



Submesoscale processes reduce water mass retention in Agulhas Rings

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Abstract. Mesoscale and submesoscale ocean processes (1–100 km) are central to global ocean circulation, water mass transformation, and both the horizontal and vertical transport of tracers such as heat and carbon. The Agulhas Current system and the Cape Basin are hotspots for such dynamics, where mesoscale and submesoscale flows interact strongly and impact the large-scale flow. Among the most prominent features in this region are anticyclonic Agulhas Rings that are shed from the Agulhas retroflection as well as cyclonic eddies, which both decay while transporting relatively warm and saline waters into the South Atlantic. In this study, we investigate the retention potential of these eddies, representing the loss of water masses into the surrounding ocean. To isolate the role of the submesoscale, we compare two global ocean model configurations with grid-refinements in the focus region: one with $1/20^\circ$ resolution that is strongly eddying but does not resolve submesoscale flows, and another with $1/60^\circ$ resolution and modified tracer and momentum advection, allowing for the simulation of realistic submesoscale motions throughout the Agulhas region. We use Lagrangian simulations within the Parcels framework, with virtual particles representing small amounts of water masses. Coherent eddies, both anticyclonic and cyclonic, are identified horizontally and vertically using automated eddy-detection and tracking algorithms. Over a 6-year period, large numbers of particles ($\mathcal{O}(10^5 - 10^7)$ per eddy) are seeded in 3D within eddies intersecting the GoodHope line and tracked to assess how long the particles remain in the eddies and the spatiotemporal patterns of their exchange with the surrounding ocean. Our results reveal that cyclones lose their water masses much faster than anticyclones. Submesoscale processes reduce the retention timescale of anticyclonic eddies by a factor of about 2. The enhanced water parcel loss in anticyclones is associated with lateral stirring driven by submesoscale fronts, filaments, and mixed-layer baroclinic instability as shown by a case study, thereby accelerating the transport of heat and salt into the South Atlantic. For cyclonic eddies, the results point in the same direction, albeit more weakly, but the smaller sample size and the weaker representation of strong cyclones in the coarser configuration prevent a robust quantification.

1 Introduction

The Agulhas Current system, located around the southern tip of South Africa at the confluence of the Indian and Atlantic Oceans, is a key component in the global overturning circulation (Lutjeharms, 2006; Biastoch et al., 2008). As the western



boundary current of the Indian Ocean, the Agulhas Current transports relatively warm and saline water southwestward along the African continental shelf before reaching the Agulhas Bank. After overshooting it in southwesterly direction, the current retroflects, and moves back eastward into the Indian Ocean with most of its waters. However, a considerable amount of approximately 15–21 Sv, depending on the observational data and method, escapes into the South Atlantic (Richardson, 2007; Daher et al., 2020), which is known as Agulhas leakage and is part of an inter-ocean exchange of heat and salt (de Ruijter et al., 1999; R  hs et al., 2019). The partitioning between these two pathways is controlled by a combination of the latitudinal position of the oceanic subtropical front and the strength of the Southern Hemisphere westerly winds, which together set the longitude of retroflection and amount of water entering the South Atlantic (Beal et al., 2011; Durgadoo et al., 2013; Gro  belindemann et al., 2025). The GoodHope line (see Fig. 1), an observational hydrographic section (Ansorge et al., 2005), separates the retroflection region from the northwestern part of the Cape Basin and the South Atlantic, as water parcels crossing it rarely return to the retroflection region and are thereby contributing to Agulhas leakage (e.g. Schmidt et al., 2021; Schubert et al., 2021; R  hs et al., 2022). The water masses entering the South Atlantic are particularly advected there by mesoscale anticyclonic eddies of radii larger than 60 km (Laxenaire et al., 2019), the Agulhas Rings, although cyclonic eddies and filaments also contribute (Beal et al., 2011; Schubert et al., 2021). However, rather than being transported directly into the South Atlantic, Agulhas water masses first enter the Cape Basin, which is framed by the Agulhas Ridge to the south, the Walvis Ridge to the northwest and the African continental shelf to the northeast. There they are subject to vigorous stirring and mixing processes (Boebel et al., 2003; Capuano et al., 2018). This highly turbulent region acts as a melting pot in which water masses of different origins are blended before being advected further into the South Atlantic (Boebel et al., 2003; Capuano et al., 2018), with mesoscale eddies decaying rapidly in the process (van Sebille et al., 2010).

The decay and coherence of an eddy can be described from different perspectives. Kinematic coherence expresses the temporal persistence of a rotating structure, as captured by closed contours of sea surface height (SSH) tracked over time (McWilliams, 1984; Chelton et al., 2011). A reduction of SSH anomalies or relative vorticity indicates a decay of dynamical intensity (e.g. Schouten et al., 2000; van Sebille et al., 2010), but this does not necessarily reflect the loss of water. Instead, material coherence formalised in the Lagrangian coherent structure framework (Haller, 2015; Haller and Beron-Vera, 2013) is more restrictive than this kinematic view. It requires *retention*, meaning that a body of water remains trapped and undistorted over a finite time, as an opposing concept to dispersion, which refers to the spreading of tracers such as heat, salt and carbon. Its application typically reveals that only a small inner core resists filamentation, with eddies leaking material across their Eulerian boundaries relatively quickly (Beron-Vera et al., 2013; Abernathey and Haller, 2018). A complementary, observationally grounded view defines coherence through the trapping of a distinct water mass characteristic of the eddy’s formation region, which Barabinot et al. (2025) term thermohaline coherence. These definitions are related but not equivalent, and estimates of eddy tracer transport differ substantially depending on which is applied. An eddy can subduct and lose its SSH signature yet may remain materially coherent (Laxenaire et al., 2019), while another may keep a distinct dynamical signature after losing a substantial fraction of its trapped water (van Sebille et al., 2010). A three-dimensional Lagrangian perspective is therefore suited as it allows for a direct quantification of water parcels trapped within coherent structures and their retention times (Cetina-Heredia et al., 2019). This is relevant for estimating the amounts of heat and salt transported by Agulhas eddies



into the South Atlantic which ultimately contribute to the global overturning circulation. Velocity fields from high-resolution ocean models can serve as the dynamical basis for virtual particles that represent individual water parcels (van Sebille et al., 2018). While the trajectories are computed solely from the velocity fields, additional properties such as density, vorticity, or kinetic energy can be sampled along the pathways, enabling subsequent offline Lagrangian analysis and making this approach particularly suited to study material eddy coherence, also in highly turbulent regions such as the Cape Basin.

Recent modelling studies suggest that submesoscale processes with horizontal scales of $\mathcal{O}(1 - 10)$ km may substantially influence the fate of Agulhas leakage. Representing these scales down to ~ 8 km in high-resolution ocean models increases total leakage into the South Atlantic by 40 % (Schubert et al., 2021). Submesoscale flows are associated with both a forward and an inverse cascade (Ferrari and Wunsch, 2009; Schubert et al., 2020). While the forward cascade occurs mainly in frontal regions driven by frontogenesis, the inverse cascade is established through the absorption of submesoscale vortices by mesoscale eddies (Schubert et al., 2020). Furthermore, submesoscale processes can enhance lateral stirring, and promote the exchange of water parcels across eddy boundaries through instabilities (McWilliams, 2016; Capet et al., 2008; Gula et al., 2022; Sinha et al., 2019). Yet, their impact on the three-dimensional material coherence and retention of Agulhas Rings, smaller anticyclones, and cyclones in the Cape Basin remains poorly understood. In particular, it is unclear to what extent submesoscale processes alter the retention of water parcels in mesoscale eddies, whether anticyclonic and cyclonic vortices respond differently, and how these effects vary with depth. Addressing these questions is essential in understanding how fine-scale processes modulate the transfer of Agulhas water masses into the South Atlantic.

In this study, we investigate the influence of submesoscale dynamics on the dynamical decay and retention of materially coherent eddies in the Cape Basin. Using Lagrangian particle tracking based on output from two high-resolution ocean model configurations, one submesoscale-permitting and one eddying but without representation of the submesoscale, we evaluate the evolution of anticyclones and cyclones and assess leakage pathways and retention times.

2 Materials and methods

To address the questions outlined above, we apply automated (Eulerian) eddy detection and tracking, and offline Lagrangian particle tracking simulations to high-resolution ocean models. This integrated approach allows to track water parcels leaking out of simulated mesoscale eddies.

2.1 Ocean model configurations

The model configurations used in this study are part of the INALT family, a global ocean model system with focus on the Agulhas region (Schwarzkopf et al., 2019) based on the NEMO(v3.6) model code (Madec and NEMO System Team, 2017). Through a nesting approach in which the numerical solutions are exchanged between a coarser global parent grid and higher-resolution supraregional child grids, the dynamics of the region but also the large-scale circulation are well captured. In the following, we consider two configurations that span the relevant range of resolved scales: The eddy-rich INALT20r.L120-KRS006 (hereafter called INALT20r), and the submesoscale-permitting INALT60.L120-KRS0020 (hereafter INALT60; Schubert and



Schwarzkopf, 2026) with very good representation of processes below the mesoscale (Schubert et al., 2019). Both were initialised from another INALT20r-configuration (INALT20r.L46-KFS013, Schwarzkopf et al., 2019) in 2010 and run until 2017 under JRA55-do(v1.3) atmospheric forcing (Tsujino et al., 2018). However, they differ in maximum horizontal resolution. While INALT20r has a global resolution at the parent grid of $1/4^\circ$ and a child grid with $1/20^\circ$ (≈ 4 km) covering the Southeast Atlantic and southwestern part of the Indian Ocean ($6.5\text{--}50^\circ$ S, 19.7° W– 70.5° E), INALT60 has an additional secondary child grid of $1/60^\circ$ resolution (≈ 1.5 km) in the core Agulhas region ($25\text{--}45^\circ$ S, $0\text{--}40^\circ$ E). Furthermore, they incorporate carefully chosen numerical schemes for tracer and momentum advection (Schubert et al., 2019). INALT60 makes use of the upstream biased (UBS) schemes which leads to a realistic conservation of smaller scales resolved by the $1/60^\circ$ grid (as validated against observational data). In INALT20r, fine-scale flows and water mass structures are not resolved, partly due to the lower resolution and partly due to its more diffusive advection schemes with additional explicit diffusion and dissipation. Apart from that, they have a similar setup, and were explicitly designed and used to identify the submesoscale impact (Schubert et al., 2020, 2021). Figure 1 visualises the focus region in the two model configurations. The Agulhas Current with its retroflexion and the rings shed into the South Atlantic are visible as regions of high speed, key features that are realistically represented as documented by Schubert et al. (2019). Still, the smaller, more fine-scale structures visible in INALT60 highlight the difference in submesoscale representation. The overall intensity and spatial complexity of the surface flows are considerably higher than in INALT20r.

2.2 Eddy detection

Regions that are associated with coherent (anti-)cyclonic eddies are identified in each daily average of the model output. This enables the tracking of water parcels within eddies, including the duration they stay in the eddy and the conditions under which they exit. To obtain an accurate three-dimensional coherent eddy mask, two complementary detection approaches are combined, starting from the ocean surface and extending to depth.

2.2.1 Eddy detection at the ocean surface

Traditional eddy detection methods identify eddy boundaries at the ocean surface using sea surface height (SSH) or absolute dynamic topography (ADT) (e.g. Chelton et al., 2011). Here, we apply the ocean eddy detection and tracking algorithm *TOEddies* (Laxenaire et al., 2018), which relies on the fact that for geostrophic eddies, closed SSH contours correspond to streamlines. The algorithm first identifies local SSH extrema as potential eddy centres, then searches for the outermost closed SSH contour around each extremum. To avoid the detection of small structures that are not robustly resolved by the data, a minimum amplitude ("persistence") threshold is applied. Compliant with Laxenaire et al. (2018), a value of 1 mm is used here. Since *TOEddies* was developed for $1/4^\circ$ satellite altimetry maps, its minimum size criterion of at least four connected grid points within a closed contour corresponds to approximately 25 km radius. Applied to the higher-resolution INALT configurations, we chose a minimum value of 20 km, to focus on mesoscale structures but exclude smaller features. Furthermore, detected features with unrealistic diameters larger than 5° are excluded from being identified as eddies.

Next to the outermost SSH contour, a characteristic contour is defined, along which the azimuthal geostrophic velocity is maximum. Sometimes both contours co-locate. While the outermost contour captures the full extent of the eddy, it is often

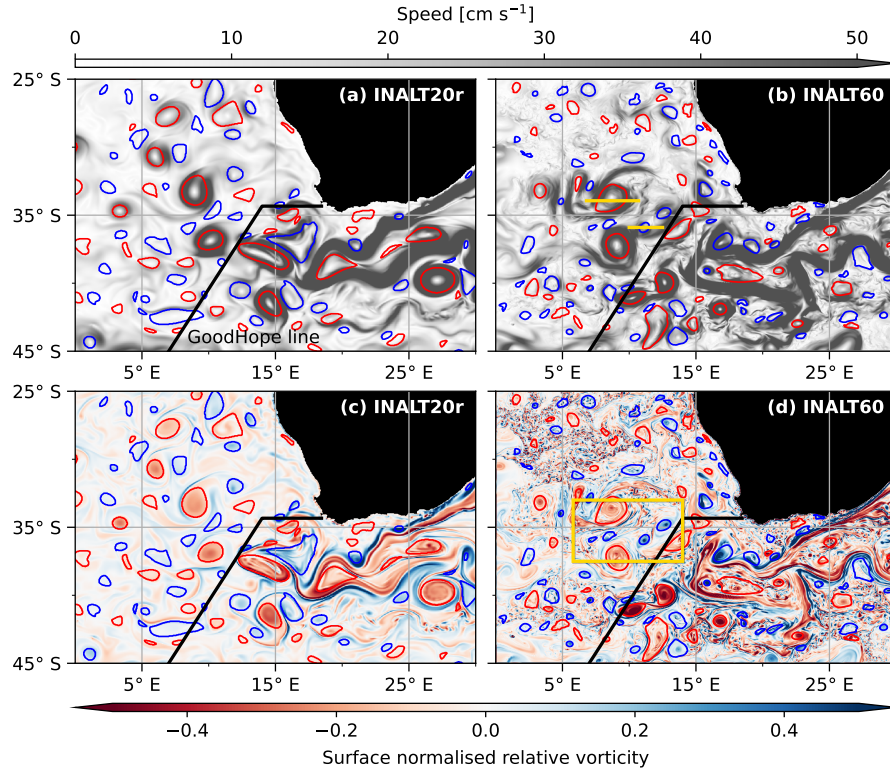


Figure 1. Overview Regional cutout of surface speed in austral winter (daily mean on 29 June 2012) in the two model configurations (a) INALT20r.L120-KRS006 and (b) INALT60.L120-KRS0020. Panels (c–d), respectively, show the surface normalised relative vorticity ζ/f , a measure of rotation. As with the closed characteristic contours originating from the surface eddy detection TOEddies (see Sect. 2.2.1), red (blue) colours indicate anticyclonic (cyclonic) rotation. The GoodHope line (solid black) separates the retroflection region south of the African continent from the Agulhas Ring path to the northwest. The golden lines in Panel (b) mark the position of the sections in Fig. 2 and the golden rectangle in Panel (d) frames the area for the exemplary Lagrangian tracking in Fig. 4.

distorted by the surrounding flow. Instead, the characteristic contours are more robust in time and define the eddy core used in the subsequent tracking. Based on the detected eddy regions, eddies are then tracked by connecting overlapping consecutive contours. The algorithm further accounts for splitting and merging events, making it particularly suited for the complex eddy interactions in the Agulhas region (Laxenaire et al., 2018).

TOEddies was here adapted for the application to numerical model output, using the daily mean SSH and surface velocities from both INALT simulations for the years 2012 to 2017. The resulting surface-detected characteristic contours for anticyclonic and cyclonic eddies in the Cape Basin for one day in austral winter are shown in Fig. 1. While individual eddy contours may appear similar at certain locations between the two configurations, both are dynamically independent. The simulations diverge rapidly due to the nonlinear nature of the system, even though INALT60 was initialised by INALT20r at the end of the year 2009.



2.2.2 Eddy detection at depth

135 Since assessing material coherence and retention requires a three-dimensional perspective, the surface-based eddy detection will be extended to the surface mixed layer depth (MLD) and supplemented below. Ertel's potential vorticity (EPV) (Ertel, 1942) can be used to define eddy boundaries and their cores at depth as shown by Barabinot et al. (2024). With the α -criterion, where α is a scaling factor of different EPV components as will be explained in the following, they focused on several regions and eddy types, among which are anticyclonic Agulhas and North Brazil Current Rings, and a cyclonic Benguela Upwelling

140 Eddy. While they simplified the general definition of EPV for application to two-dimensional vertical sections of in situ data, EPV is inherently three-dimensional and well suited for use with gridded numerical model data. The general equation (Müller, 1995; Barabinot et al., 2024)

$$q = (\nabla \times \mathbf{u} + \mathbf{f}) \cdot \nabla b = \underbrace{(w_y - v_z) \cdot b_x + (u_z - w_x) \cdot b_y}_{q_h} + \underbrace{(v_x - u_y + f) \cdot b_z}_{q_v} \quad (1)$$

with the three-dimensional velocity vector $\mathbf{u} = (u, v, w)$ (i.e. the zonal, meridional and vertical components) and the Coriolis parameter $\mathbf{f} = (0, 0, f)$, is given under the Boussinesq approximation, using buoyancy $b = -g \frac{\sigma}{\sigma_0}$ with potential density σ , a density reference σ_0 taken as a volume-weighted average over the entire domain, and Earth's gravitational acceleration g . Subscripts of x, y, and z indicate partial derivatives with respect to the subscripted variable (e.g. $u_y = \partial u / \partial y$) while other subscripts indicate components. The equation can be further split into a horizontal component q_h and a vertical component q_v . q_v dominates in the eddy core where the water column is both strongly stratified and rotating, combining vertical stratification

150 with absolute vorticity. q_h becomes larger at eddy boundaries, where density surfaces are tilted as vertical velocity shear acts on large horizontal buoyancy gradients, reducing the dominance of q_v . Barabinot et al. (2024) reduce q_h to a single term EPV_x , computed along the one horizontal direction sampled by a ship section, whereas both horizontal buoyancy-gradient directions are maintained here. Gridded model output thus allows the framework to be kept three-dimensional. q_v closely corresponds to their vertical term EPV_z with the additional relative vorticity component u_y , which is absent in a vertical

155 section. The eddy boundary is first identified via the dimensionless ratio $|EPV_x| / |EPV_z|$, later supplemented by a scaled difference of $|EPV_x|$ and $|EPV_z|$ similarly used here. A related criterion discussed by Barabinot et al. (2025) is the ratio of the anomaly ΔEPV_z to EPV_x exceeding a threshold, to isolate the interior from the surrounding frontal region which is subject to symmetric instabilities. Both studies argue that these EPV ratios are difficult to evaluate from ship sections, as the repeated spatial derivatives amplify measurement noise (Barabinot et al., 2024, 2025), a limitation that does not apply to

160 gridded daily-mean model fields, which permit the direct evaluation of q_h and q_v throughout the water column. This three-dimensional formulation is introduced here for the first time.

Following Barabinot et al. (2024) to define eddy boundaries, the horizontal and vertical components are set in relation through the scaling factor $\alpha = Ro/2$, where the Rossby number is approximated from the models as $Ro \approx |\zeta_{curv} / f|$, with the curvature vorticity $\zeta_{curv} = V / R_s$, the flow speed $V = \sqrt{u^2 + v^2}$ and the radius of streamline curvature R_s (Bell and

165 Keyser, 1993; Wang et al., 2025). This scaling follows the empirical value found by Barabinot et al. (2024) to characterise eddy boundaries across a range of in situ eddies, who note that the appropriate value is resolution-dependent and increases



with eddy baroclinicity. Our approximation of Ro from curvature vorticity provides a per-eddy estimate consistent with this dependence. A further scaling by the signs of ζ_{curv} and f enables eddy-type differentiation on both hemispheres in Eq. (2) via a threshold E_{EPV} .

$$170 \quad (|q_h| - \alpha |q_v|) \cdot \text{sgn}(\zeta_{curv} \cdot f) \begin{cases} > +E_{EPV} & \text{(anticyclonic)} \\ < -E_{EPV} & \text{(cyclonic)} \end{cases} \quad (2)$$

Since $|q_h| - \alpha |q_v|$ is negative throughout the eddy interior and tends towards zero outside, regardless of eddy type and on which hemisphere, the sign of $\zeta_{curv} \cdot f$ here additionally determines the polarity: it is negative for anticyclones (where ζ_{curv} and f have opposite signs) and positive for cyclones (where both share the same sign), yielding values above $+E_{EPV}$ and below $-E_{EPV}$ respectively. While $E_{EPV} = 0$ describes the eddies' outer boundary (Barabinot et al., 2024, without eddy-type separation), we find the coherent core to be well described below the surface mixed layer with $E_{EPV} = 7 \cdot 10^{-10} [s^{-3}]$, as is illustrated by the bold red and blue lines in Fig. 2. Since E_{EPV} is a dimensional threshold, we verified that the results presented in Sect. 3 are not critically sensitive to the exact choice of this value. Thresholds of similar order of magnitude yield comparable core structures and do not alter the qualitative differences found between the two configurations.

An alternative approach for eddy detection at depth would employ the Okubo–Weiss parameter (Okubo, 1970; Weiss, 1991) (OW), which characterises the relation between rotation and strain. Although OW can dynamically define eddies (e.g. Isern-Fontanet et al., 2006), this method is more sensitive to threshold selection and proves less suitable in this case (see Fig. 2). OW defines eddies much deeper and less consistent for consecutive days (not shown). As also visible here, some eddies have a (small) velocity signature down to the seafloor, but it is questionable whether there is water trapped at these depths (van Aken et al., 2003), since this depends on the ratio of rotational and translational velocity of the eddy (Flierl, 1981). Moreover, EPV has the additional benefit of linking dynamics to density gradients, and is therefore more appropriate to monitor material coherence and trapped volumes.

To robustly describe eddies from the surface to depth, both eddy detection methods, *TOEddies* and the α -criterion, are used conjointly. However, this means, that in the following only eddies with an initially pronounced surface signature are considered, which nonetheless make up the major portion of larger mesoscale eddies in the southeastern part of the Cape Basin (Laxenaire et al., 2019; Hall and Lutjeharms, 2011).

2.3 Lagrangian simulations and eddy statistics

Lagrangian particle tracking allows individual fluid parcels to be followed through a prescribed flow field, enabling quantification of water mass pathways and retention within coherent structures, complementary to the Eulerian eddy detection described above. Here, the Parcels framework (Delandmeter and van Sebille, 2019) is used, with daily mean three-dimensional velocity output from both INALT20r and INALT60 serving as offline input to compute particle trajectories.

To track how water parcels are exchanged between eddies and their surroundings, large numbers of particles are seeded into previously detected eddies ($\mathcal{O}(10^5 - 10^7)$ per eddy). Following other studies of Agulhas leakage (Schmidt et al., 2021; Schubert et al., 2021), the GoodHope line (Ansorge et al., 2005) serves as a separator of the dynamical regimes, as particles crossing it

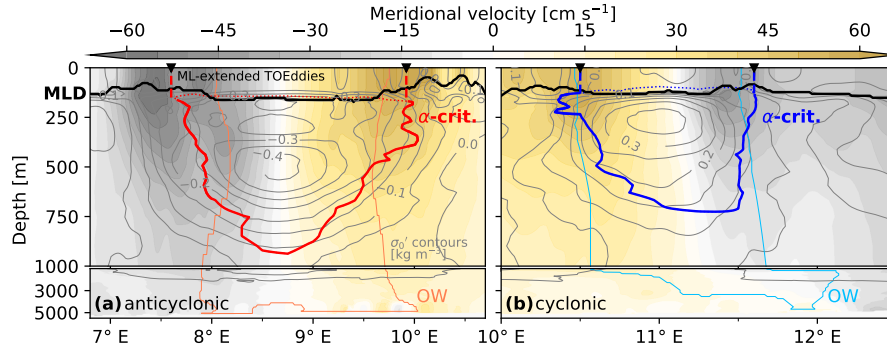


Figure 2. Zonal section through eddies Panel (a) and (b) present exemplary boundaries at depth contouring the three-dimensional thermohaline coherent cores of an anticyclonic (red) and cyclonic (blue) eddy, respectively, as represented in the ocean model INALT60. Their latitudinal positions are indicated by the golden lines in Fig. 1b. The edges of surface-detected eddies from TOEddies (black triangles, see Sect. 2.2.1) are extended downward (dashed coloured) to approximately the surface mixed layer depth (MLD), where they connect to contours derived from the α -criterion (thick coloured and thin dotted, see Sect. 2.2.2). An alternative eddy detection approach also functional at depth, based on the Okubo–Weiss parameter (OW), is displayed by thin, lighter-coloured lines. For dynamical context, the background shading shows the cross-sectional (meridional) velocity component, while anomalies of potential density are indicated by thin grey contours.

200 rarely return to the retroflexion region but move towards the South Atlantic. Surface eddy tracks from TOEddies intersecting the GoodHope line are considered, when they point (north-)westward and are sufficiently long-lived (at least 30 days in total, of which more than 10 days after crossing), and initially coherent in the vertical, as determined by the α -criterion. This ensures that seeded particles remain within a well-defined eddy structure at release, rather than being immediately dispersed into the surrounding flow.

Over the six-year period, 38 anticyclonic and 12 cyclonic tracks qualify for INALT20r, and 27 anticyclonic and 20 cyclonic tracks for INALT60, placing both configurations within the observed range of approximately 4–6 Agulhas Rings per year (Guerra et al., 2018; Laxenaire et al., 2020). A notable difference between the configurations is visible in the surface tracks themselves: in INALT20r, tracks follow relatively straight, undisturbed paths across the GoodHope line at a steady angle towards the northwest. In INALT60, several tracks are considerably shorter, which does not necessarily imply that the eddy decayed completely, but rather that TOEddies could no longer associate consecutive surface contours with the same track, likely due to a splitting or merging event, or the eddy having subducted below the surface. A clustering of track endings is visible at about 33° S, 6.5° E in INALT60, which may be related to the more detailed bathymetric representation in the higher-resolution configuration: while the analysis is beyond the scope of this manuscript, we hypothesise that this generally deep (4500–5000 m) region is surrounded by isolated seamounts, which could introduce topographic steering effects that are smoothed out in INALT20r. Consistent with this, the mean eddy path in INALT20r runs slightly further north (see Fig. 8e, k of Schubert et al. (2019) or black contours in Fig. 10a–b of this manuscript), potentially bypassing the topographic features

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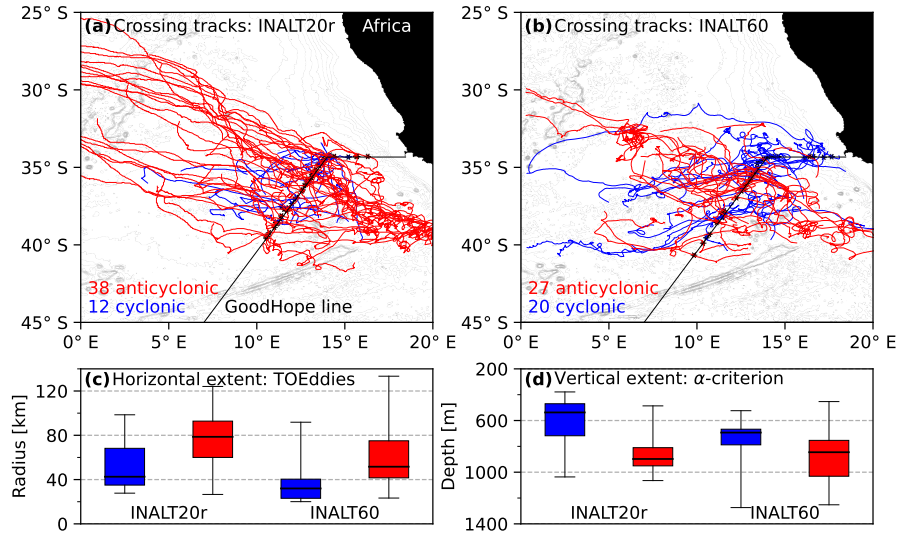


Figure 3. Eddies at GoodHope line Intersections of tracks of TOEddies-detected eddies with the GoodHope line mark the start location for the subsequent Lagrangian simulations in (a) INALT20r and (b) INALT60. Grey thin lines show the bathymetry in 500 m intervals in and around the Cape Basin. Box plots display the median (thick line), interquartile range (box), and full range (whiskers) for the (c) horizontal and (d) vertical extent for all long-lived (> 30 days in total, > 10 days after crossing) anticyclonic (red) and cyclonic (blue) eddies at the moments of crossing.

that disturb tracking in INALT60. Note that in the following the Lagrangian particle tracking would continue beyond this point regardless of whether the surface eddy track terminates.

After identifying qualifying surface eddy tracks, the intersections of those with the GoodHope line define the seeding locations, as illustrated by crosses in Fig. 3a–b. At these locations, particles are seeded three-dimensionally throughout the water column, wherever TOEddies detected a characteristic eddy contour at the surface above and the criterion in Eq. (2) is satisfied (see coloured contours in Fig. 2). The range of sizes of the identified eddies at the time of GoodHope crossing is summarised in Fig. 3c–d. As expected (Boebel et al., 2003), anticyclonic eddies are generally larger than cyclones in both horizontal and vertical extent, with median radii of 80 km (INALT20r) and 52 km (INALT60), and median depths of 898 m and 845 m, respectively. These values agree well with observed Agulhas Ring radii of maximum velocity ranging from 45 to 160 km and water mass anomalies extending between 600–800 m (Duncombe Rae et al., 1996; van Aken et al., 2003) and up to 1500 m (Pegliasco et al., 2015). Cyclones are smaller and shallower, with median radii of 43 km (INALT20r) and 32 km (INALT60), and median depths of 537 m and 693 m. Observed cyclone diameters of approximately 111 km from altimetric data (Hall and Lutjeharms, 2011) reflect the full outer extent rather than the radius of maximum velocity and are therefore slightly larger than the model values. Regardless of polarity, eddies in INALT20r tend to be wider than those in INALT60, while cyclones in INALT60 reach somewhat greater depths.



To ensure a uniform particle density across both configurations, particles are placed on the native horizontal INALT60 T-grid points for both INALT20r and INALT60 simulations, and every 10 metres along the depth axis. Particles are then advected using the three-dimensional velocity components of the respective INALT configuration. Adapted to the respective grid spacing and speed values to ensure that particles cannot traverse a grid point and thereby miss characteristic oceanographic features (Schmidt et al., 2021), the particles' positions are time-stepped every 60 minutes for INALT20r and 15 minutes for INALT60, and daily positions are stored for analysis. In addition to their positions, the particles' ambient temperature, salinity and α -criterion value (i.e. left part of Eq. (2)) are recorded, together with information on any potential *TOEddies*-detected eddy above each particle's location (including its type, magnitude, and size), and the local curvature of the trajectory.

2.4 Retention metric

The conceptual basis of the Lagrangian approach is illustrated in Fig. 4, which shows snapshots of a representative anticyclonic eddy at four stages of its evolution after crossing the GoodHope line. Particles seeded into the eddy at release are coloured red as long as they are identified as belonging to the eddy core, and grey once they have left. The eddy gradually loses particles to its surroundings over the first 100 days, until it is squeezed between two cyclonic eddies, after which the remaining particles are no longer associated with the original coherent eddy structure.

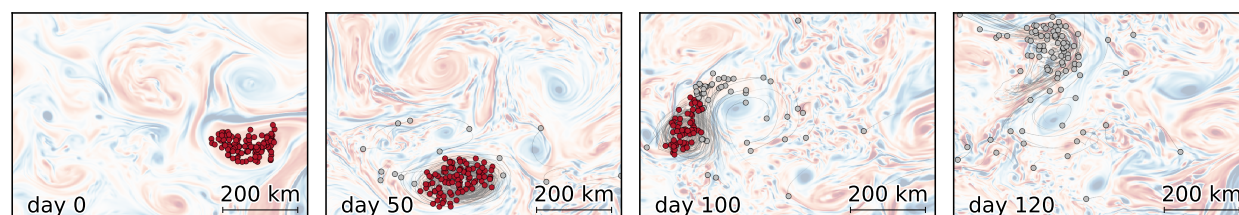


Figure 4. Particle tracking Conceptual illustration of the evolution of an eddy. Snapshots from a Lagrangian simulation show how the water parcels of an eddy mix into the surroundings. Simulated particles are coloured red if they have remained within the original anticyclone, grey if they have left. The black tails visualise the particles' trajectories of the preceding two weeks. As a measure of anticyclonic (cyclonic) rotation, the red (blue) background displays the surface normalised relative vorticity from INALT60. The frames show the area between 5.5–14.5° E and 38.5–32° S as indicated by the golden frame in Fig. 1d. An animation of the full evolution is provided as supplementary material.

To quantify this evolution systematically, a retention metric is computed at each time step of the simulation. For every particle, retention within the eddy is assessed based on three criteria applied in combination. First, a *TOEddies*-detected eddy of the same type must be present at the ocean surface above the particle's location. Second, for particles below the MLD, the α -criterion must additionally be satisfied, ensuring that the particle is within a dynamically coherent subsurface structure. Third, the local curvature of the particle trajectory must match the sense of rotation of the eddy. This third criterion alone would be insufficient, as particles advected outward along filaments extending from the eddy interior can exhibit rotation-compliant curvature without being part of the coherent core (as visible, for example, at the rims of the larger Agulhas Rings in Fig. 1).



To account for eddies that subduct and are no longer detectable at the surface by *TOEddies*, a spatial relaxation for the particles is applied: if the surface criterion is not met but the remaining criteria are satisfied within the same horizontal neighbourhood, the particle is still counted as retained. This also provides robustness against isolated gaps or uncertainties in the eddy detection, which, while less frequent in model output than in satellite altimetry, cannot be entirely excluded. Finally, a tolerance of two days is applied, allowing particles to temporarily fail the retention criteria before being permanently classified as having left the eddy, as long as all criteria are met again within that window. This is particularly relevant in the case of splitting or merging events, of which there are 426 and 519 in INALT60, and 317 and 377 in INALT20r, respectively, according to the *TOEddies* tracking within the region displayed in Fig. 3a–b downstream (i.e. northwest of) the GoodHope line during the considered period of 2012 to 2017. As such interactions modify the concept of a single, uniquely defined eddy trajectory (Ioannou et al., 2024), retention as defined here also measures persistence as part of a network of coherent eddies of a given polarity, not only within one identical structure.

Retention at each time step is then expressed as the fraction of originally seeded particles that still satisfy all applicable criteria, providing a continuous measure of the eddy’s ability to trap and transport water masses over time. The resulting retention curves combining all Lagrangian simulations form the basis of the analysis presented in the following section. For these curves, a retention timescale τ for comparing the configuration and eddy polarities is defined as the point at which this fraction falls below the e^{-1} threshold ($\approx 36.8\%$). Together with a loss fraction L_{16} , the fraction of particles lost within the first 16 days, the fast initial signal of submesoscale-driven erosion versus the slow core decay is captured. A detailed derivation and discussion of both quantities is given in Appendix A.

270 3 Results and discussion

Eddy decay in the Cape Basin is examined in the following from two complementary perspectives: the retention of water parcels within coherent structures and the dynamical evolution of eddy properties. Both allow to assess how submesoscale processes shape the transport of Agulhas water masses through anticyclones and cyclones in the region.

Considering first the dynamical strength of eddies after crossing the GoodHope line, a consistent picture emerges. The mean SSH anomaly at the eddy centre, computed relative to the long-term mean, declines continuously for both anticyclones and cyclones and slowly approaches the climatological mean within the six months shown (Fig. 5). For anticyclonic eddies, no significant difference between the two model configurations, without (INALT20r) and with (INALT60) submesoscale representation, is apparent, although INALT60 shows a slightly faster decline after day 75. For cyclonic eddies, the initial SSH anomaly is slightly larger in INALT60, though this difference diminishes within the first weeks of tracking. Schubert et al. (2019) showed that SSH anomalies in INALT60 agree well with observations, while INALT20r tends to underestimate the strength of cyclones and small anticyclones. They further suggest that submesoscale processes strengthen mesoscale eddies, in particular cyclones. Indeed, the initial SSH anomaly of cyclones here is slightly larger in INALT60 than in INALT20r at the start of the tracking period, though this difference is not continuous over time. That no large differences are apparent overall may partly be explained by the selection criterion applied here. Only dynamically long-lived eddies that persist well beyond the

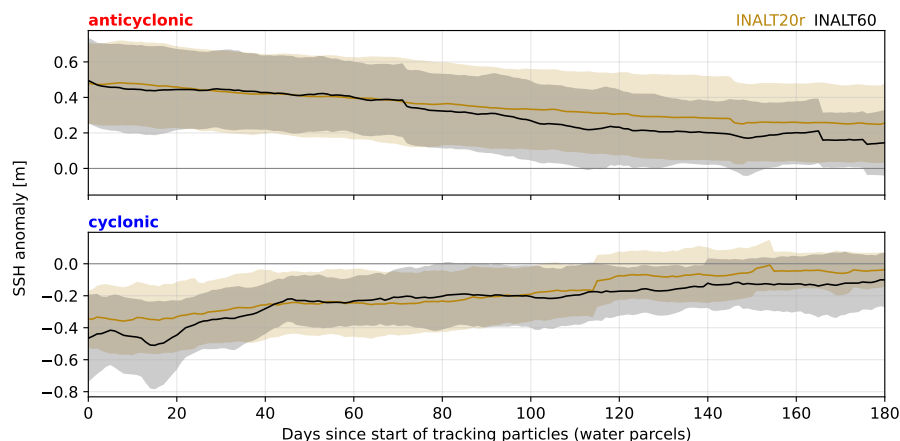


Figure 5. Dynamical decay Sea surface height (SSH) anomaly at the eddy centre for anticyclonic (top) and cyclonic eddies (bottom) since crossing the GoodHope line in INALT20r (gold) and INALT60 (black) relative to the 2012–2017 climatological mean at the respective grid point. The ensemble mean (thick) and standard deviation (shading) are scaled by the initial eddy volume.

285 GoodHope crossing are considered. Shorter-lived or weaker eddies, which might otherwise reveal more pronounced differences between the configurations, are therefore excluded from the analysis. Furthermore, the volume-weighted ensemble emphasises large Agulhas Rings, for which the two configurations show similar SSH amplitudes, while the smaller anticyclones that differ more strongly between configurations (Schubert et al., 2019) contribute relatively little to the ensemble mean shown here.

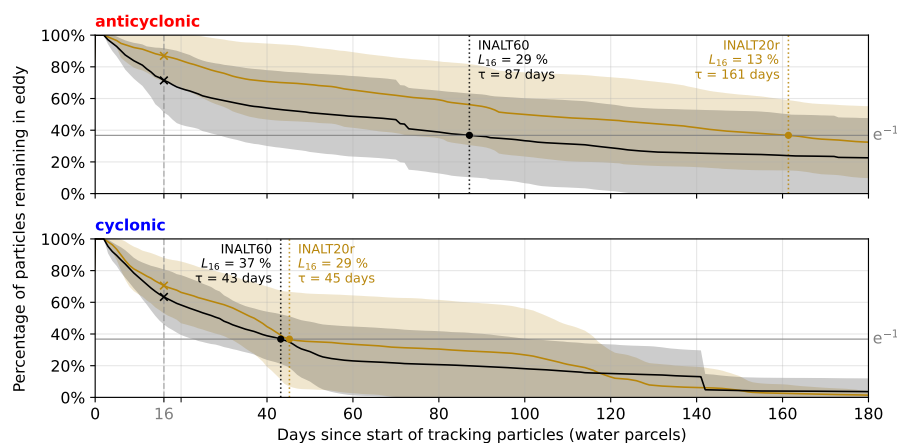


Figure 6. Retention times Amount of particles remaining in anticyclonic (top) and cyclonic eddies (bottom) since crossing the GoodHope line in INALT20r (gold) and INALT60 (black). The ensemble mean (thick) and the standard deviation (shading) are scaled by the initial eddy volume. The intersections of the curves with the e^{-1} threshold (horizontal thin grey) marked by a filled circle give a retention timescale τ and the crosses mark L_{16} , the amount of particles lost after the first 16 days.



While the dynamical surface signature thus evolves similarly in both configurations, it remains unclear whether submesoscale processes nonetheless affect the ability of eddies to retain and transport water masses. The Lagrangian simulations allow a statistical assessment of how effectively eddies of both polarities retain their water masses across the two model configurations INALT20r and INALT60. Counting the fraction of originally seeded particles that remain within their source eddy at each time step yields a retention curve that declines continuously over time for each individual eddy. These curves are ensemble-averaged across all eddies of the same polarity and model configuration, weighted by the initial particle count (Fig. 6). Given the uniform seeding with the same spacing, this weight is proportional to the initial eddy volume, allowing the retention timescales to be interpreted in terms of the water volumes carried by each eddy, potentially together with their associated hydrographic properties. Splitting and merging events within the same polarity are accounted for and do not interrupt the tracking, as the retention criterion is evaluated independently at each time step based on the daily eddy masks rather than specific eddy tracks, as described above. A particle found within a coherent eddy structure of the correct polarity at two consecutive time steps is therefore considered retained, whether it remains in the same eddy or transitions into a split or merged successor. Part of the retention signal reported below may thus also reflect redistribution into such successors not only persistence within a single eddy (Sect. 2.4).

For cyclonic eddies, the retention curves of INALT20r and INALT60 are closely aligned, with both configurations reaching the e^{-1} (36.8 %) retention level after nearly identical times (45 and 43 days, respectively). However, this crossing point alone is misleading. Both mean curves converge only temporarily around e^{-1} , while INALT60 remains moderately less retentive than INALT20r for the first 120 days, as reflected for example in the larger fraction of particles lost within the first 16 days L_{16} (37 % in INALT60 compared to 29 % in INALT20r). The sharp decline in the cyclonic curves beyond approximately 140 days reflects the decreasing number of eddies contributing to the ensemble at that point and should not be interpreted physically. Beyond the limited sample size, the representation of cyclonic eddies in INALT20r may itself be a restricting factor. Without submesoscale dynamics in the non-permitting configuration, strong cyclones in particular are less well represented when comparing to observations (Schubert et al., 2019), making a meaningful comparison of water mass retention between the two configurations more difficult for this eddy type. Anticyclonic eddies, predominantly Agulhas Rings, are considerably more retentive in both configurations, and show a strong sensitivity to representation of submesoscale processes. In INALT60, anticyclones lose their water parcels about twice as fast as in INALT20r, with retention timescales of 87 and 161 days, respectively, and on average already 29 % of particles lost after 16 days compared to 13 %. This systematic difference points to a direct role of submesoscale processes in eroding the material coherence of anticyclonic eddies in the Cape Basin. Idealised single-eddy simulations by Brannigan et al. (2017) find that submesoscale instabilities are associated with smaller scales in cyclones than in anticyclones. While they are resolved in anticyclones with 2 km grids, which is slightly coarser than INALT60, cyclones require a finer resolution of 0.25 km. The associated filaments rotate outward in anticyclones but inward in cyclones, concentrating submesoscale activity at the eddy rim in anticyclones and near the centre in cyclones (Shi et al., 2024). As retention is by definition only lost once a particle crosses the eddy boundary, this peripheral erosion in anticyclones translates directly into the retention signal, whereas a comparable disturbance confined to the cyclone's centre need not do so. Note that using

the outermost rather than the characteristic contour (as defined in Sect. 2.4) adds only a few days to the retention timescale, indicating that this choice is not relevant for the results.

325 Direct comparison of the specific retention timescales with other studies is limited by varying definitions of coherence (see Introduction) and how they are implemented. Retention timescales for eddies in other regions, for example the Gulf of Mexico (Bello-Fuentes et al., 2021), the East Australian Current System (Cetina-Heredia et al., 2019), or across the Pacific, Indian, and Southern Oceans and the Mediterranean Sea (Condie and Condie, 2016), are of similar magnitude for both polarities, unlike the asymmetry found here. The high retention within anticyclones is a special feature to the Agulhas system. Agulhas Rings are
 330 known to be exceptionally long-lived compared to other anticyclones (Nencioli et al., 2018; Casanova-Masjoan et al., 2017), pointing to their pronounced role for the global overturning circulation.

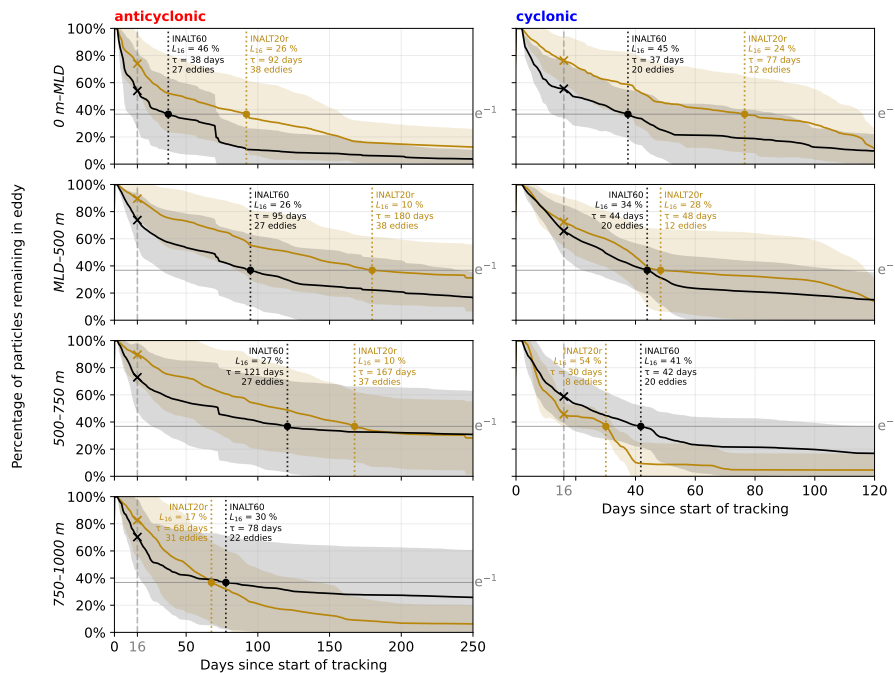


Figure 7. Depth dependency Amount of particles remaining in anticyclonic (left) and cyclonic (right) eddies as a function of days since the start of tracking as in Fig. 6, but shown separately for four depth layers: surface mixed layer (0 m–MLD), MLD–500 m, 500–750 m, and 750–1000 m (anticyclonic only).

The depth-dependent retention curves extend the picture established above by revealing how coherence varies throughout the water column (Fig. 7). Particles are grouped according to the depth layer in which they were released. Four layers are considered: the surface mixed layer, below the mixed layer but above 500 m, 500 to 750 m, and 750 to 1000 m depth, of which the latter is investigated only for anticyclonic eddies, as cyclones in both configurations rarely extend beyond 750 m, leaving insufficient particle numbers for robust statistics at greater depths. To attribute each particle to an initial depth layer, the mixed layer depth is determined once at the time of eddy release (crossing of GoodHope). MLD varies across the ensemble,
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typically ranging between 11 and 294 metres depending on season and eddy characteristics. The retention analysis is performed as before, but for each release depth cluster individually. Particles are thereby not required to remain within their initially attributed depth layer and vertical movement within or across layers along their trajectory does not affect whether a particle is classified as retained.

For anticyclonic eddies, the difference in retention is consistent across all depth layers down to 750 m, with particle numbers from INALT60 declining faster than those of INALT20r in each layer. However, the relative difference between the two configurations decreases with depth, and in the deepest layer considered (750–1000 m) the curves converge and even show a reversal after approximately 65 days. Largest retention across both configurations is found below the mixed layer depth, pointing to the subsurface core as the dynamically most coherent part of the eddy. This is a feature that also dominates the overall retention signal (Fig. 6) given the larger number of particles seeded at these depths. Shielded from direct atmospheric forcing and instabilities concentrated in the upper ocean, the subsurface eddy core is less susceptible to erosion by surface-intensified submesoscale fronts and filaments (e.g. Schubert et al., 2020; Laxenaire et al., 2019; McWilliams, 2016), which is also evident in the decreasing model difference with depth.

For cyclonic eddies, the depth separation reveals a distinct difference to the combined picture. Within the surface mixed layer, retention in INALT20r exceeds that of INALT60, similar to the pattern seen for anticyclones, but this layer contributes less to the overall retention signal given the smaller particle numbers compared to the MLD–500 m layer, which dominates in volume. The 500–750 m layer for cyclones needs to be interpreted carefully, as the number of particles reaching these depths may be insufficient for robust statistics beyond the first few weeks of tracking, particularly in INALT20r where cyclones tend to be shallower (see Fig. 3d). As a result, the overall cyclonic retention signal is dominated by the MLD–500 m layer, with both the surface mixed layer and the 500–750 m layer contributing relatively little due to their smaller particle numbers.

Such a systematic, three-dimensional view of particle retention across an ensemble of eddies over several years in the same region has, to our knowledge, not been presented before. A comparison in this direction is given by Condie and Condie (2016), who considered two fixed depth levels across a set of individual eddies in different regions. They found shorter retention times near the surface than at depth for cyclonic eddies, but the opposite for anticyclonic eddies, for which the retention was longer near the surface. Here, the subsurface core is the most retentive part of the eddy for both polarities. This discrepancy may partly be due to their fixed-depth approach with only horizontal particle advection, which cannot capture particles migrating between depth layers or the vertical structures resolved here, which will be discussed further below.

To identify processes that may drive the systematic difference in retention between INALT20r and INALT60, a representative case study is presented in Fig. 8. For each configuration, one anticyclone that crossed the GoodHope line in austral winter (June 2014) was selected based on its retention curve closely following the respective ensemble mean (Fig. 8c), deviating by no more than 14–16 % at any point during the first 120 days. The early ~30 % drop in retained particles within the first two weeks in INALT60 (Fig. 8c) is representative of a large part of the ensemble, in which 37 % of anticyclones exhibit a comparable drop of at least 30 % within the same window. Though, the two selected eddies are to be understood as illustrative examples. A systematic (e.g. ensemble-based composite) analysis remains beyond the scope of this study and is left for future work.

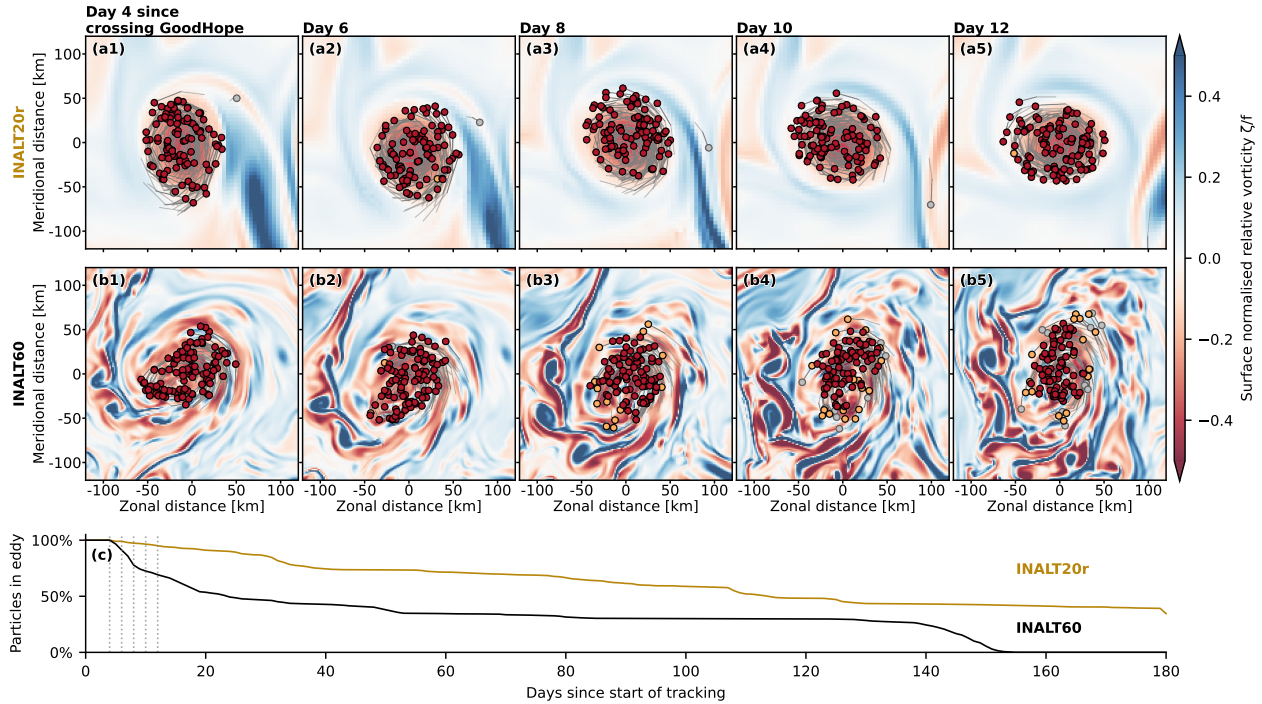


Figure 8. Water parcels leaving an Agulhas Ring Temporal evolution of a representative Agulhas Ring in the Cape Basin in (a1–5) IN-ALT20r and (b1–5) INALT60. For each configuration, one anticyclone was selected whose particle retention (c) closely follows the ensemble mean (see Fig. 6). Both eddies crossed GoodHope in June 2014. Rows (a) and (b) show surface normalised relative vorticity ζ/f at days 4, 6, 8, 10, and 12 after crossing the GoodHope line. Superimposed on each panel are 100 randomly selected Lagrangian particles, coloured red if still within the eddy core as defined by the retention metric (Sect. 2.4), orange if outside the core but within the outermost TOEddies contour, and grey if outside both boundaries. Attached grey lines show daily mean particle trajectories over the preceding two days. Panel (c) shows the individual retention curves, with vertical dashed lines marking the days shown in rows (a) and (b).

The two eddies evolve remarkably differently. In INALT20r, the ring loses water parcels gradually and continuously, with particles departing slowly from its periphery over the entire tracking period, and the surrounding flow field remains largely concentric throughout (Fig. 8a). In INALT60, by contrast, a sharp drop of approximately 30 % in retained particles occurs within the first two weeks of tracking, coinciding with a flow field dominated by filaments and submesoscale vortices, as illustrated by the surface normalised relative vorticity (Fig. 8b). From around day 8 onward, particles leave the eddy preferentially at its southeastern and northeastern flanks. The small-scale features appear to actively draw water parcels out of the eddy core. One process that could drive such exchange at the eddy rim is mixed-layer baroclinic instability, which is investigated in the following. Such instabilities are a key driver of submesoscale dynamics in the surface mixed layer (Boccaletti et al., 2007), where the difference in retention timescales between the two configurations is most pronounced.

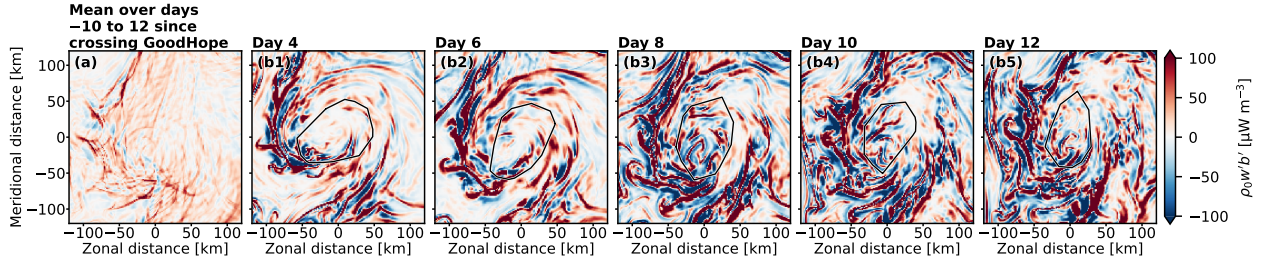


Figure 9. Mixed-layer instability Vertical buoyancy flux $\rho_0 w' b'$ averaged over 0–60 m depth for the same anticyclonic eddy in INALT60 as shown in Fig. 8b. This depth range approximately corresponds to the mixed layer depth of this eddy at the time of release. Fields are computed from daily mean output at days 4, 6, 8, 10, and 12 after crossing the GoodHope line. Anomalies are defined relative to the eddy-centred mean over a period starting 10 days prior to the crossing and ending 12 days after. The black contour outlines the convex hull of the Lagrangian particles identified as belonging to the eddy core by the retention metric (Sect. 2.4, red in Fig. 8b).

At a mixed layer front, horizontal density gradients store eddy available potential energy (EAPE) that can be released through baroclinic instability, generating submesoscale mixed layer eddies (Schubert et al., 2020). EAPE of a front increases with its vertical extent, making this process particularly active in winter when the mixed layer is deepest (Capuano et al., 2018). The mean vertical buoyancy flux $VBF = \rho_0 \overline{w' b'}$, with reference density $\rho_0 = 1025 \text{ kg m}^{-3}$ and anomalies of the vertical velocity w and buoyancy b (as defined in Sect. 2.2.2) relative to their mean over the period of 10 days before and 12 days after the GoodHope crossing, quantifies this energy transfer from the front to the submesoscale eddies (von Storch et al., 2012). Figure 9a shows that VBF is mainly positive during the investigated period around the INALT60 anticyclone from Fig. 8b. This indicates a source of eddy kinetic energy (EKE) by transfer from EAPE and thus baroclinic mixed-layer instability. The spatiotemporal evolution of the instantaneous $\rho_0 w' b'$ (Fig. 9b) displays larger areas of positive fluxes developing progressively along the eddy boundary, most pronounced at the southeastern to northeastern flank by day 6, highlighting the active phase of the baroclinic instability. Subsequently, the resulting kinetic energy is visible in the form of submesoscale vortices (Fig. 8b), while $\rho_0 w' b'$ becomes spatially fragmented. The timing of this sequence coincides with the onset of particle loss seen in Fig. 8c, suggesting that mixed-layer instability is a key driver of the early retention drop in INALT60.

While the case study illustrates the role of mixed-layer instability for one representative anticyclone, the aggregated particle trajectories from all simulations reveal systematic spatial patterns where water parcels are expelled from the eddies across the Cape Basin (Fig. 10a). For anticyclonic eddies, the spatial exit distribution differs distinctly between the two configurations. In INALT20r, particles leave the eddy across a widespread area extending into the northwestern Cape Basin towards the Walvis Ridge, corresponding to the longer and more undisturbed ring paths seen in Fig. 3a and the slower retention loss evident in Fig. 6. The SSH standard deviation contours (black lines in Fig. 10a) further indicate a more northerly and narrower mean ring path in INALT20r compared to INALT60 and observations (Schubert et al., 2019). In INALT60, exits are concentrated in the central Cape Basin, closer to the GoodHope line. This reflects the faster loss of water parcels already evident in the retention curves, in line with the fast decay of Agulhas Rings within the Cape Basin investigated by van Sebille et al. (2010).

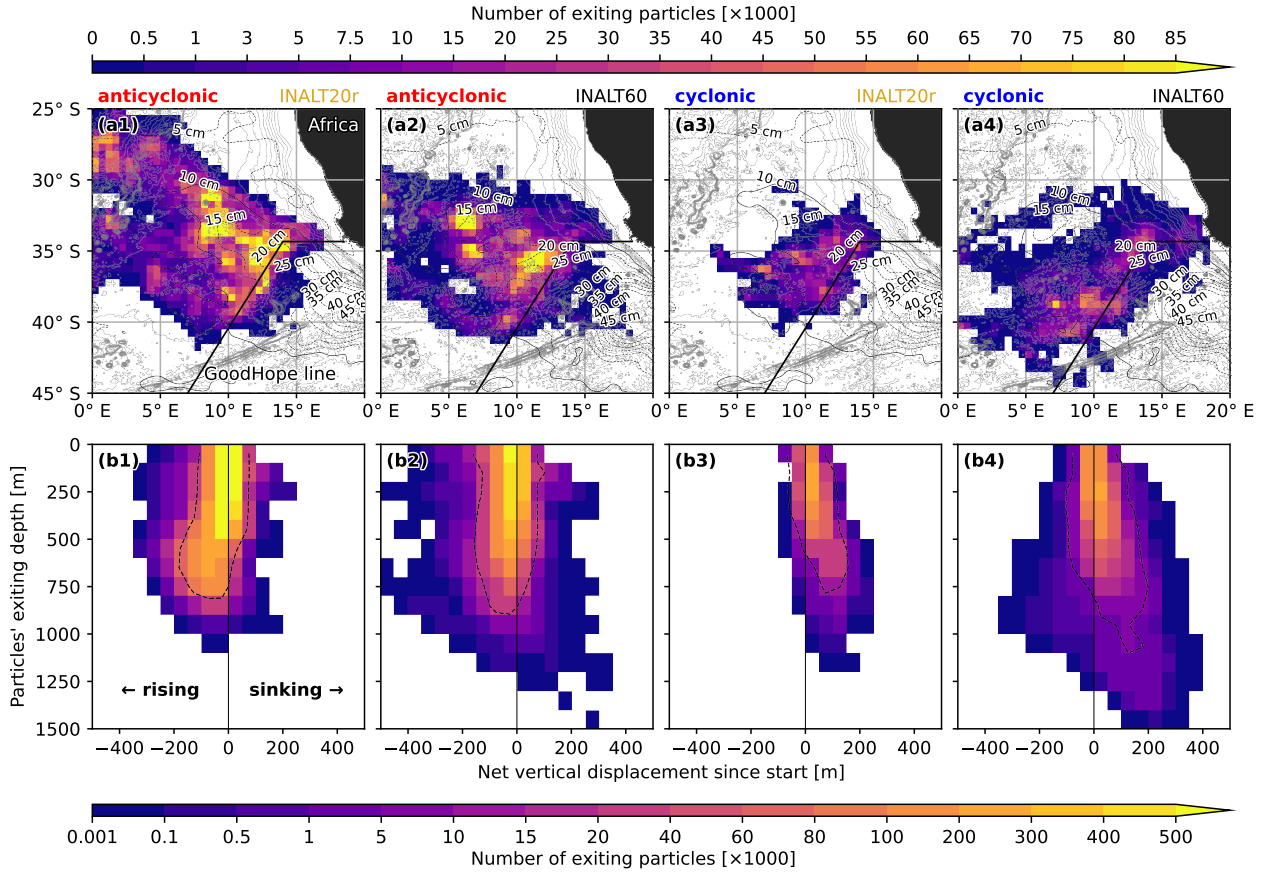


Figure 10. Exit maps Maps of the Cape Basin illustrating the locations where Lagrangian particles most likely leave an anticyclonic (a1–2) or cyclonic eddy (a3–4) in the INALT20r (left) and INALT60 (right) simulations. Black contours indicate the standard deviation of linearly detrended sea surface height (2012–2017) in 5 cm intervals, with the 10 cm contour drawn as a solid line. Grey thin lines mark the bathymetry in 500 m intervals. Row (b) displays the net vertical displacement of particles at the time of leaving the eddy, for anticyclonic (b1–2) and cyclonic eddies (b3–4) in INALT20r (left) and INALT60 (right). Particles are binned by their exit depth (y-axis) and the net vertical displacement accumulated between the start of tracking (since crossing the GoodHope line) and the moment of exit (x-axis), where positive (negative) values indicate net sinking (rising) on a downward-positive depth axis. The black dashed contour encloses 95% of all exiting particles within each category. Only particles that left the eddy within the tracking time of a year are considered.

For cyclonic eddies, the spatial exit patterns are more similar between the two configurations. With exits concentrated in the southeastern Cape Basin, this shows their generally shorter lifetimes (Chelton et al., 2011) and their tendency to travel more (south-)westward, i.e. transverse to the anticyclones. In both configurations and for both eddy polarities, the vast majority of particles proceed further and exit into the Cape Basin rather than returning towards the retroflection region, confirming that the GoodHope line serves as an effective separator of the two dynamical regimes.



The net vertical displacement of water parcels at the time of exit reveals a systematic difference between the two eddy types (see Fig. 10b) and gives a measure of the vertical velocities. Particles leaving anticyclonic eddies show a tendency towards net rising, while particles exiting cyclonic eddies show a clearer net downward displacement. This asymmetry is consistent with the vertical velocity structure expected during eddy decay. The relaxation of the density perturbations associated with eddy decay results in upwelling within anticyclones and downwelling in cyclonic features (McGillicuddy Jr, 2016). Furthermore, cyclonic vorticities and associated downward velocities are generally stronger than their anticyclonic counterparts, because vortex stretching and ageostrophic instabilities limit anticyclonic vorticity to $\zeta/f \gtrsim -1$, whereas cyclonic vorticity has no such constraint (McWilliams, 2016). This may explain the more pronounced net sinking signal observed for cyclones in both configurations. Vertical velocities within and around mesoscale eddies are typically of order $10\text{--}40\text{ m d}^{-1}$ (Klein and Lapeyre, 2009), with the largest values found at eddy boundaries and in submesoscale filaments rather than in the eddy interior. The mean vertical velocity experienced by particles averaged over their entire time within the eddy is approximately 6 m d^{-1} in INALT20r and 14 m d^{-1} in INALT60, being at the lower end of this range because this reflects a long residence time rather than isolated active periods. On individual days, considerably larger values are found in the submesoscale-permitting configuration at the eddy rims. A similarly strong sensitivity of vertical Lagrangian transport to resolved submesoscale dynamics has been shown by Liu et al. (2021) comparing two model configurations of the Gulf of Mexico with similar horizontal resolutions as used here (1 km vs. 5 km). These vertical velocities are dynamically important as they drive an ageostrophic secondary circulation at eddy boundaries, with upwelling on the lighter side and downwelling on the denser side of the frontal zone, which in turn generates further vorticity through vortex stretching (McWilliams, 2016). This circulation facilitates the exchange of water parcels between the eddy interior and the surrounding ocean, contributing to the water parcel loss quantified by the retention curves. While no systematic difference in the direction or magnitude of vertical displacement is apparent between INALT20r and INALT60, a fraction of particles in INALT60 shows higher experienced vertical velocities and therefore more extreme vertical displacements in both directions, reflecting the more energetic submesoscale dynamics at eddy boundaries in the submesoscale-permitting configuration.

Some important aspects and limitations of the present analysis should be kept in mind when interpreting these results. First of all, the material retention timescales shown here, of the order of months, are considerably shorter than the lifetimes of Agulhas Rings tracked from satellite altimetry, which frequently persist for more than a year as they cross the South Atlantic (Laxenaire et al., 2018, 2019, 2020; Ioannou et al., 2024). Part of this difference reflects the distinction between kinematic and material coherence introduced above: altimetric tracking follows the persistence of the dynamical surface signature, whereas the Lagrangian metric used here follows the water parcels themselves. The timescales presented here should thus not be understood as eddy lifetimes, but rather material retention timescales. An eddy can have a coherent dynamical signature long after part of its original water has been exchanged with the surroundings (compare the SSH anomaly in Fig. 5 with the retention curves in Fig. 6). However, the difference is unlikely to be only definitional. In situ observations show that the cores of Agulhas Rings retain the thermohaline characteristics of their formation region for months to years (Laxenaire et al., 2019, 2020; Barabinot et al., 2025), which is direct evidence of thermohaline coherence and implies that comparatively little core water is exchanged over the eddy lifetime. Such long-lived thermohaline coherence provides an observational bound on material coherence, and it



is longer than the retention timescales found here. This suggests that the modelled retention, and in particular the fast initial loss, may partly overestimate the true rate of core water exchange. The Lagrangian simulations are performed offline using daily-mean velocity fields, the highest temporal resolution saved for the full water column, as the native model time step is of the order of minutes. This offline approach is standard in Lagrangian ocean analysis, but daily averaging has two opposing effects on the results that are not easily disentangled. It removes part of the high-frequency submesoscale variance associated with the transient fronts and filaments identified in this section as drivers of water parcel loss. Therefore, the apparent submesoscale impact on retention is reduced, while retention itself increases. On the contrary, temporal averaging also smooths the eddy boundary, making it more permeable and instead reducing retention. As INALT60 carries more energy at finer and faster scales than INALT20r (Schubert et al., 2019), the two configurations are unlikely to be affected equally, and the resulting bias on the retention difference between them cannot be established from the present simulations. Advection on the native model time step would be needed to bound these effects. Yet, working offline with daily means offers flexibility for testing and refining the Lagrangian retention framework within an otherwise large and computationally expensive ocean model, particularly INALT60.

Regarding the α -criterion, we note that it was originally formulated for mesoscale eddy boundaries after filtering scales below approximately 10 km. Resolved submesoscale features and internal gravity waves can locally produce extreme EPV-component ratios that blur this boundary (Barabinot et al., 2024). Applied without such pre-filtering to the submesoscale-permitting INALT60, the criterion may therefore locally register resolved submesoscale structures at the eddy rim as boundary distortions. This effect is mitigated by the spatial relaxation and temporal tolerance built into the retention metric (Sect. 2.4), which prevent submesoscale intrusions from being misclassified as a permanent loss of coherence. As a further sensitivity test, both configurations were regridded to a common $1/4^\circ$ resolution, which is even coarser than the 10 km filter suggested by Barabinot et al. (2024). The resulting retention curves were qualitatively similar to those obtained without regridding (Figs. 6, 7), though the exact quantitative differences were not systematically evaluated. Lastly, as the retention metric counts a particle as retained when it passes into a coherent successor eddy of the same polarity after a splitting or merging event (Sect. 2.4), it aggregates persistence across a whole part of the eddy network rather than tracking the fate of individual eddy cores. Consequently, it cannot resolve how much of the retained water remained within a single structure versus how much was redistributed across several successors, which would require tracking the splitting and merging network itself during the Lagrangian simulations, and could be future work.

Nonetheless, the overall results above highlight the role of submesoscale processes in eroding the material coherence of anticyclonic eddies in the Cape Basin, with direct implications for the distribution of Agulhas water masses into the South Atlantic.

4 Summary and conclusions

In this study, we investigated the role of submesoscale processes in shaping the water mass retention of mesoscale eddies in the Cape Basin, using offline Lagrangian particle tracking in two ocean model configurations that differ in their representation of submesoscale dynamics: the eddy-rich but non-submesoscale-permitting INALT20r and the submesoscale-permitting



INALT60 (Schwarzkopf et al., 2019; Schubert et al., 2019; Schubert and Schwarzkopf, 2026). Central to this approach is a three-dimensional eddy detection combining surface-based *TOEddies* tracking (Laxenaire et al., 2018) with the EPV-based α -criterion (Barabinot et al., 2024) at depth. This three-dimensional formulation was introduced here for the first time.

The dynamical surface signature of both anticyclonic and cyclonic eddies, as measured by the SSH anomaly at the eddy centre, evolves similarly in both configurations following the crossing of the GoodHope line, which separates the retroflection region from the central Cape Basin. There is no systematic difference attributable to submesoscale representation, though cyclones exhibit a slightly larger initial SSH anomaly in INALT60. In contrast, the Lagrangian retention curves reveal distinct differences between the two configurations for anticyclonic eddies. In INALT60, anticyclones lose their water parcels almost twice as fast as in INALT20r, with e^{-1} retention timescales of 87 and 161 days, respectively, and a fast particle loss after 16 days of 29 % and 13 %. This difference is consistent across all considered depth layers down to 750 m, though it decreases with depth, pointing to the responsible submesoscale processes in the upper part of the water column. The subsurface core is the most coherent part of the eddy in both configurations. For cyclonic eddies, the results point in a similar direction, though this comparison is limited by the smaller sample size and the weaker representation of strong cyclones in INALT20r.

A case study of a representative Agulhas Ring identifies mixed-layer baroclinic instability as a key mechanism driving the enhanced water mass loss in INALT60. Positive vertical buoyancy flux develops progressively at the eddy boundary, indicating the conversion of eddy available potential energy to eddy kinetic energy. The resulting submesoscale vortices draw water parcels from the eddy, producing a fast particle drop visible in the INALT60 retention curve. This process is not well represented in INALT20r, where the flow field remains largely concentric and particle loss is gradual.

The spatial distribution of particle exits and their net vertical displacement reveal further asymmetries. In INALT20r, particles exit across a widespread area extending into the northwestern Cape Basin, consistent with the longer undisturbed ring paths in this configuration. In INALT60, exits are concentrated closer to the GoodHope line, reflecting the faster retention loss. Particles leaving anticyclonic eddies show a slight tendency towards net rising, while those exiting cyclonic eddies show net downward displacement, which is a known distinction in vertical velocity structure between the two eddy polarities (McGillicuddy Jr, 2016).

These findings have direct implications for ocean modelling and for our understanding of the inter-ocean exchange and its role in the Atlantic heat and salt budget. Eddy-rich but non-submesoscale-permitting configurations, such as those commonly used at resolutions of $1/10^\circ$ to $1/20^\circ$, may systematically overestimate the retention of water masses within Agulhas Rings. As a consequence, the release of heat and salt anomalies into the Cape Basin and subsequently into the South Atlantic may be delayed and spatially displaced compared to submesoscale-permitting simulations. Capuano et al. (2018) showed that only at submesoscale-resolving resolution models can correctly depict the inter-ocean transfer of thermocline waters and the associated heat and salt anomalies penetrating into the Atlantic. Given that Agulhas leakage is a key source of heat and salt for the South Atlantic, which ultimately feeds into the Atlantic Meridional Overturning Circulation (AMOC), such biases in eddy retention could affect the simulated strength and variability of the large-scale overturning. Longer retention timescales mean that Agulhas water remains longer confined within eddies, limiting exchange across ring boundaries and reducing modification by ambient waters. The consequent differences in water mass properties propagate downstream. Salt anomalies are reflected in



the North Brazil Current (Biaosoch et al., 2009), from where temperature and salinity anomalies continue northward into the North Atlantic (Schulzki et al., 2024). Thus, the properties of water masses supplied to the AMOC depend critically on the modifications they experience within the Cape Basin during their transit (Rühs et al., 2019).

Beyond the physics, the retention timescales quantified here are relevant for the dispersal of marine organisms. Mesoscale eddies are known to act as coherent transport vehicles for plankton and other biological material, or oxygen-depleted water (Schütte et al., 2016; Condie and Condie, 2016). The submesoscale-driven reduction in retention timescales suggests that the biological isolation provided by Agulhas Rings may be considerably shorter than previously assumed from coarser models.

Future work could build on this analysis in several directions. The case study presented above relied on two representative eddies to illustrate the mixed-layer baroclinic instability. Extending this to a systematic, ensemble-based composite analysis across many eddies could reveal more information on this mechanism and its representativeness. Tracking the eddy identity within the wider eddy network during the Lagrangian simulations would further allow a distinction between water retained within a single structure and water redistributed across successive eddies. It would also be of interest to look at the vertical structure of particle exchange in more detail. While we characterised the net vertical movement of particles and the depth at which they leave the eddy, the entry depth and water mass origin, together with the associated vertical velocities during specific stages of eddy decay, were not examined here. This could be combined with a targeted tracking of the heat and salt carried by the retained and exiting water masses, connecting the retention timescales derived here more directly to estimates of the Agulhas leakage heat and salt transport. Lastly, the submesoscale-permitting resolution in INALT60 was only feasible within a regionally nested configuration. Applying such resolution across the global domain, potentially even coupled to the atmosphere, and running such simulations over the multi-decadal timescales relevant to AMOC variability remain computationally out of reach. A submesoscale parametrisation is therefore needed that represents not only the dynamical surface signature of Agulhas Rings but also their water mass retention, the properties of these water masses, and their downstream imprint on different regions of the Atlantic.

Appendix A: Retention timescales

Since submesoscale processes can promote the exchange of water parcels across eddy boundaries (e.g. McWilliams, 2016; Sinha et al., 2019), enhanced particle loss is expected to occur at the outer and less coherent parts of an eddy on comparatively short timescales, while the coherent core, better shielded from these processes, should retain particles over a longer time. This suggests that particle retention may not be controlled by a single characteristic timescale, but rather by two distinct scales operating on short and long terms respectively. We test this by fitting a two-timescale (bi-exponential) mixture model to the mean retention curves shown in Fig. 6, separately for each ocean model configuration and eddy polarity. Following Lawless (2003), we treat each tracked particle population as a mixture of two individual subpopulations (fast and slow), both described by its own exponential function and related in proportions p_{fast} and p_{slow} with $p_{\text{fast}} + p_{\text{slow}} = 1$. This gives

$$S(t) = p_{\text{fast}} \cdot e^{-t/\tau_{\text{fast}}} + p_{\text{slow}} \cdot e^{-t/\tau_{\text{slow}}} \quad (\text{A1})$$



where t is the time in days since the start of tracking the particles, and τ_{fast} and τ_{slow} are the fast and slow characteristic decay timescales. In the terminology of Lawless (2003), $S(t)$ is a survivor function, which is interpreted here as retention within the eddies at time t .

Table A1. Bi-exponential mixture model fit parameters for the mean retention curves shown in Fig. 6, for each model configuration and eddy polarity. τ_{fast} and τ_{slow} are the fast and slow characteristic timescales, p_{fast} and $p_{\text{slow}} = 1 - p_{\text{fast}}$ the corresponding proportions, and $\langle \tau \rangle$ the weighted mean retention time. N_{eddies} is the number of eddies contributing to the mean.

Configuration	Polarity	τ_{fast} [days]	p_{fast}	τ_{slow} [days]	p_{slow}	$\langle \tau \rangle$ [days]	N_{eddies}
INALT20r	anticyclonic	17	10 %	>180*	90 %	>163*	38
INALT60	anticyclonic	16	32 %	149	68 %	106	27
INALT20r	cyclonic	11	12 %	65	88 %	59	12
INALT60	cyclonic	21	51 %	84	49 %	52	20

* The bi-exponential fit extrapolates beyond the 180-day observation window. This value should be interpreted as a lower bound rather than a well-constrained estimate.

Applying this decomposition to Fig. 6 yields, for each configuration and eddy polarity, a fast and slow timescale together with their respective proportions, and a weighted mean retention time (Table A1). Results differ considerably between the configurations: For anticyclones in INALT60, about a third of particles is attributed to the fast-decaying subpopulation, with a characteristic timescale of $\tau_{\text{fast}} = 16$ days, while the remaining two thirds follow the slower, core-retention timescale of $\tau_{\text{slow}} = 149$ days. This agrees with the two-timescale framework outlined above. However, for INALT20r, the fast subpopulation accounts for only 10–12 % of particles across polarities, so that the mean retention curve is largely dominated by the slow component. Note that τ_{fast} and τ_{slow} alone are not directly comparable across configurations. They must always be interpreted together with their proportions, which differ between INALT20r and INALT60. For example, for cyclones, INALT60 shows $\tau_{\text{fast}} = 21$ days with $p_{\text{fast}} = 51$ %, whereas INALT20r has a shorter $\tau_{\text{fast}} = 11$ days albeit with a lower $p_{\text{fast}} = 12$ %. This does not mean that INALT20r exhibits a stronger fast-loss signal, possibly attributable to submesoscale processes, but just a smaller subpopulation undergoing it.

This interdependence between the timescales and their proportions complicates a direct and intuitive comparison of the fitted parameters across configurations and polarities. Moreover, since p_{fast} is small for INALT20r, its mean retention curve can be closely approximated by a single exponential function anyway. Lastly, because the underlying loss curves are not smooth, particularly in panels combining few eddies as it is the case for Fig. 7, the fitted decomposition can be disproportionately determined by individual drops in particle number that arise from events in a single eddy when many particles are lost at once. For these reasons, we use two simpler, model-free measures in the main text and figures instead. First, the crossing of the curve with e^{-1} , which is by definition the characteristic timescale τ of a mono-exponential function. For INALT60, where a genuine fast-loss component is present, it provides a conservative yet comparable estimate of the mean retention time. To still capture the fast initial loss signal without requiring a bi-exponential fit, which is not always well constrained, we use a second number:



L_{16} , the fraction of particles lost within the first 16 days, the rounded mean value of the four fitted τ_{fast} from above, applied as a common window. Both measures are directly comparable across all configurations and polarities.

Despite the interpretive limitations of the individual fitted parameters of the decomposition, the weighted mean retention times $\langle \tau \rangle$ (Table A1) point to a similar result as later shown in Sect. 3: $\langle \tau \rangle$ is shorter for the submesoscale-permitting INALT60 than for INALT20r regardless of eddy polarity, and this difference is especially pronounced for anticyclones while it is not that clear for cyclonic eddies.

Code and data availability. The submesoscale-permitting ocean model INALT60 is published (Schubert and Schwarzkopf, 2026), and INALT20r is available upon request. Eddy detection was performed using TOEddies v0.7 (https://gitlab.in2p3.fr/ipsi/lmd/dpao/Detection_eddies) and the Lagrangian simulations are based on Parcels v3.1.2 (van Sebille et al., 2025). All scripts and notebooks used for eddy detection, particle tracking and analysis are made available by Mock (2026).

Author contributions. LCM, RS and AB designed the study. LCM, SS and LG contributed to refining the eddy detection methods, with LG adapting TOEddies for use with INALT model output. LCM ran the Lagrangian particle simulations with Parcels and the eddy detections, and performed the analysis. LCM prepared the manuscript with contributions from all co-authors. All authors contributed to the discussion and interpretation of the results.

Competing interests. The authors declare that they have no conflict of interest.

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