: the outermost closed contour of ADT around each extremum and the contour where the mean azimuthal velocity of the eddy is maximum (in this step the geostrophic

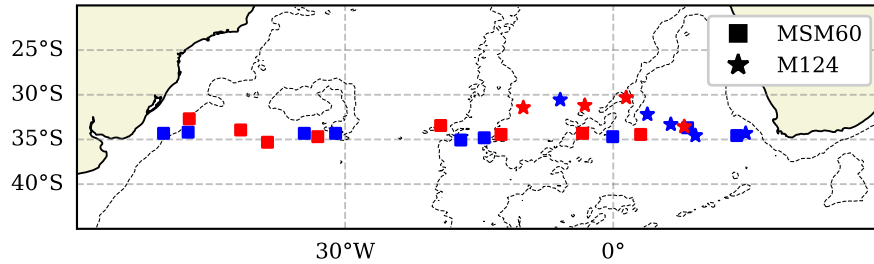


Figure 1. Location of the cyclones (blue) and anticyclones (red) sampled during the campaigns M124 and MSM60.

velocities computed from ADT maps are used). For both contour, an equivalent radius associated with the area delimited by the contour is computed: R_{out} for the outer contour and $R_{V_{max}}$ for the maximum velocity contour.

2.2 Argo Profiles Data

The Argo floats international program (Argo, 2026) collects data inside the ocean using free drifting profiling floats. They provide a large number of CTD (conductivity, temperature and depth) profiles in the upper 2000m of the ocean. We use the delayed mode Argo data with quality control flags equal to 1 and 2 (corresponding to good and probably good observation). We perform an additional quality filter following Laxenaire et al. (2019), by selecting only the profiles containing at least one observation in the upper 20 m and one at a depth greater than 950 m, and having a vertical sampling interval no coarser than 25, 50, 75, 100, and 200 m for, respectively, the depth intervals 0–100 m, 100–300 m, 300–500 m, 500–1000 m, and below 1000 m. The data satisfying these criteria are then interpolated at a 10 m-depth step. For each profile, the standard thermodynamic variables are computed using the Gibbs SeaWater (GSW) Oceanographic Toolbox of the Thermodynamic Equation of SeaWater TEOS-10 (McDougall and Barker, 2011): conservative temperature, absolute salinity and potential density referenced to the ocean surface (σ_0). By performing colocation of Argo profiles and TOEddies we can divide Argo floats into three categories: those falling outside eddies of both polarities, called environment profiles, those falling inside the outer contour of anticyclones and those falling inside the outer contour of cyclones. Among profiles sampling an eddy we distinguish between those sampling the eddy core (i.e. falling inside the maxspeed contour) and those sampling the eddy edge (between the maxspeed and the outer contour). We use the environment profiles to compute a local climatology for each float: a square of side 3° is constructed around each profile, then the climatological average of potential density is computed selecting all the Argo profiles sampling the environment in the box, whose dates are within 30 calendar days from the date of the given Argo profile. In the following, only the profiles having at least 20 Argo profiles used to compute the reference profile are retained. With this step, we lose less than 1 % of the total profiles. The local climatological profile is then removed from each potential density profile to obtain a potential density anomaly (PDA) profile. After performing all the quality filters, we retain 157,419 total profiles in the South Atlantic, defined as the region between 60°W and 30°E and between 3°S and 48°S (the domain is shown in Fig. 2a).



2.3 Campaigns Dataset: M124 and MSM60 campaigns

Data collected during 2 oceanographic cruises in the South Atlantic are used: the *Maria S. Merian* MSM60 expedition (Jan - Feb 2017) that provided the first basin-wide section across the South Atlantic following the SAMBA/SAMOC line at 34.5 °S; and the *FS Meteor* M124 expedition (Feb - Mar 2016), which aimed at studies on differences in the vertical structure of the water column within and outside of mesoscale eddies. Instruments used include CTD, underway CTD (uCTD), and lower and ship mounted Acoustic Doppler Current Profilers (IADCP and sADCP). The raw profiles of potential density are interpolated at a 10 m depth step, to keep the same vertical step used for Argo floats when applying the eddy detection algorithm. The climatological profiles are computed from environment Argo profiles as described in Sect. 2.2. The two campaigns sampled a total of 14 cyclones and 12 anticyclones, whose locations are shown in Fig. 1. The velocity field measured by the ADCP allows to characterize the structure of an eddy independently of both altimetry and the IPDA method we propose in this study (see Sect. 2.4) and it is the only independent confirmation of the presence of subsurface eddies that are invisible to altimetry. In particular, with a single transect passing through an eddy, it is possible to estimate its center and boundary: one approach is to use the point of zero-crossing of the azimuthal velocity as an estimate of the center, and the point of maximum azimuthal velocity as the boundary of the eddy. It should also be noted that CTD profiles from the campaigns constitute an independent dataset, but the reference profiles used to compute the density anomaly are based on Argo profiles, so the frame of reference of the density anomaly is shared with the methodology.

2.4 Integrated Potential Density Anomaly algorithm (IPDA)

We develop a detection algorithm applied to vertical profiles of potential density anomaly (PDA) from the TOEddies Argo co-localization dataset that allows individual profiles to be reclassified as in cyclonic eddies, anticyclonic eddies and in the environment. The method, hereafter referred to as the IPDA algorithm, complements the surface-based detection provided by TOEddies by using Argo profiles to diagnose the vertical structure associated with each detected eddy. Contrary to TOEddies co-localisation process, which determines the position of each Argo profile relative to the surface-detected eddy shape, the IPDA provides an independent classification based on the vertical density structure observed by the Argo profile. To account for spatial variability in eddy vertical structure, the IPDA algorithm is calibrated separately for different regions of the South Atlantic. The domain is divided into 3 °x3 ° subregions, as shown in Fig. 2a. For each region, Argo profiles colocated within eddy cores (inside the maximum-velocity contours) are used to compute a mean density anomaly profile and define two vertical integration limits Z_{LOW} and Z_{UP} as the depths where the profiles changes sign, around its extremum (minimum value of the mean profile for anticyclones, and maximum for cyclones). This provides a region-specific estimate of eddy thickness and accounts for spatial variability in eddy vertical extent. Only regions containing at least 30 Argo profiles are retained. It should be noted that this selection step is different from the previous one used to retain only profiles with a solid climatology (see Sect. 2.2).

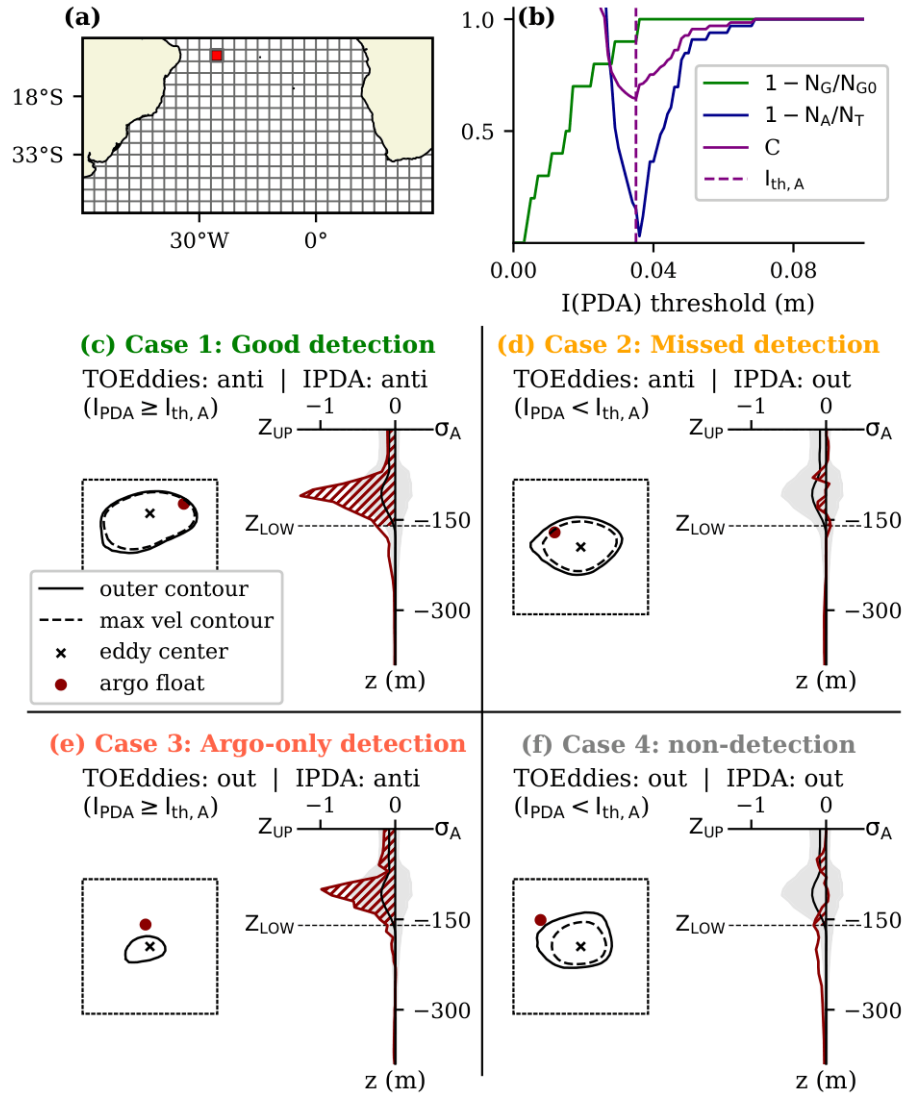


Figure 2. Example of anticyclonic eddy detection method. (a) 3°x3° grid, with the selected grid cell in red. (b) Curves of the first term (green) and the second term (blue) composing the cost function (purple), as a function of the I(PDA) threshold. The purple dashed line represents the optimal threshold. (c) Example of a good detection (dark red profile). The grey shaded area indicates the mean $\pm$ standard deviation of eddy core profiles in the region, the black line is the mean eddy core profile. Panels (d)-(e)-(f) are examples of a missed detection, Argo-only detection and consistent non-detection respectively.

For each vertical profile of each subregion, we compute the Integral of the Potential Density Anomaly, I(PDA), within the corresponding regional depth limits, as

$$I(PDA) = -\frac{1}{\rho_0} \int_{Z_{LOW}}^{Z_{UP}} \sigma'_0 dz \quad (1)$$



150 where $\rho_0 = 1027 \text{ kg/m}^3$ is the reference seawater density, σ'_0 is the anomaly of potential density (the difference between the potential density profile and the climatological profile, computed per depth level), Z_{LOW} and Z_{UP} are respectively the lower and upper boundaries, defined earlier. The I(PDA) has units of meters and can be interpreted as a steric-height anomaly associated with the vertically integrated density anomaly. We note that anticyclones have an isopycnal deformation that carries waters that are lighter than the environment (and the opposite for cyclones), thus the density anomaly computed over geopotential levels is negative, and, by construction, the I(PDA) positive (negative for cyclones). After computing the I(PDA) for each profile, the eddy detection algorithm identifies an anticyclonic profile when $I \geq I_{\text{th,A}}$, and a cyclonic profile when $I \leq I_{\text{th,C}}$, where $I_{\text{th,A}}$ and $I_{\text{th,C}}$ are region-specific thresholds, that we define later. For a given value of the I(PDA) threshold $I_{\text{th,A}}$, we can have the following four cases for an anticyclone (respectively for a cyclone):

1. **Case 1 (c1): good detection.** The profile is inside a TOEddies anticyclone (cyclone) and $I(\text{PDA}) \geq I_{\text{th,A}}$ ($I(\text{PDA}) \leq I_{\text{th,C}}$). In this case the profile is detected as an anticyclone (cyclone) by both TOEddies and IPDA method (Fig. 2c).
2. **Case 2 (c2): missed detection.** The profile is inside a TOEddies anticyclone (cyclone) and $I(\text{PDA}) < I_{\text{th,A}}$ ($I(\text{PDA}) > I_{\text{th,C}}$). In this case the profile, detected as an anticyclone (cyclone) by TOEddies, is not detected by the IPDA method (Fig. 2d).
3. **Case 3 (c3): Argo-only detection.** The profile has an outside TOEddies colocalisation and $I(\text{PDA}) \geq I_{\text{th,A}}$ ($I(\text{PDA}) \leq I_{\text{th,C}}$). In this case the profile, in the environment according to TOEddies, is detected as an anticyclone (cyclone) by the IPDA method (Fig. 2e).
4. **Case 4 (c4): consistent non-detection.** The profile has an outside TOEddies colocalisation and $I(\text{PDA}) < I_{\text{th,A}}$ ($I(\text{PDA}) > I_{\text{th,C}}$). In this case we have an environment profile according to both TOEddies and the IPDA method (Fig. 2f).

The calibration of the algorithm consists in finding the value of the I(PDA) threshold that maximises agreement between TOEddies and IPDA and minimises the inconsistent detections. At the same time, the calibration allows the IPDA to identify additional eddy-associated profiles that are not captured by the surface-based TOEddies colocation, taking into account all the profiles in the selected grid cell. By selecting a range of I(PDA) thresholds, a cost function is defined and computed for every value of the I(PDA) thresholds as:

$$C = \sqrt{\frac{1}{2} \left(1 - \frac{N_G}{N_{G_0}}\right)^2 + \frac{1}{2} \left(1 - \frac{N_A}{N_T}\right)^2} \quad (2)$$

175 where N_G is the number of good detections (c1), N_{G_0} is the number of good detections for the initial threshold $I_{\text{th}} = 0m$ (it corresponds to the number of TOEddies-identified profiles for which I(PDA) is consistent with the polarity assigned by TOEddies), N_A is the number of eddy profiles detected by IPDA method (c1+c3), N_T is the number of eddy profiles detected by TOEddies (c1+c2). We note that the values of N_G and N_A change with the IPDA threshold.

The first term in the cost function, $\frac{1}{2} \left(1 - \frac{N_G}{N_{G_0}}\right)^2$, penalises the loss of good detections as the threshold is increased. It is minimized when the number of good detections approaches its maximum reference value N_{G_0} . The second term, $\frac{1}{2} \left(1 - \frac{N_A}{N_T}\right)^2$,

180



penalizes deviations of the total number of IPDA detections from the number of TOEddies detections. Importantly, this term does not require the two approaches to identify exactly the same profiles. Indeed, if we define N_{Aonly} as the number of Argo-only detections (c3), and N_M as the number of missed detections (c2), and using $N_T = N_M + N_G$ and $N_A = N_G + N_{Aonly}$, the second term of the cost function can be rewritten as $1 - \frac{N_A}{N_T} = \frac{N_M - N_{Aonly}}{N_T}$. Thus, the second term measures the imbalance
185 between missed detections and Argo-only detections. In particular, it is not minimized by imposing $N_{Aonly} = 0$. Instead, it allows the IPDA method to identify additional eddies not detected by TOEddies. This is consistent with the objective of the IPDA method, which is not simply to reproduce the altimetry-based TOEddies detections, but also to identify potentially genuine eddies that are not detected by altimetry.

We look for the value of the I(PDA) threshold that minimises the cost function. We call this value the optimal threshold.
190 Note that every region has its own thresholds, one for the anticyclones ($I_{th,A}$) and one for the cyclones ($I_{th,C}$). In Fig. 2 an example of anticyclonic eddy detection with the IPDA method for a grid cell is shown, with the trend of the cost function and its various components as a function of the I(PDA) threshold in panel (b).

After eddy detection, profiles are further classified as surface- or subsurface-intensified. Because surface density is strongly influenced by atmospheric forcing, only density anomalies below the mixed-layer depth (MLD) are considered. The MLD
195 is computed following Chen et al. (2022), based on the calculation of the first and second derivatives of density profiles, as the level of curvature maximum above the gradient maximum, which meets the 0.03 kg/m^3 density difference threshold with respect to the surface value. For each detected eddy profile, peaks in the density-anomaly profile are identified using a prominence threshold of 0.05 kg/m^3 , with negative and positive extrema for anticyclones and cyclones, respectively. Here, the prominence of an extremum is defined as the difference in density anomaly between the extremum and the lowest contour
200 level reached when moving away from the extremum along the vertical profile. Thus, a peak is detected when it protrudes by at least 0.05 kg/m^3 from the surrounding baseline. This threshold was adopted to exclude weak-amplitude fluctuations, with sensitivity tests showing that the resulting surface- and subsurface-intensified classifications are robust to reasonable variations in this threshold. Among the peaks identified in each profile, the deepest one is selected. Based on the typical vertical density structure of surface and subsurface cyclones and anticyclones (see Fig. 3), the following criterion is used to classify the profile:
205 an eddy profile is classified as subsurface-intensified if the density anomaly changes sign between the depth of the selected peak and the MLD. Otherwise it is classified as surface-intensified.

3 Results

3.1 Frequency maps

We present in Fig. 4a-d the frequency of eddy detections as found from TOEddies compared to the Argo eddy detection method
210 separately for anticyclones and cyclones for the study period. The optimal threshold used is computed for each grid cell for all Argo profiles in the region and shown in Fig. 4 e-f.

We note that the optimal threshold varies considerably across the South Atlantic study area (Fig. 4e-f), spanning from values lower than 0.04 m in the eastern tropical part to values higher than 0.18 m in the Agulhas region for anticyclonic eddy detection.

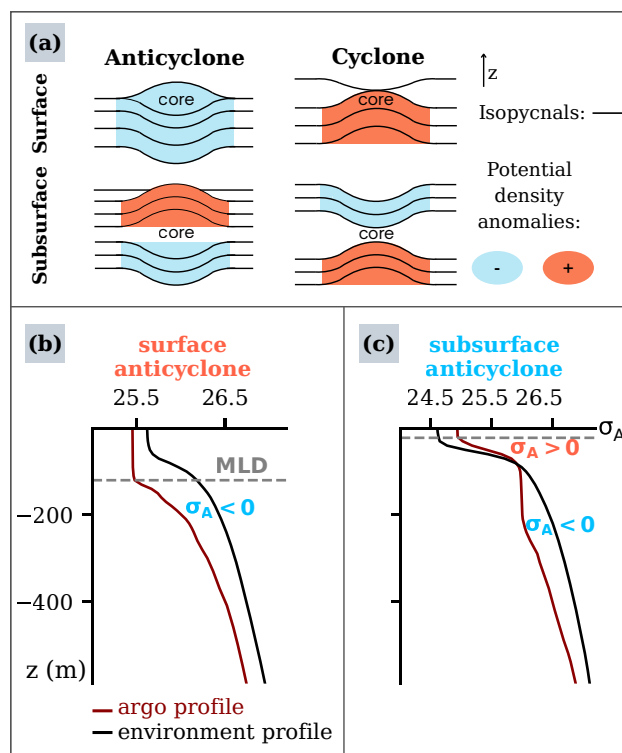


Figure 3. (a) Schematic of isopycnal displacements and potential density anomaly for surface- and subsurface-intensified anticyclonic and cyclonic eddies, modified from Assassi et al. (2016). Example of (b) a surface-, (c) a subsurface-intensified anticyclones.

This spatial variation reflects the diversity of the eddy structure across the South Atlantic. The spatial distribution of the eddy occurrence, as detected by TOEddies and by the Argo method reveals similar patterns (Fig. 4a-d), that underlines the ability of our method to detect eddies. Maximum eddy activity occurring in the Agulhas Region and along primary eddy propagation pathways. We also note a slightly higher percentage of eddy detection by our algorithm in the tropical part, a region where altimetry is known to be less effective. Statistics about the percentage of detected profiles in the South Atlantic are presented in Table 1.

To investigate in more detail the ability of the Argo detection method to identify mesoscale eddies, we show in Fig. 5 the percentage of good detections, Argo-only detections and missed detections (as defined in Sect. 2.4). The percentage of good detections (case 1), computed with respect to the total number of detected profiles (TOEddies + IPDA), is about 35 % for anticyclones and 32 % for cyclones. Spatially, it is not homogeneously distributed (Fig. 5a and b), with higher consistency in regions of maximum eddy activity (we can observe in particular the Agulhas corridor for anticyclones and the Benguela cyclones corridor in Fig. 5a and b respectively), and lower consistency in low latitudes.

When comparing the IPDA method and TOEddies, approximately 29 % of the total number of detected profiles (TOEddies + IPDA) are classified as anticyclonic eddies by TOEddies (within the outer eddy contour) but not identified as eddy profiles

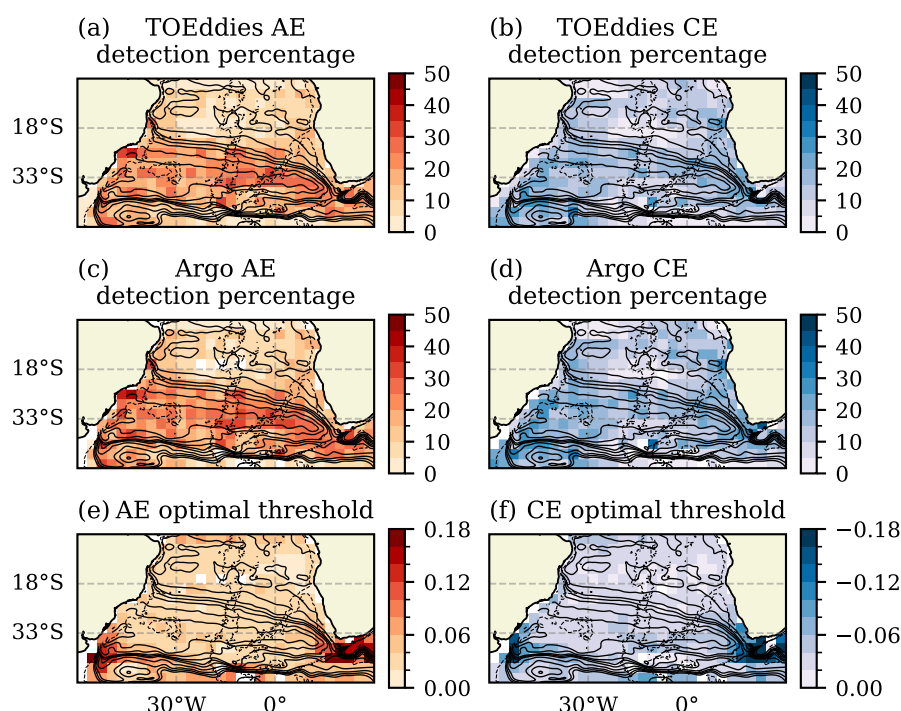


Figure 4. (a) Percentage of occurrence of altimeter-detected anticyclones, (c) percentage of Argo-detected anticyclones, (e) value of the I(PDA) threshold that optimizes the cost function. Panels (b), (d) and (f) represent the same variables for cyclones. The black contours represent the steric height anomaly computed between 1500 and 400 dbar.

Table 1. Percentage of eddies as identified by altimetry and Argo. AE refers to anticyclones, CE to cyclones.

Eddy type	AE (%)	CE (%)	All (%)
Within TOEddies eddy core profiles	9.21	8.24	17.45
Within TOEddies eddy boundary profiles	4.89	4.46	9.35
Within Argo-only identified eddies	8.24	7.97	16.21
Out of eddies	-	-	56.99

by the IPDA method (case 2: missed detections). For cyclonic eddies, the corresponding percentage is 30 %. When considering only profiles located within the eddy core (i.e., inside the maximum velocity contour defined by TOEddies), the percentage of missed detections decreases. The IPDA algorithm fails to identify 19 % of anticyclonic eddy (AE) profiles and 19 % of cyclonic eddy (CE) profiles detected by TOEddies. This suggests the IPDA method agrees better on the strongest part of eddies

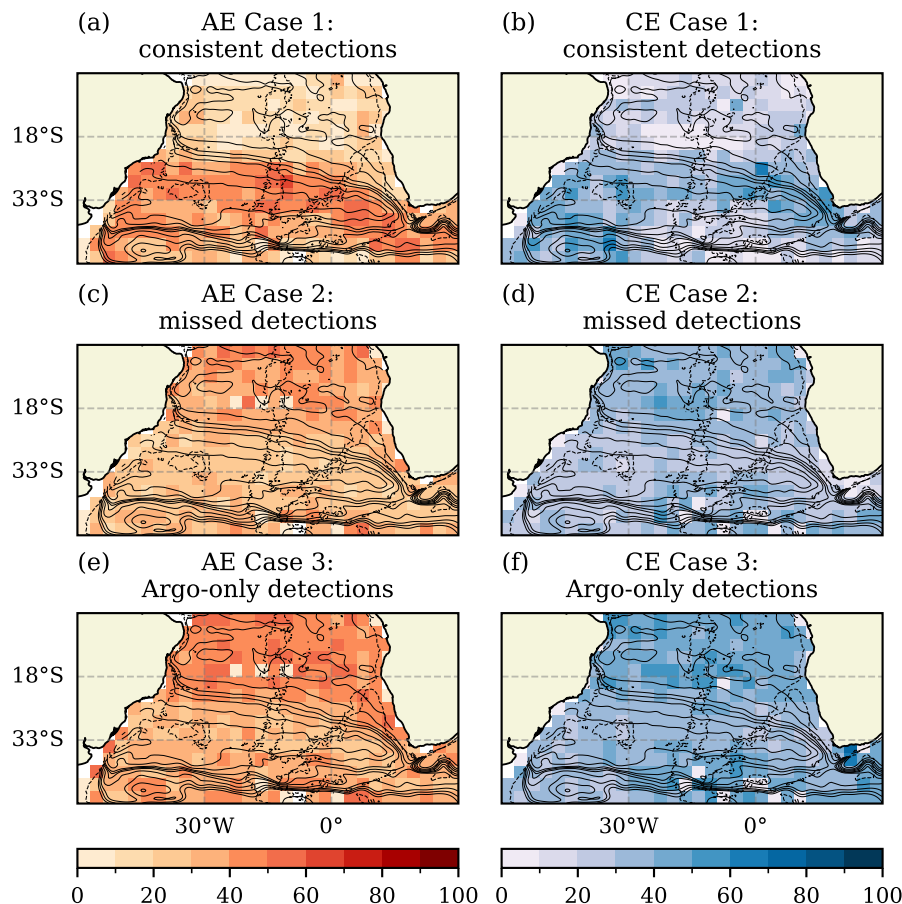


Figure 5. (a) Percentage of good detections, (c) percentage of missed detections, (e) percentage of Argo-only detections for anticyclones. Panels (b), (d) and (e) are the same plots, for cyclones. The percentage is computed with respect to the total number of eddy profiles (IPDA or TOEddies detected) per 3° grid cell.

than on their outer regions. The missed profiles are not uniformly distributed across the study region and most are found in the lower latitudes (Fig. 5c and d).

To assess in more detail the consistency of the missed profiles between the two methods, we perform a delayed colocalisation analysis. For each Argo profile location, we compare it with the TOEddies output 5 days before and 5 days after the observation time. Among the missed anticyclonic detections, 35 % are not located inside the TOEddies outer contour 5 days earlier, and 34 % are not located inside the outer contour 5 days later. The corresponding values for CE profiles are 34 % and 36 %, respectively. These percentages increase when considering profiles located inside TOEddies boundary, suggesting that the main uncertainty of the IPDA detection algorithm concerns profiles located within the outer eddy boundary, rather than within the eddy core.



A small subset of the eddies missed by the IPDA method is found to have the opposite polarity assigned relative to the TOEddies classification. Specifically, about 1.1 % of the profiles identified as anticyclonic eddies (AE) by TOEddies are classified as cyclonic eddies (CE) by the IPDA method, while about 1.2 % of the profiles identified as CE by TOEddies are classified as AE by the IPDA method.

245 Conversely, the IPDA method identifies a substantial number of new eddy detections with respect to TOEddies (case 3). Specifically, 36 % of the total number of detected profiles (TOEddies + IPDA) are detected as anticyclonic eddy (AE) profiles by the IPDA method but not by TOEddies, while the corresponding fraction is 38 % for the cyclonic eddies (CE). Spatially, these Argo-only detections are concentrated in the low latitudes for anticyclones (see Fig. 5e), similarly with what was obtained by Chen et al. (2021), while reproducing better the spatial distribution of eddies in other areas. For cyclones, the spatial
 250 distribution of Argo-only detections is more homogeneous (Fig. 5f). It should be noted that, because the algorithm is calibrated on eddies that are already detectable from altimetry, the fraction of eddies identified by our method without a corresponding altimetric signature should be interpreted as a lower bound on the population of eddies missed by altimetry, rather than as a complete estimate of their occurrence. We note that of the profiles detected as Argo-only anticyclonic detections, 14 % would be in TOEddies anticyclones 5 days before (12 % for CE), and about 13 % would be in TOEddies anticyclones 5 days after (14
 255 % for CE). An example of this detection discrepancy is shown in Fig. 6, where a profile close to 16 °E and 39 °S is detected as an anticyclone by the IPDA method, but falls just outside the outer contour detected by TOEddies (second row in the figure). If we look at the TOEddies detection 5 days before (first row) and 5 days after (third row) the profile was taken, we notice that the anticyclonic eddy has a bigger contour and the position of the Argo float would then fall inside the eddy.

Fig. 7a shows a linear relation for both anticyclones (positive maximum speed) and cyclones (negative maximum speed)
 260 between the maximum velocity as captured by altimetry, and the I(PDA) values. In panel (b), the relationship between the maximum speed and the extremum of the PDA (min(PDA) for anticyclones and max(PDA) for cyclones) seems roughly linear but with greater variation. This indicates that using I(PDA) as a metric to detect eddies instead of PDA extremum is a better choice, since it represents the integrated vertical structure.

It is important to note that the maximum velocity measured by altimetry is only an approximation of the real speed of
 265 the eddy, as, especially for subsurface eddies, the signal on the surface is modified by the surface layers above the eddy. For example, Laxenaire et al. (2019) showed that the surface speed signal computed from altimetry fields of an Agulhas Ring weakened as the eddy propagated, and that this decreasing surface signal was the result of the subduction of the eddy in the ocean interior, and not a dissipation of the eddy.

3.2 Method validation with campaigns dataset

270 To validate our eddy detection algorithm with an independent dataset, we apply it to the two field campaigns described in Sect. 2.3. Crucially, in these campaigns the eddies were located independently from ADCP velocities, that is without using either altimetry or the density signal on which the method relies. This provides a fully independent test, and for eddies with no clear altimetric signature the ADCP is the only independent confirmation that a coherent eddy is present; cases recovered

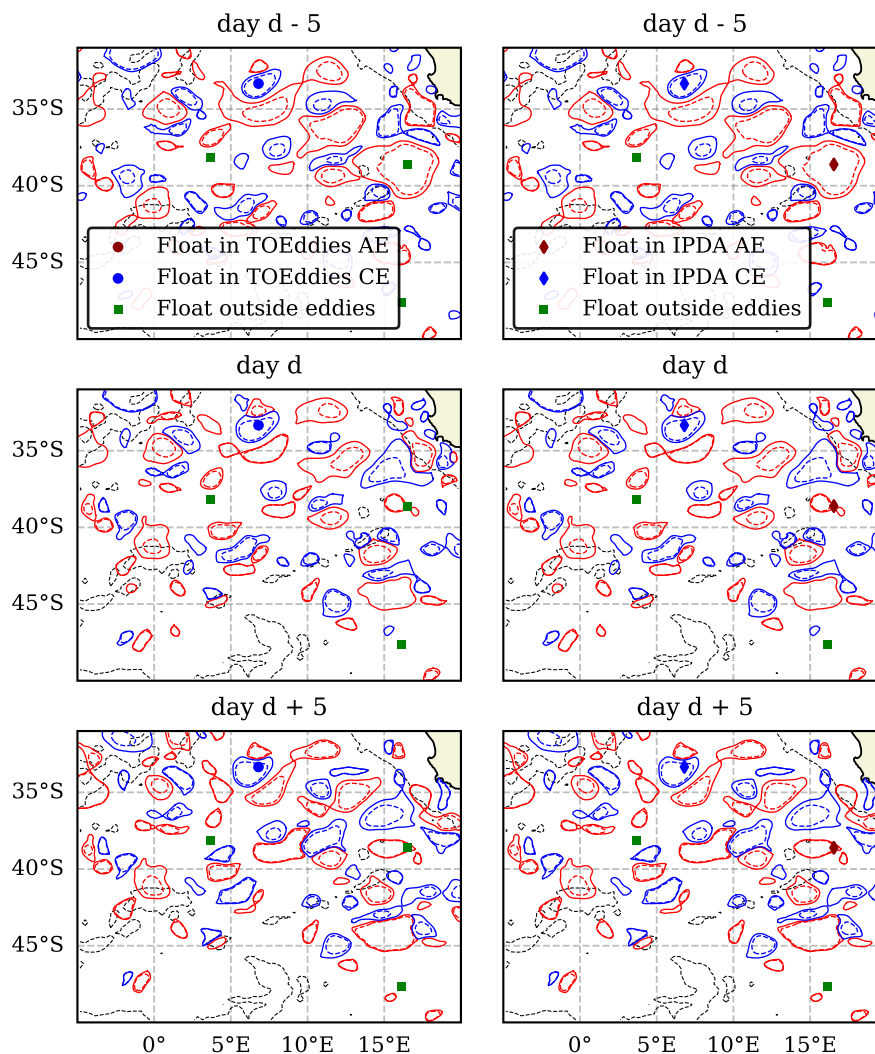


Figure 6. Snapshot of TOEddies-detected eddies on June 19, 2017 (2nd row), with Argo floats on the same day. Snapshot of TOEddies-detected eddies 5 days before (top row) and 5 days after (bottom row), with Argo floats on June 19, 2017.

here by IPDA but absent from TOEddies are therefore direct evidence that the method reaches beyond the altimetry-detectable
 275 population.

Given that uCTD profiles of campaign M124 sample down to 400 m and that our eddy detection algorithm was calibrated taking 1000 m as a reference depth for I(PDA) calculation, we recalibrate the algorithm taking a reference depth of 400 m, in order to obtain new thresholds that we can apply to uCTD data. The results are presented in Table 2. Given the relatively small sample size, the percentages should be interpreted with some caution. Moreover, given the large vertical extent of the eddies in

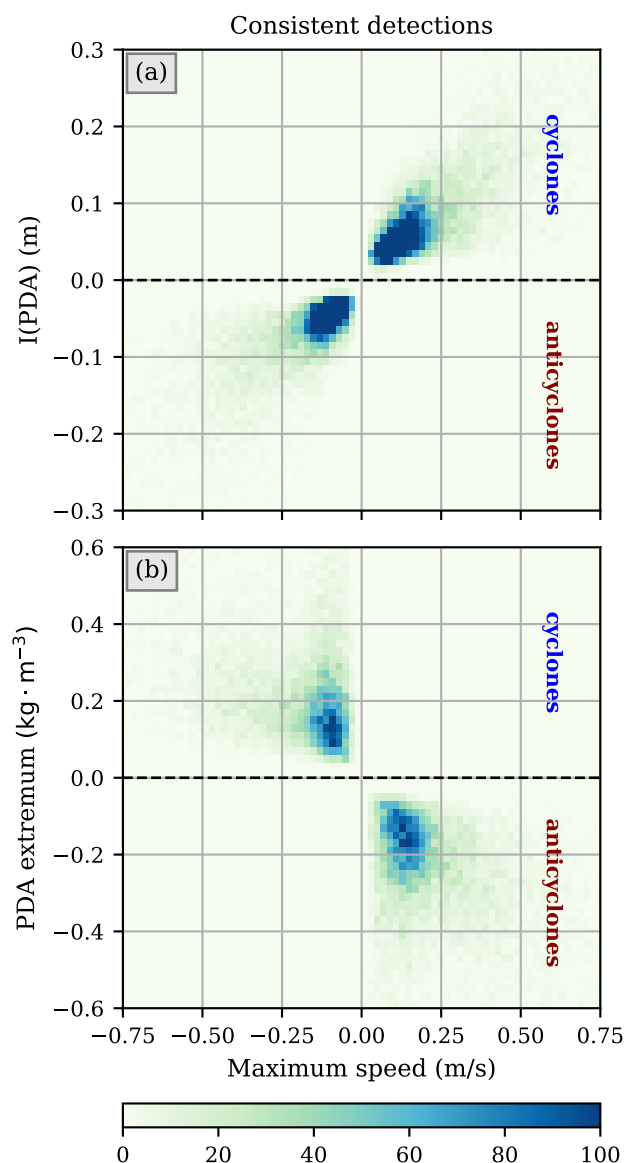


Figure 7. 2D histogram showing (a) the relation between the maximum velocity as measured by altimetry, and the value of I(PDA) and (b) the relation between the maximum velocity and the extremum of the PDA profile.

280 this region, the 400 m reference depth may not capture their full vertical structure, and results based on this threshold should therefore be interpreted with care.

Taking into account the new thresholds with 400 m as reference depth, for the campaign M124, of the total 91 anticyclonic profiles detected by TOEddies as being inside the outermost closed contour, 68 are also detected by the IPDA method, giving about 75 % of consistent detections. When restricting to the profiles in the eddy core (detected inside the maximum velocity



Table 2. Percentages of good, missed and Argo-only detections for the two campaigns.

campaign	M124	M124	MSM60	M124	M124	MSM60
ref depth (m)	400 m	1000 m	1000 m	400 m	1000 m	1000 m
eddy type	AE	AE	AE	CE	CE	CE
consistent detections	68 (70 %)	4	17 (53 %)	20 (44 %)	2	15 (46 %)
missed detections	23 (24 %)	1	6 (19 %)	17 (38 %)	1	9 (27 %)
Argo-only detections	6 (6 %)	0	9 (28 %)	8 (18 %)	2	9 (27 %)
total number of detections	97	5	32	45	5	33

contour by TOEddies), the percentage increases to about 84 %. Our IPDA method is thus better at detecting profiles inside the maximum velocity contour. When considering the total number of detected eddies (TOEddies + IPDA), we have about 70 % of good detections, 24 % of missed detections and 6 % of Argo-only detections (Table 2). We note that most of the missed detections come from an anticyclone with small vertical extent (upper 100 meters) and low velocities (less than 10 cm/s).

If we restrict to CTD profiles, which measure down to more than 1000 m deep, we can use the eddy detection threshold computed using a reference depth of 1000 m. For these profiles, we notice that the agreement between TOEddies and our IPDA method increases (Table 2).

For cyclones, using the 400 m reference depth, 20 out of the 37 profiles colocated with TOEddies and 14 out of the 26 inside the maximum velocity contour are consistent with our IPDA method, giving about 54 % of consistent detections in both cases. When considering the total number of detected eddies (TOEddies + IPDA), we have about 44 % of good detections, 38 % of missed detections and 18 % of Argo-only detections (Table 2). We note that most of the missed cyclonic profiles are from a cyclone located near (4 °E, 32 °S), shown in Fig. 8. When looking at the vertical structure, we note weak density anomalies and isopycnal displacement, together with weak perpendicular velocities as measured by the ADCP (less than 10 cm/s).

For the campaign MSM60, we disposed of CTD casts measuring down to more than 1000 m, so the initial thresholds computed with 1000 m reference depth could be used. 17 out of the 23 profiles colocated with TOEddies and 10 out of the 11 inside the maximum velocity contour are consistent with our IPDA method, giving respectively 74 % and 91 % consistent detections. For the cyclones we have about 63 % and 73 % of consistent detections. The percentages of good, missed and Argo-only detections are shown in Table 2.

We can state the effectiveness of our method at detecting strong eddies, with a general better agreement between our method and TOEddies when considering anticyclones.

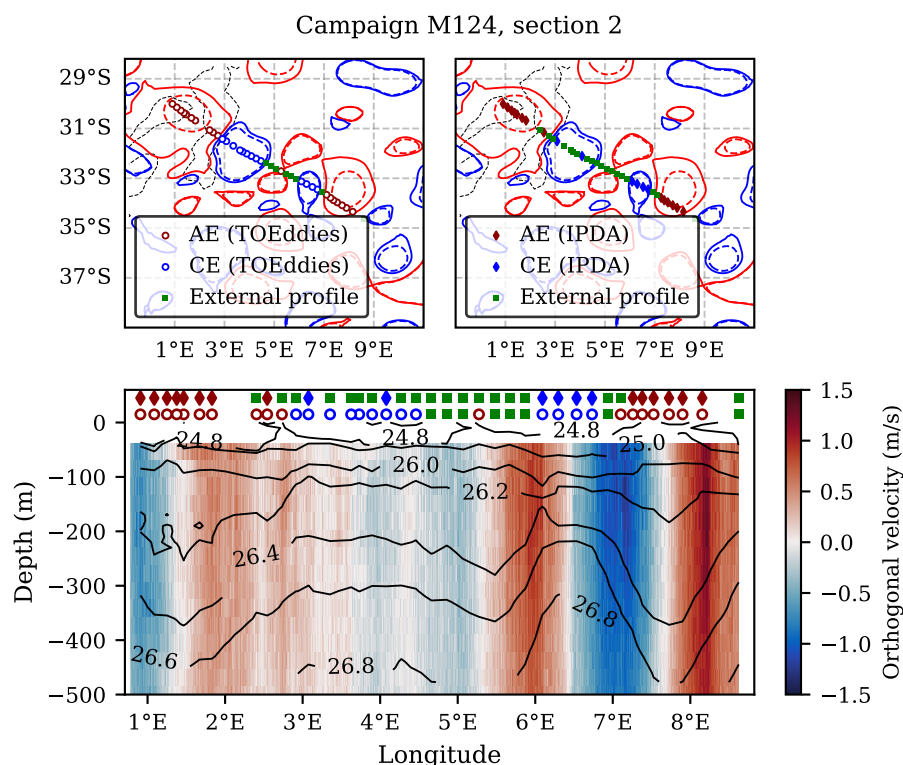


Figure 8. Section 2 of the M124 campaign, with TOEddies plot and positions of the CTD/uCTD profiles (first row), and section of orthogonal velocity measured by the ADCP (color shading), and potential density (black contours). The detection from TOEddies and IPDA method are illustrated with different markers for every sampled vertical profile along the section.

305 3.3 Surface vs subsurface distribution

To assess the robustness of the surface–subsurface classification, we focus first on consistent detections, defined as profiles identified as eddies both by TOEddies and by the IPDA method. Within this subset, we further restrict the analysis to profiles exhibiting the strongest density anomalies, ensuring that only well-defined eddy signatures are considered. Fig. 9 shows the distribution of surface and subsurface detection for Anticyclones and Cyclones in the South Atlantic. About 63 % of the anticyclonic profiles (7631 of the total 12,098 consistent detections) are surface intensified, and 37 % (4467 profiles) subsurface intensified. Spatially, surface eddies predominate in the Cape Basin year-round, while subsurface eddies are more common along the propagation pathways of Agulhas Rings. For cyclones, when considering consistent detections, the percentages are inverted, with about 36 % (3687 of the total 10,260 consistent detections) of the profiles that are surface intensified, and about 64 % (6573 profiles) are subsurface intensified.

315 For cyclones, using the IPDA method we find about 40 % of surface profiles (9069 of the total 22,398 cyclonic profiles) and 60 % subsurface profiles (13,329 profiles). Of the surface detections, about 41 % are consistent with TOEddies, and 59 %

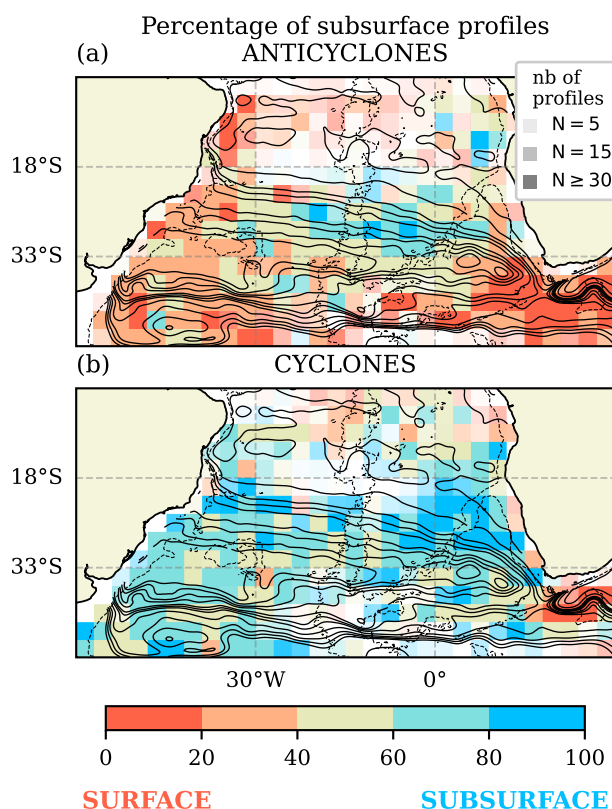


Figure 9. Percentage of subsurface profiles per 3° grid cell, considering consistent detections (TOEddies and IPDA method), for (a) anticyclones; (b) cyclones. Full red grid cells means that all profiles are surface-intensified, full blue means all profiles are subsurface-intensified, and the shades are for intermediate cases. Transparency indicates the number of profiles per grid cell, with opacity increasing linearly with N up to $N = 30$; cells containing 30 or more profiles are shown at full opacity.

are Argo-only detected cyclones. Of the subsurface detections, 49 % are consistent with TOEddies, and 51 % are Argo-only detections. Interestingly, the IPDA method provides more new surface detections than subsurface detections, although they are comparable. This is at least partly expected, since the IPDA detection thresholds are calibrated on altimetry-detected eddies.

320 3.4 Vertical structure of eddies

We now look at the vertical structure of the detected cyclones and anticyclones, in terms of eddy depth, thickness and intensity.

With reference to the schematics of the isopycnal structure of eddies presented in Fig. 3, the depth of the eddy core is defined as the depth where the profile changes sign (if there's a change of sign in the profile), or the minimum depth. The spatial distribution of the depth of the core (Fig. 10a and b) reflects the subsurface distribution shown in Fig. 9, with the core of the eddies being on average deeper in the grid cells with more subsurface eddies, and more shallow in the cells having more surface eddies. In particular, we can observe the signal of the subduction of the core of Agulhas Rings by noticing that the eddy

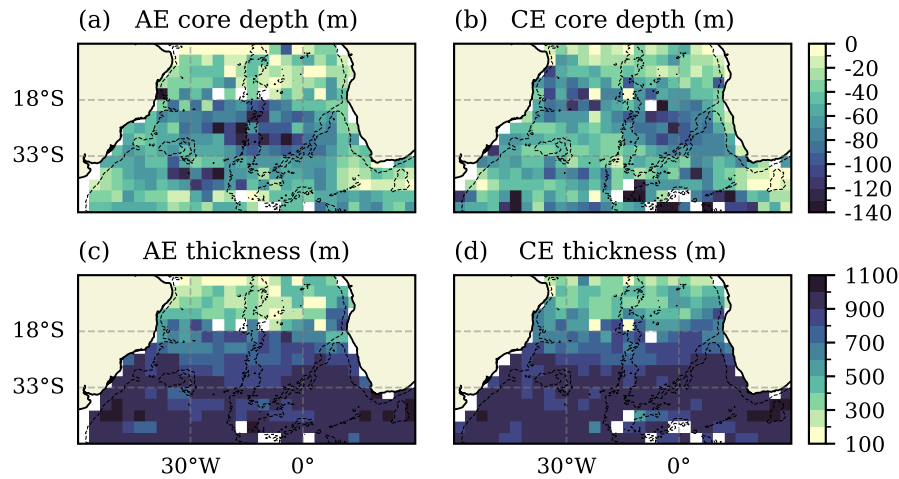


Figure 10. (a) Mean depth of the eddy core; (c) mean eddy thickness for anticyclones, per 3 ° grid cell. Panels (b) and (d) are the same for cyclones.

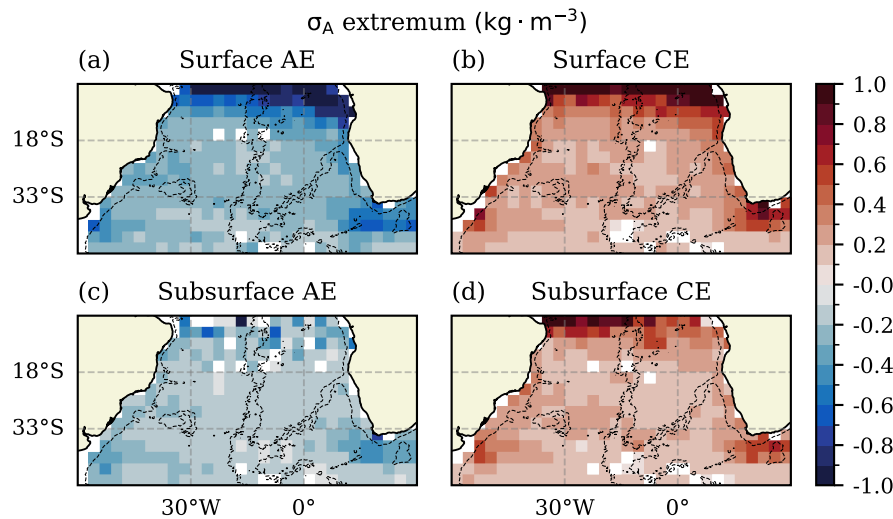


Figure 11. Mean density anomaly extremum per 3 ° grid cell for anticyclones (left plot) and cyclones (right plot). Panels a-b are for surface profiles, panels c-d for subsurface profiles.

core is in the first 20 to 30 meters in the Cape Basin, to down to more than 100 m depth of the eddy core in the propagation pathway after crossing the Walvis Ridge (Fig. 10a).

We define the eddy thickness as the depth range around the peak (maximum for cyclones and minimum for anticyclones) where the eddy profile has the same sign. We observe in Fig. 10c and d latitudinal differences in the eddy thickness, with thinner

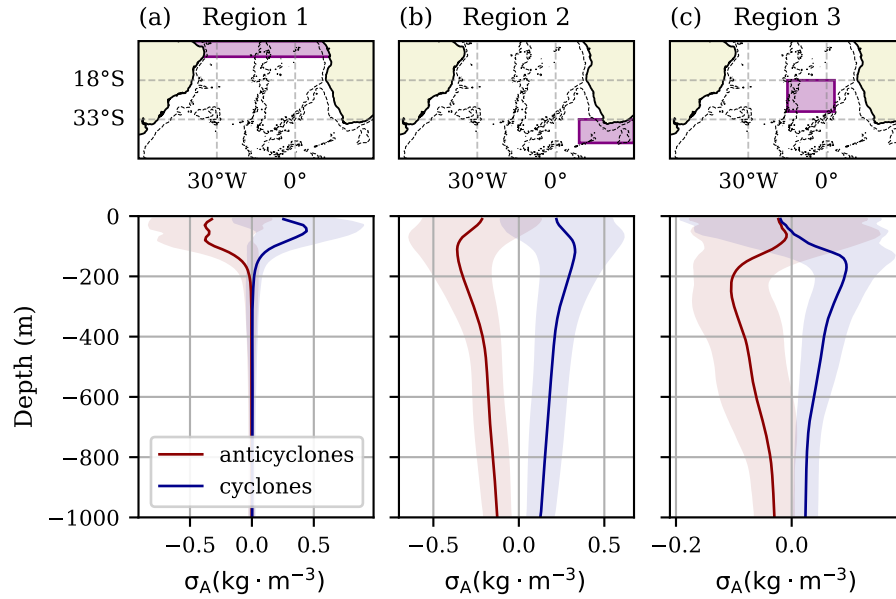


Figure 12. Mean eddy profiles in three areas: (a) tropical band, (b) Agulhas Current, (c) Agulhas Rings pathway.

eddies in the tropical part of the domain (typical eddy thickness of about 100 to 200 m, and thicker eddies in the subtropical part, with eddies more than 1000 m thick. The pattern is spatially similar for anticyclones and cyclones.

We show in Fig. 11 the spatial distribution of the potential density anomaly extremum (minimum for anticyclones and maximum for cyclones). Two features emerge: the presence of high values of potential density anomaly in the tropical latitudes for both polarities (more than 1 kg/m^3 on average), and in the Agulhas Region (around 0.5 kg/m^3 on average). We notice stronger anomalies for the surface eddies (Fig. 11a and b) compared to subsurface eddies (Fig. 11c and d). We can observe the signal of subducting Agulhas Rings in the subsurface plot.

To sum up the analysis of the vertical structure of eddies, we can divide the South Atlantic eddies into three categories: the tropical eddies, with thin (about 100 m thickness) eddies and strong density anomalies; intense and very thick (more than 1000 m) eddies present in the Agulhas Region and in the Brazil-Malvinas confluence region; and eddies with less strong anomalies but thick and deeper located between the Walvis Ridge and the Mid-Atlantic Ridge. The mean profiles of these regions are shown in Fig. 12.

4 Discussion

In this section, we focus on cyclonic and anticyclonic trajectories in the Cape Basin.

As pointed out in Sect. 9, anticyclones tend to be more surface-intensified in the Cape Basin and subsurface-intensified as they propagate and enter the subtropical gyre. An analogous pattern is also observed for cyclones in the Cape Basin. This

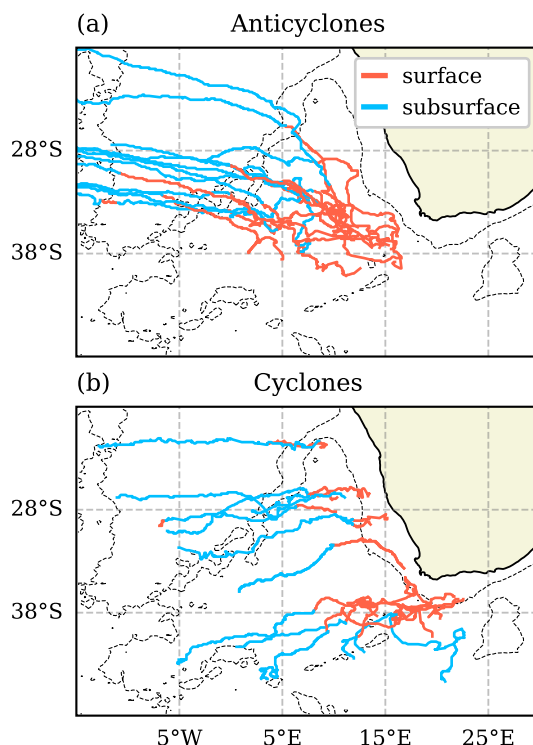


Figure 13. Trajectories subducting in the Cape Basin: (a) anticyclones; (b) cyclones.

suggests a transition from surface profiles at the beginning of the eddy trajectories, to subsurface profiles for both anticyclonic and cyclonic eddies in this region.

When selecting with TOEddies long trajectories being sampled by many Argo floats and that are consistent detections, we can observe this transition for both polarities (Fig. 13). These eddies form as surface structure in the Cape Basin and progressively subduct into the ocean interior as they propagate northeastward (anticyclones) or southeastward (cyclones), with cyclones subducting more quickly (Ioannou et al., 2022; Baudena et al., 2025). This Lagrangian view of surface-to-subsurface subduction, followed along individual eddy trajectories sampled by successive Argo floats, is one of the central results of this study: it shows that an eddy detected as surface-intensified early in its life can evolve into a subsurface-intensified structure, a transition that surface altimetry alone cannot capture. This highlights the potential of combining satellite altimetry with Argo observations and demonstrated the importance of accounting for the full vertical structure of the ocean, rather than relying solely on surface fields.

The existence of subsurface Agulhas Rings has been known for a long time (e.g. the observation of subsurface eddies by Arhan et al. (1999) and Garzoli et al. (1999)). The subduction of these eddies in the ocean interior was observed following the trajectory of an Agulhas Ring (Laxenaire et al., 2019). Laxenaire et al. (2020) suggested that most Agulhas Rings subside at some point, especially those taking the Northern Route, while crossing the Walvis Ridge and entering the South Atlantic.

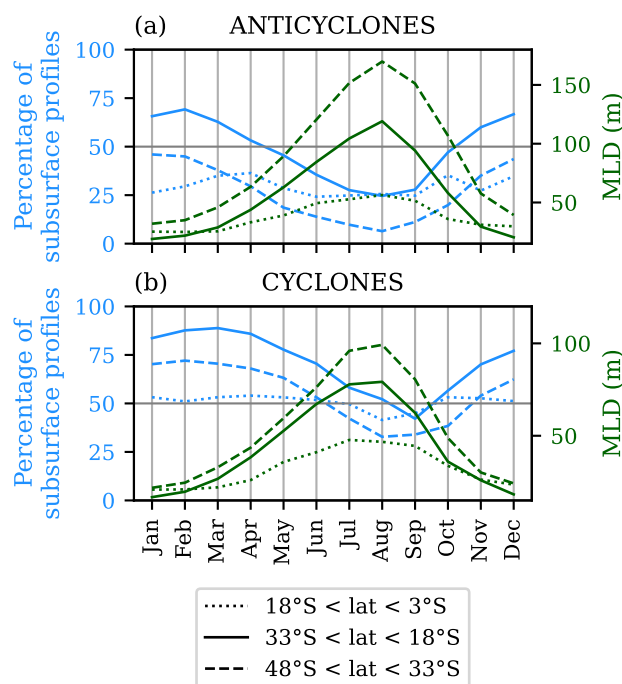


Figure 14. Percentage of subsurface eddies per month (blue curves) and mean mixed layer depth (green curves), for anticyclones (panel a) and for cyclones (panel b) detected with IPDA method, for different latitude ranges.

Numerically, Herbette et al. (2004) showed that this transition from surface to subsurface could happen via lateral advection subducting below lighter waters.

For anticyclones, subduction occurs either within the Cape Basin or near the crossing of the Walvis Ridge (Fig. 13). The transition to a subsurface-intensified state occurs in late spring or early summer for most trajectories for both cyclones and anticyclones, suggesting a possible link with the seasonal cycle of air–sea fluxes, particularly the enhanced wintertime surface buoyancy loss that may precondition the upper ocean for subduction. Seasonal variability (Fig. 14) indicates that for both polarities surface eddies are more frequent during austral winter, whereas subsurface eddies are more frequent in austral summer. For each eddy polarity considered separately, the analysis is based on approximately 700 Argo profiles per month, ranging for about 300 eddy profiles per month in the low-latitude band, to about 1000 eddy profiles per month in the high-latitude band.

In winter, enhanced mixing and interaction with the atmosphere deepens the mixed layer, allowing a larger number of eddies to interact with the atmosphere. This explains the higher occurrence of surface eddies (whose cores lie in the mixed layer and thus interact with the atmosphere). In summer, heating and restratification lead to a thinner mixed layer, limiting the interaction of eddies with deeper cores with the atmosphere. As a result, subsurface eddies become more prevalent during summer.

We note that this seasonality of subsurface eddies is reminiscent of the seasonality of so-called “anomalous eddies”. These are cold-core anticyclones and warm-core cyclones, characterized by sea surface temperature (SST) signatures opposite to conventional eddies, which traditionally associate anticyclones with warm cores and cyclones with cold cores. Their prevalence

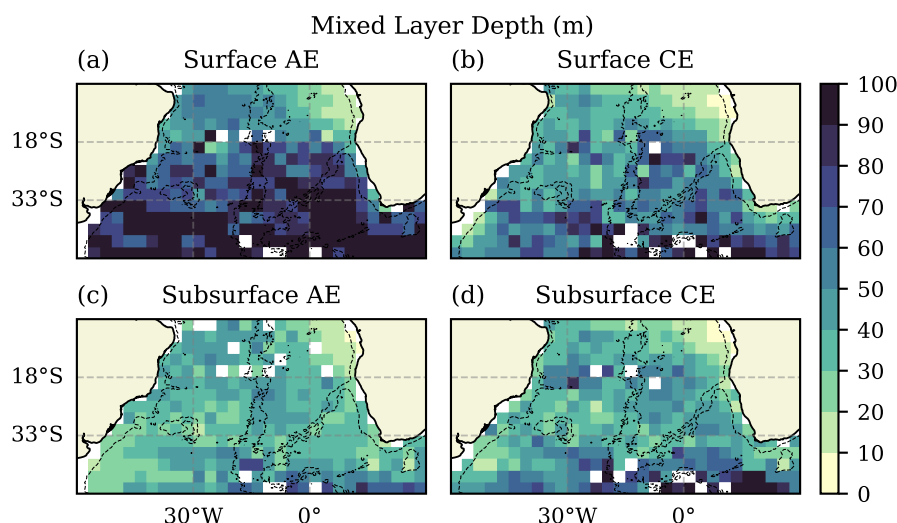


Figure 15. Mean Mixed Layer Depth per 3° grid cell, for anticyclones (left column) and cyclones (right columns). Panels (a)-(b) are for surface profiles, panels (c)-(d) for subsurface profiles.

is strongly linked to seasonality, with more anomalous eddies during summer (Moschos, E. et al., 2022; Sun et al., 2019). This seasonal dependence is also largely explained by the evolution of surface mixed layer depth. These anomalous eddies and subsurface eddies can indeed be linked, with the isopycnal shape of subsurface eddies (see Fig. 3) in most cases associated with negative temperature anomalies for anticyclones and positive for cyclones. In Fig. 14, we can also note that the percentage of subsurface profiles varies differently with latitude, with generally more surface eddies and low seasonal variability in tropical latitudes, along with low MLD variability, and more subsurface profiles and higher MLD and subsurface profiles seasonal variability for mid latitudes.

Indeed, the presence of surface or subsurface eddies is intimately related to the mixed layer depth. When taking into account surface eddy profiles, we note a deeper ML for anticyclones (Fig. 15a) with respect to cyclones (Fig. 15b), with a latitudinal gradient (deeper ML at high latitudes and shallower ML at low latitudes). It is typical of surface anticyclones to deepen the isopycnals (and so also the ML). On the other hand, cyclones have the tendency of bringing upward deeper isopycnals, having as an effect a shallower ML. As for subsurface eddies (Fig. 15c and d), they have a shallow ML, and they don't show the same latitudinal and longitudinal gradients in the ML as surface eddies.

In Fig. 16, looking at the spatial distribution for summer (panels a-b) and winter (panels c-d), surface anticyclones are present in the Cape Basin in both seasons, with a broader extent during winter. Subsurface eddies are more prominent in summer. Even during winter, a subsurface eddy signal appears in the Agulhas Corridor, likely representing subducted Agulhas Rings.

To investigate the mean vertical structure of eddies subducting in the Cape Basin, we selected the Argo profiles that were colocated inside the maximum velocity contour of the eddies in the trajectories shown in Fig. 13 and that were also detected as eddies by our IPDA method (consistent detections). Fig. 17 shows the mean vertical profiles of potential density of surface and

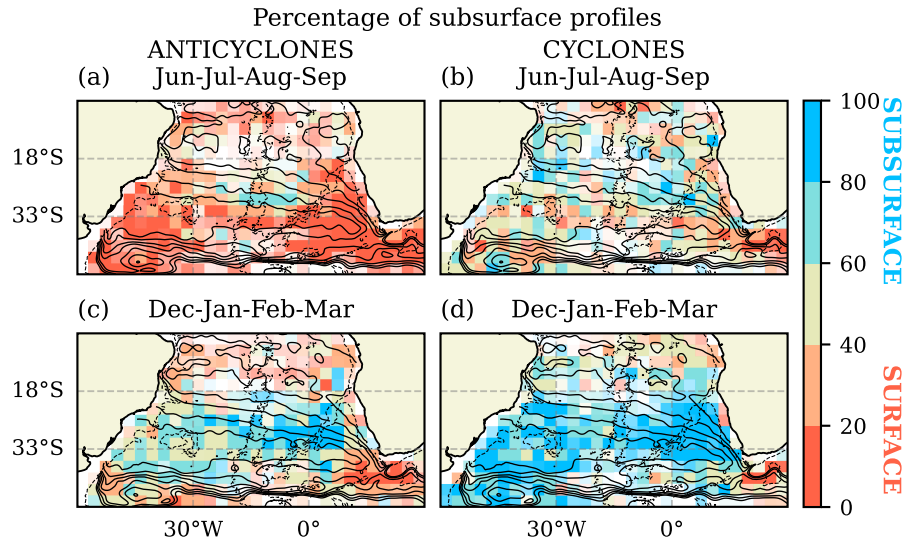


Figure 16. Percentage of subsurface eddies per 3° grid cell, for anticyclones (left column) and cyclones (right column). Panels (a)-(b) are for winter months and panels (c)-(d) for summer months. Transparency indicates the number of profiles per grid cell, with opacity increasing linearly with N up to $N = 30$; cells containing 30 or more profiles are shown at full opacity, as in Fig. 9.

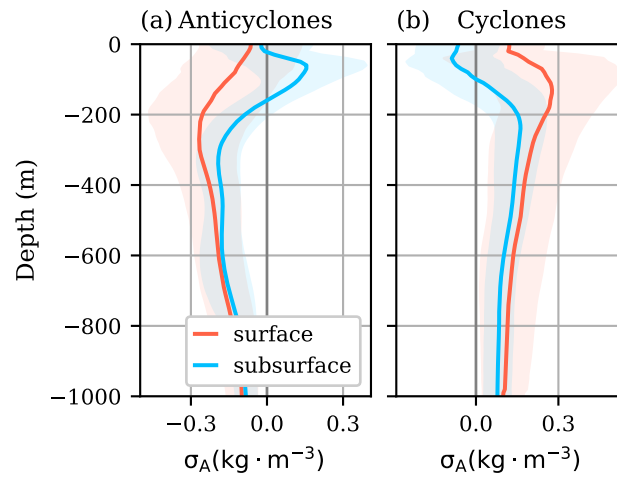


Figure 17. Mean profile of surface and subsurface anticyclones (panel a) and cyclones (panel b). The profiles used to compute the mean are those colocated with the trajectories that subduct in the Cape Basin (Fig. 13). The shaded area represents mean $\pm$ standard deviation.

subsurface AEs and CE of the trajectories subducting in the Cape Basin. On average, AEs present larger density anomalies, especially for subsurface profiles. The mean subsurface cyclone profile appears to have weaker density anomalies at depth than the surface one. This is less evident for anticyclones. The spread of the distribution of surface profiles (shaded pink area in Fig. 17) is higher than for subsurface profiles. We also note, in the mean subsurface anticyclonic profile, two small peaks in the



negative part of the profile. This could be linked to the presence of two superposed cores in the profiles of some trajectories. Indeed, Agulhas Rings having two cores have been observed on multiple occasions (an anticyclone sampled by Argo floats by Laxenaire et al. (2019), eddies sampled during cruises include the ones in Guerra et al. (2018), McCartney and Woodgate-Jones (1991), Garzoli et al. (1999) and Casanova-Masjoan et al. (2017)) and they are thought to be the result of the merging of other anticyclones with cores at different depths.

Despite these insights, some limitations should be considered when interpreting the results. The analysis of subducting trajectories was restricted to consistent detections, i.e. eddies for which an altimetric signature was also available. Moreover, because the current methodology identifies individual eddy occurrences rather than tracking continuous trajectories, it limits our ability to investigate the temporal evolution and persistence of these features and, consequently, to fully characterize their potential contribution to subduction processes. Further analysis of air-sea fluxes and their temporal evolution relative to the eddy trajectories would be needed to better constrain the physical mechanisms driving the subduction process. In addition, the calibration of the detection thresholds is based on eddies that can be detected by altimetry, potentially limiting their applicability to subsurface-intensified eddies that lack a surface signature. Moreover, the sparse and uneven spatial and temporal sampling of Argo profiles limits the representativeness of the observed eddy population and the comparison with altimetry.

5 Conclusions

In this paper we have developed a method that detects mesoscale eddies directly from Argo vertical profiles of potential density anomaly. By collocating every available in situ Argo profile with the eddies identified from the TOEddies altimetry atlas, we calibrated region-dependent detection thresholds using data from 2000 to 2025; in this framework altimetry is used to locate eddies and to set the thresholds, while the detection itself operates on the in situ density anomalies. This extends two-dimensional altimetric eddy identification into the vertical dimension, allowing the subsurface structure of eddies to be systematically characterised from in situ observations.

To assess the robustness of the algorithm, we applied it to an independent dataset from two field campaigns that sampled 12 anticyclones and 14 cyclones in the South Atlantic, with the eddies located independently from ADCP velocities. The validation indicates that the method is more effective for anticyclones than for cyclones. This contrast is at least partly expected: cyclones in our sample tend to be more subsurface-intensified and to have weaker near-surface density signatures, and because the thresholds are calibrated on altimetry-detectable eddies the method is inherently less sensitive to such weaker or subsurface-dominated signals. Accordingly, the fraction of eddies detected without a surface altimetric signature should be read as a lower bound on the population missed by altimetry rather than a complete estimate.

Using the resulting eddy profiles, we classified eddies according to whether their signatures were surface- or subsurface-intensified. Our results suggest a different spatial pattern of surface and subsurface eddies for anticyclones and cyclones, with cyclones tending to be more subsurface intensified. A similar feature is the presence of more surface eddies in the tropical region and in the Cape Basin. For both cyclones and anticyclones, a pattern of subduction of eddies in the Cape Basin was



observed, with a transition from surface to subsurface that was suggested by the spatial distribution of subsurface eddies and was confirmed when looking at individual trajectories sufficiently sampled by Argo floats.

435 The vertical distribution of eddy signatures was also found to be related to the seasonal evolution of the mixed layer. Winter was associated with a larger proportion of surface-intensified eddies and deeper mixed layers, whereas summer was characterized by a greater occurrence of subsurface-intensified eddies and shallower mixed layers. These results suggest that the seasonal modulation of mixed-layer depth may influence the vertical expression and detectability of mesoscale eddies, and potentially contribute to the transition between surface- and subsurface-intensified structures.

440 Overall, this study demonstrates the potential of combining satellite altimetry with Argo observations to investigate the three-dimensional structure of mesoscale eddies over large spatial and temporal scales. The approach complements conventional surface-based eddy detection and offers new opportunities to investigate the evolution, subduction, and subsurface persistence of eddies. Its main limitations are the sparse and uneven Argo sampling, which conditions the comparison with altimetry, and the calibration of thresholds on altimetry-detectable eddies; targeted in situ sampling of subsurface-intensified eddies, such as
445 those collected during the campaigns considered here, is therefore the most direct way to further constrain the population that altimetry does not capture. The increasing availability of such observations, included from dedicated campaigns and sustained observing programs, provides growing opportunities to improve their characterisation.

Crucially, the ability of the method to recover eddies once their surface altimetric signature has faded shows that these features have not dissipated but persist and continue to propagate at depth, carrying their trapped water masses and thermohaline
450 properties far from their region of formation. Detecting this post-subduction phase, which surface altimetry misses, is a necessary step toward quantifying the contribution of mesoscale eddies to the subsurface transport of heat, salt and biogeochemical tracers across the South Atlantic.

Data availability. Hydrographic and velocity measurements from the M124 cruise (Karstensen et al., 2016) aboard the RV Meteor are available on PANGAEA: <https://doi.org/10.1594/PANGAEA.902947> (Wöfl and Schade, 2019), <https://doi.org/10.1594/PANGAEA.863015>
455 (Karstensen and Krahmann, 2016) <https://doi.org/10.1594/PANGAEA.869740> (Karstensen and Wöfl, 2016).

Hydrographic and velocity measurements from the MSM60 cruise (Karstensen et al., 2019) aboard the RV Maria S. Merian are available on PANGAEA: <https://doi.org/10.1594/PANGAEA.915898> (Karstensen, 2020), <https://doi.org/10.1594/PANGAEA.915906> (Karstensen et al., 2020).

The Argo float data (Argo, 2026) are available from the Coriolis Global Data Assembly Centre (GDAC): <https://doi.org/10.17882/42182>.
460 The global $1/8^\circ$ TOeddies atlas can be accessed at https://thredds-su.ipsl.fr/thredds/catalog/ipsl_thredds/guez/Atlas_Toeddies_v2/catalog.html.

Author contributions. BA, SS and AI contributed to the conceptualization of the study. BA performed the data analysis and conceived the original draft. Additions and revisions have been made by BA, SS and AI.



Competing interests. The contact author has declared that none of the authors has any competing interests.

465 *Acknowledgements.* This work was supported by the European Union's Horizon Europe ERC Synergy Grant program under grant agreement No. 101118693 (WHIRLS), the TOEddies and BIOSWOT CapeCauldron CNES-TOSCA research grants. We also acknowledge the mesoscale calculation server SPIRIT (<https://mesocentre.ipsl.fr/>) dedicated to Institut Pierre Simon Laplace modeling effort for technical and computational support.



References

- 470 Argo: Argo float data and metadata from Global Data Assembly Centre (Argo GDAC), <https://doi.org/10.17882/42182>, 2026.
- Arhan, M., Mercier, H., and Lutjeharms, J. R. E.: The disparate evolution of three Agulhas rings in the South Atlantic Ocean, *Journal of Geophysical Research: Oceans*, 104, 20 987–21 005, <https://doi.org/10.1029/1998JC900047>, 1999.
- Assassi, C., Morel, Y., Vandermeirsch, F., Chaigneau, A., Pegliasco, C., Morrow, R., Colas, F., Fleury, S., Carton, X., Klein, P., and Cambra, R.: An Index to Distinguish Surface- and Subsurface-Intensified Vortices from Surface Observations, *Journal of Physical Oceanography*, 46, 2529–2552, <https://doi.org/10.1175/JPO-D-15-0122.1>, 2016.
- 475 Bashmachnikov, I. and Carton, X.: Surface signature of Mediterranean water eddies in the Northeastern Atlantic: effect of the upper ocean stratification, *Ocean Science*, 8, 931–943, <https://doi.org/10.5194/os-8-931-2012>, 2012.
- Baudena, A., Laxenaire, R., Catalano, C., Ioannou, A., Leymarie, E., Picheral, M., Poteau, A., Speich, S., Stemmann, L., and Kiko, R.: A Lagrangian perspective reveals the carbon and oxygen budget of an oceanic eddy, *Communications Earth & Environment*, 6, 318, <https://doi.org/10.1038/s43247-025-02262-9>, 2025.
- 480 Bryden, H. L. and Brady, E. C.: Eddy momentum and heat fluxes and their effects on the circulation of the equatorial Pacific Ocean, *Journal of Marine Research*, 47, 55–79, <https://doi.org/10.1357/002224089785076389>, 1989.
- Casanova-Masjoan, M., Pelegrí, J. L., Sangrà, P., Martínez, A., Grisolia-Santos, D., Pérez-Hernández, M. D., and Hernández-Guerra, A.: Characteristics and evolution of an Agulhas ring, *Journal of Geophysical Research: Oceans*, 122, 7049–7065, <https://doi.org/10.1002/2017JC012969>, 2017.
- 485 Chaigneau, A., Le Texier, M., Eldin, G., Grados, C., and Pizarro, O.: Vertical structure of mesoscale eddies in the eastern South Pacific Ocean: A composite analysis from altimetry and Argo profiling floats, *Journal of Geophysical Research: Oceans*, 116, 2011JC007 134, <https://doi.org/10.1029/2011JC007134>, 2011.
- Chelton, D. B., Schlax, M. G., Samelson, R. M., and De Szoek, R. A.: Global observations of large oceanic eddies, *Geophysical Research Letters*, 34, 2007GL030 812, <https://doi.org/10.1029/2007GL030812>, 2007.
- 490 Chelton, D. B., Schlax, M. G., and Samelson, R. M.: Global observations of nonlinear mesoscale eddies, *Progress in Oceanography*, 91, 167–216, <https://doi.org/10.1016/j.pocean.2011.01.002>, 2011.
- Chen, G., Chen, X., and Huang, B.: Independent Eddy Identification With Profiling Argo as Calibrated by Altimetry, *Journal of Geophysical Research: Oceans*, 126, e2020JC016 729, <https://doi.org/10.1029/2020JC016729>, 2021.
- 495 Chen, Y. and Yu, L.: Signature of Mesoscale Eddies on Air-Sea Heat Fluxes in the North Indian Ocean, *Journal of Geophysical Research: Oceans*, 129, e2023JC019 878, <https://doi.org/10.1029/2023JC019878>, 2024.
- Chen, Y., Speich, S., and Laxenaire, R.: Formation and Transport of the South Atlantic Subtropical Mode Water in Eddy-Permitting Observations, *Journal of Geophysical Research: Oceans*, 127, e2021JC017 767, <https://doi.org/10.1029/2021JC017767>, 2022.
- Cornec, M., Laxenaire, R., Speich, S., and Claustre, H.: Impact of Mesoscale Eddies on Deep Chlorophyll Maxima, *Geophysical Research Letters*, 48, e2021GL093 470, <https://doi.org/10.1029/2021GL093470>, 2021.
- 500 Cui, W., Wang, W., Zhang, J., and Yang, J.: Multicore structures and the splitting and merging of eddies in global oceans from satellite altimeter data, *Ocean Science*, 15, 413–430, <https://doi.org/10.5194/os-15-413-2019>, 2019.
- Dilmahamod, A. F., Aguiar-González, B., Penven, P., Reason, C. J. C., De Ruijter, W. P. M., Malan, N., and Hermes, J. C.: SIDDIES Corridor: A Major East-West Pathway of Long-Lived Surface and Subsurface Eddies Crossing the Subtropical South Indian Ocean, *Journal of Geophysical Research: Oceans*, 123, 5406–5425, <https://doi.org/10.1029/2018JC013828>, 2018.
- 505



- Doglioli, A. M., Blanke, B., Speich, S., and Lapeyre, G.: Tracking coherent structures in a regional ocean model with wavelet analysis: Application to Cape Basin eddies, *Journal of Geophysical Research: Oceans*, 112, 2006JC003 952, <https://doi.org/10.1029/2006JC003952>, 2007.
- Dufois, F., Hardman-Mountford, N. J., Greenwood, J., Richardson, A. J., Feng, M., and Matear, R. J.: Anticyclonic eddies
510 are more productive than cyclonic eddies in subtropical gyres because of winter mixing, *Science Advances*, 2, e1600282, <https://doi.org/10.1126/sciadv.1600282>, 2016.
- Faghmous, J. H., Frenger, I., Yao, Y., Warmka, R., Lindell, A., and Kumar, V.: A daily global mesoscale ocean eddy dataset from satellite altimetry, *Scientific Data*, 2, 150 028, <https://doi.org/10.1038/sdata.2015.28>, 2015.
- Frenger, I., Gruber, N., Knutti, R., and Münnich, M.: Imprint of Southern Ocean eddies on winds, clouds and rainfall, *Nature Geoscience*, 6,
515 608–612, <https://doi.org/10.1038/ngeo1863>, 2013.
- Garzoli, S. L., Richardson, P. L., Duncombe Rae, C. M., Fratantoni, D. M., Goñi, G. J., and Roubicek, A. J.: Three Agulhas rings observed during the Benguela Current Experiment, *Journal of Geophysical Research: Oceans*, 104, 20971–20985, <https://doi.org/10.1029/1999JC900060>, 1999.
- Guerra, L. A. A., Paiva, A. M., and Chassignet, E. P.: On the translation of Agulhas rings to the western South Atlantic Ocean, *Deep Sea
520 Research Part I: Oceanographic Research Papers*, 139, 104–113, <https://doi.org/10.1016/j.dsr.2018.08.005>, 2018.
- Herbette, S., Morel, Y., and Arhan, M.: Subduction of a Surface Vortex under an Outcropping Front, *Journal of Physical Oceanography*, 34, 1610–1627, [https://doi.org/10.1175/1520-0485\(2004\)034<1610:SOASVU>2.0.CO;2](https://doi.org/10.1175/1520-0485(2004)034<1610:SOASVU>2.0.CO;2), 2004.
- Ienna, F., Bashmachnikov, I., and Dias, J.: Meddies and Their Sea Surface Expressions: Observations and Theory, *Journal of Physical Oceanography*, 52, 2643–2656, <https://doi.org/10.1175/JPO-D-22-0081.1>, 2022.
- 525 Ioannou, A., Speich, S., and Laxenaire, R.: Characterizing Mesoscale Eddies of Eastern Upwelling Origins in the Atlantic Ocean and Their Role in Offshore Transport, *Frontiers in Marine Science*, 9, 835 260, <https://doi.org/10.3389/fmars.2022.835260>, 2022.
- Ioannou, A., Guez, L., Laxenaire, R., and Speich, S.: Global Assessment of Mesoscale Eddies with TOEddies; Comparison between Multi-Datasets and Colocation with In-Situ Measurements, <https://doi.org/10.20944/preprints202410.0651.v1>, 2024.
- Jayne, S. R. and Marotzke, J.: The Oceanic Eddy Heat Transport, *Journal of Physical Oceanography*, 32, 3328–3345,
530 [https://doi.org/10.1175/1520-0485\(2002\)032<3328:TOEHT>2.0.CO;2](https://doi.org/10.1175/1520-0485(2002)032<3328:TOEHT>2.0.CO;2), 2002.
- Johnson, G. C. and McTaggart, K. E.: Equatorial Pacific 13°C Water Eddies in the Eastern Subtropical South Pacific Ocean, *Journal of Physical Oceanography*, 40, 226–236, <https://doi.org/10.1175/2009JPO4287.1>, 2010.
- Karstensen, J.: Physical oceanography (CTD) during Maria S. Merian cruise MSM60/1, <https://doi.org/10.1594/PANGAEA.915898>, 2020.
- Karstensen, J. and Krahmann, G.: Physical oceanography during METEOR cruise M124, <https://doi.org/10.1594/PANGAEA.863015>, 2016.
- 535 Karstensen, J. and Wölfl, A.-C.: Raw multibeam EM122 data: METEOR cruise M124 (SE Atlantic), <https://doi.org/10.1594/PANGAEA.869740>, 2016.
- Karstensen, J., Speich, S., Morard, R., Bumke, K., Clarke, J., Giorgetta, M., Fu, Y., Köhn, E., Pinck, A., Manzini, E., Lübben, B., Baumeister, A., Reuter, R., Scherhag, A., de Groot, T., Louropoulou, E., Geißler, F., and Raetke, A.: Oceanic & atmospheric variability in the South Atlantic Cruise No. M124 29. February - 18. March 2016 Cape Town (Republic South Africa) - Rio de Janeiro (Brazil), Cruise report,
540 Bremen, Germany, https://doi.org/10.3289/CR_M124, 2016.
- Karstensen, J., Speich, S., Asdar, S., Berbel, G. B. B., Branlard, L., Carvalho, A., Chidichimo, M. P., Cotrim da Cunha, L., da Silva Calixto, A., Edsgren, C., Guerrero, R., Hummels, R., Jones, S., Kersale, M., Lebehot, A., Marshall, T., Mohale, N., Rogge, A., Sato, O. T., Schrandt,



- J., Stöven, T., and Sutti Otera, B.: Seamount Observatory and SAMOC Overturning, Cruise No. MSM60, January 04 - February 01, 2017, Cape Town (South Africa) - Montevideo (Uruguay), https://doi.org/10.2312/cr_msm60, 2019.
- 545 Karstensen, J., Czeschel, R., and Krahmann, G.: ADCP current measurements (38 and 75 kHz) during Maria S. Merian cruise MSM60/1, <https://doi.org/10.1594/PANGAEA.915906>, 2020.
- Laxenaire, R., Speich, S., Blanke, B., Chaigneau, A., Pegliasco, C., and Stegner, A.: Anticyclonic Eddies Connecting the Western Boundaries of Indian and Atlantic Oceans, *Journal of Geophysical Research: Oceans*, 123, 7651–7677, <https://doi.org/10.1029/2018JC014270>, 2018.
- Laxenaire, R., Speich, S., and Stegner, A.: Evolution of the Thermohaline Structure of One Agulhas Ring Reconstructed from Satellite
- 550 Altimetry and Argo Floats, *Journal of Geophysical Research: Oceans*, 124, 8969–9003, <https://doi.org/10.1029/2018JC014426>, 2019.
- Laxenaire, R., Speich, S., and Stegner, A.: Agulhas Ring Heat Content and Transport in the South Atlantic Estimated by Combining Satellite Altimetry and Argo Profiling Floats Data, *Journal of Geophysical Research: Oceans*, 125, e2019JC015511, <https://doi.org/10.1029/2019JC015511>, 2020.
- Le Vu, B., Stegner, A., and Arsouze, T.: Angular Momentum Eddy Detection and Tracking Algorithm (AMEDA) and Its Application to
- 555 Coastal Eddy Formation, *Journal of Atmospheric and Oceanic Technology*, 35, 739–762, <https://doi.org/10.1175/JTECH-D-17-0010.1>, 2018.
- Li, C., Zhang, Z., Zhao, W., and Tian, J.: A statistical study on the subthermocline submesoscale eddies in the northwestern Pacific Ocean based on Argo data, *Journal of Geophysical Research: Oceans*, 122, 3586–3598, <https://doi.org/10.1002/2016JC012561>, 2017.
- Lozier, M. S.: Evidence for Large-Scale Eddy-Driven Gyres in the North Atlantic, *Science*, 277, 361–364,
- 560 <https://doi.org/10.1126/science.277.5324.361>, 1997.
- Martin, A. P., Richards, K. J., Bracco, A., and Provenzale, A.: Patchy productivity in the open ocean, *Global Biogeochemical Cycles*, 16, <https://doi.org/10.1029/2001GB001449>, 2002.
- Mason, E., Pascual, A., and McWilliams, J. C.: A New Sea Surface Height–Based Code for Oceanic Mesoscale Eddy Tracking, *Journal of Atmospheric and Oceanic Technology*, 31, 1181–1188, <https://doi.org/10.1175/JTECH-D-14-00019.1>, 2014.
- 565 McCartney, M. and Woodgate-Jones, M.: A deep-reaching anticyclonic eddy in the subtropical gyre of the eastern South Atlantic, *Deep Sea Research Part A. Oceanographic Research Papers*, 38, S411–S443, [https://doi.org/10.1016/S0198-0149\(12\)80019-7](https://doi.org/10.1016/S0198-0149(12)80019-7), 1991.
- McCoy, D., Bianchi, D., and Stewart, A. L.: Global observations of submesoscale coherent vortices in the ocean, *Progress in Oceanography*, 189, <https://doi.org/10.1016/j.pocean.2020.102452>, 2020.
- McDougall, T. J. and Barker, P. M.: Getting started with TEOS-10 and the Gibbs Seawater (GSW) Oceanographic Toolbox, SCOR/IAPSO
- 570 WG127, ISBN 978-0-646-55621-5, data available at: <http://www.teos-10.org> (last access: October 2026), 2011.
- McGillicuddy, D. J., Anderson, L. A., Bates, N. R., Bibby, T., Buesseler, K. O., Carlson, C. A., Davis, C. S., Ewart, C., Falkowski, P. G., Goldthwait, S. A., Hansell, D. A., Jenkins, W. J., Johnson, R., Kosnyrev, V. K., Ledwell, J. R., Li, Q. P., Siegel, D. A., and Steinberg, D. K.: Eddy/Wind Interactions Stimulate Extraordinary Mid-Ocean Plankton Blooms, *Science*, 316, 1021–1026, <https://doi.org/10.1126/science.1136256>, 2007.
- 575 McWilliams, J. C.: Submesoscale, coherent vortices in the ocean, *Reviews of Geophysics*, 23, 165–182, <https://doi.org/10.1029/RG023i002p00165>, 1985.
- Mkhinini, N., Coimbra, A. L. S., Stegner, A., Arsouze, T., Taupier-Letage, I., and Béranger, K.: Long-lived mesoscale eddies in the eastern Mediterranean Sea: Analysis of 20 years of AVISO geostrophic velocities, *Journal of Geophysical Research: Oceans*, 119, 8603–8626, <https://doi.org/10.1002/2014JC010176>, 2014.



- 580 Moreton, S., Ferreira, D., Roberts, M., and Hewitt, H.: Air-Sea Turbulent Heat Flux Feedback Over Mesoscale Eddies, *Geophysical Research Letters*, 48, e2021GL095407, <https://doi.org/10.1029/2021GL095407>, 2021.
- Morrow, R., Coleman, R., Church, J., and Chelton, D.: Surface Eddy Momentum Flux and Velocity Variances in the Southern Ocean from Geosat Altimetry, *Journal of Physical Oceanography*, 24, 2050–2071, [https://doi.org/10.1175/1520-0485\(1994\)024<2050:SEMFV>2.0.CO;2](https://doi.org/10.1175/1520-0485(1994)024<2050:SEMFV>2.0.CO;2), 1994.
- 585 Moschos, E., Barboni, A., and Stegner, A.: Why Do Inverse Eddy Surface Temperature Anomalies Emerge? The Case of the Mediterranean Sea, *Remote Sensing*, <https://doi.org/10.3390/rs14153807>, 2022.
- Nencioli, F., Dong, C., Dickey, T., Washburn, L., and McWilliams, J. C.: A Vector Geometry–Based Eddy Detection Algorithm and Its Application to a High-Resolution Numerical Model Product and High-Frequency Radar Surface Velocities in the Southern California Bight, *Journal of Atmospheric and Oceanic Technology*, 27, 564–579, <https://doi.org/10.1175/2009JTECHO725.1>, 2010.
- 590 Pegliasco, C., Chaigneau, A., and Morrow, R.: Main eddy vertical structures observed in the four major Eastern Boundary Upwelling Systems, *Journal of Geophysical Research: Oceans*, 120, 6008–6033, <https://doi.org/10.1002/2015JC010950>, 2015.
- Pinot, J.-M., Tintoré, J., and Gomis, D.: Multivariate analysis of the surface circulation in the Balearic Sea, *Progress in Oceanography*, 36, 343–376, [https://doi.org/10.1016/0079-6611\(96\)00003-1](https://doi.org/10.1016/0079-6611(96)00003-1), 1995.
- Sallée, J.-B., Speer, K., Rintoul, S., and Wijffels, S.: Southern Ocean Thermocline Ventilation, *Journal of Physical Oceanography*, 40, 509–
- 595 529, <https://doi.org/10.1175/2009JPO4291.1>, 2010.
- Stammer, D.: Global Characteristics of Ocean Variability Estimated from Regional TOPEX/POSEIDON Altimeter Measurements, *Journal of Physical Oceanography*, 27, 1743–1769, [https://doi.org/10.1175/1520-0485\(1997\)027<1743:GCOOVE>2.0.CO;2](https://doi.org/10.1175/1520-0485(1997)027<1743:GCOOVE>2.0.CO;2), 1997.
- Subirade, C., L'Hégaret, P., Speich, S., Laxenaire, R., Karstensen, J., and Carton, X.: Combining an Eddy Detection Algorithm with In-Situ Measurements to Study North Brazil Current Rings, *Remote Sensing*, 15, 1897, <https://doi.org/10.3390/rs15071897>, 2023.
- 600 Sun, W., Dong, C., Tan, W., and He, Y.: Statistical Characteristics of Cyclonic Warm-Core Eddies and Anticyclonic Cold-Core Eddies in the North Pacific Based on Remote Sensing Data, *Remote Sensing*, 11, 208, <https://doi.org/10.3390/rs11020208>, 2019.
- Villar, E., Farrant, G. K., Follows, M., Garczarek, L., Speich, S., Audic, S., Bittner, L., Blanke, B., Brum, J. R., Brunet, C., Casotti, R., Chase, A., Dolan, J. R., d'Ortenzio, F., Gattuso, J.-P., Grima, N., Guidi, L., Hill, C. N., Jahn, O., Jamet, J.-L., Le Goff, H., Lepoivre, C., Malviya, S., Pelletier, E., Romagnan, J.-B., Roux, S., Santini, S., Scalco, E., Schwenck, S. M., Tanaka, A., Testor, P., Vannier, T.,
- 605 Vincent, F., Zingone, A., Dimier, C., Picheral, M., Searson, S., Kandels-Lewis, S., Tara Oceans Coordinators, Acinas, S. G., Bork, P., Boss, E., De Vargas, C., Gorsky, G., Ogata, H., Pesant, S., Sullivan, M. B., Sunagawa, S., Wincker, P., Karsenti, E., Bowler, C., Not, F., Hingamp, P., and Iudicone, D.: Environmental characteristics of Agulhas rings affect interocean plankton transport, *Science*, 348, 1261447, <https://doi.org/10.1126/science.1261447>, 2015.
- Villas Bôas, A. B., Sato, O. T., Chaigneau, A., and Castelão, G. P.: The signature of mesoscale eddies on the air-sea turbulent heat fluxes in the South Atlantic Ocean, *Geophysical Research Letters*, 42, 1856–1862, <https://doi.org/10.1002/2015GL063105>, 2015.
- 610 Wöhl, A.-C. and Schade, M.: AtlantOS data products from multibeam EM122 data: METEOR cruise M124 (Atlantic), <https://doi.org/10.1594/PANGAEA.902947>, 2019.
- Wunsch, C.: Where do ocean eddy heat fluxes matter?, *Journal of Geophysical Research: Oceans*, 104, 13235–13249, <https://doi.org/10.1029/1999JC900062>, 1999.
- 615 Zhang, Z., Wang, W., and Qiu, B.: Oceanic mass transport by mesoscale eddies, *Science*, 345, 322–324, <https://doi.org/10.1126/science.1252418>, 2014.



Zhang, Z., Li, P., Xu, L., Li, C., Zhao, W., Tian, J., and Qu, T.: Subthermocline eddies observed by rapid-sampling Argo floats in the subtropical northwestern Pacific Ocean in Spring 2014, *Geophysical Research Letters*, 42, 6438–6445, <https://doi.org/10.1002/2015GL064601>, 2015.

620 Zhang, Z., Zhang, Y., and Wang, W.: Three-compartment structure of subsurface-intensified mesoscale eddies in the ocean, *Journal of Geophysical Research: Oceans*, 122, 1653–1664, <https://doi.org/10.1002/2016JC012376>, 2017.