

# Eddies on the Edge: Cyclonic Frontal Dynamics along the Agulhas Current

**Gustav Rautenbach**

`g.rautenbach@saeon.nrf.ac.za`

South African Environmental Observation Network, Egagasini Node

**Steven Herbette**

Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Univ. Brest CNRS - IRD - Ifremer

**Jennifer Veitch**

South African Environmental Observation Network, Egagasini Node

**Pierrick Penven**

Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Univ. Brest CNRS - IRD - Ifremer

**Gildas Cambon**

Laboratoire d'Océanographie Physique et Spatiale (LOPS), IUEM, Univ. Brest CNRS - IRD - Ifremer

**Michael Roberts**

South African Environmental Observation Network, Egagasini Node

---

## Research Article

**Keywords:** frontal eddies, Agulhas Current, Marine Protected Areas, numerical model, eddy tracking, circulation

**Posted Date:** October 6th, 2026

**DOI:** <https://doi.org/10.21203/rs.3.rs-10165272/v1>

**License:** © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

**Additional Declarations:** No competing interests reported.

---

# Eddies on the Edge: Cyclonic Frontal Dynamics along the Agulhas Current

Gustav Rautenbach<sup>1,2\*</sup>, Steven Herbette<sup>3†</sup>, Jennifer Veitch<sup>1,4†</sup>,  
Pierrick Penven<sup>3†</sup>, Gildas Cambon<sup>3†</sup>, Michael Roberts<sup>2,5†</sup>

<sup>1</sup>South African Environmental Observation Network, Egagasini Node,  
Cape Town, South Africa.

<sup>2</sup>Coastal and Marine Research Unit, Nelson Mandela University,  
Gqeberha, South Africa.

<sup>3</sup>Laboratoire d’Océanographie Physique et Spatiale (LOPS), IUEM,  
Univ. Brest CNRS - IRD - Ifremer, Plouzané, Brest, France.

<sup>4</sup>Nansen-Tutu Center, Marine Research Institute, Department of  
Oceanography, University of Cape Town, Rondebosch, Cape Town,  
South Africa.

<sup>5</sup>Ocean and Earth Science, University of Southampton, Southampton,  
United Kingdom.

\*Corresponding author(s). E-mail(s): [g.rautenbach@saeon.nrf.ac.za](mailto:g.rautenbach@saeon.nrf.ac.za);

†These authors contributed equally to this work.

## Abstract

Cyclonic frontal eddies frequently occur inshore of the Agulhas Current along the east coast of South Africa where numerous Marine Protected Areas (MPAs) have been designated, yet their structure, evolution, and role in coastal circulation remain poorly quantified due to observational limitations. Here, we investigate the frequency, life cycle, and dynamics of these eddies using a realistic ocean simulation combined with an eddy detection algorithm. Over the 5-year simulation, 366 cyclonic frontal eddies were identified, recurring approximately every 5 days and exhibiting a wide range of lifespans (4–42 days), spatial scales (11–28 km), and velocities (translation:  $0.15 - 0.18 \text{ m s}^{-1}$ ; tangential:  $0.1 - 0.74 \text{ m s}^{-1}$ ) that are comparable to local and global observations. Two distinct eddy types are identified in the KwaZulu-Natal (KZN) Bight: stationary eddies confined to the KZN Bight and propagating eddies that advect downstream along the coast. Potential vorticity analysis and Lagrangian particle tracking from a long-lived case study reveals that these eddies are surface-intensified features originating from

the inshore frictional boundary layer of the Agulhas Current. The associated circulation governs their spatio-temporal evolution and drives strong vertical mixing along the coast. Through particle retention and transient counter-currents the frontal eddies strongly influence coastal connectivity, with important implications for MPAs along the South African east coast.

**Keywords:** frontal eddies, Agulhas Current, Marine Protected Areas, numerical model, eddy tracking, circulation

+

## 1 Introduction

The Agulhas Current is the western boundary current of the South Indian Ocean Subtropical Gyre. The current modulates oceanographic conditions along the entire east coast of South Africa (Figure 1). It originates at 27° S, the southern end of the Mozambique Channel, and flows southwestward along the east coast of South Africa (Lutjeharms 2007). With velocities peaking at 1.8 m s<sup>-1</sup>, a horizontal width of 200 km, and a depth extent of 3000 m at 32° S, the Agulhas Current is one of the most intense western boundary currents in the World Ocean (Beal et al. 2015), transporting an average of 76 Sv of warm Indian Ocean water poleward (Gunn et al. 2020; McMonigal et al. 2020). At the southern tip of the Agulhas Bank, near 40° S, it veers abruptly eastward to become a free-flowing jet, the Agulhas Return Current, which forms the southern branch of the South Indian Ocean Subtropical Gyre. This phenomenon, known as the Agulhas Retroflection, is accompanied by the shedding of large anticyclonic eddies (Agulhas Rings) (Lutjeharms and Van Ballegooyen 1988; Schouten et al. 2002), as well as a range of smaller features that make this region one of the most turbulent in the World Ocean (Schubert et al. 2021). Due to their role in the leakage of warm Agulhas water into the South Atlantic, the generation and fate of these turbulent features have recently been scrutinised to better understand their dynamical behaviour and their potential impact on the variability of the Atlantic Meridional Overturning Circulation (Beal et al. 2011).

[Fig. 1 about here.]

From the southern boundary of the Mozambique Channel to the southern tip of the Agulhas Bank, two portions of the Agulhas Current can be distinguished according to their flow characteristics: the northern and southern Agulhas Current (Lutjeharms 2007). South of Gqeberha (26° E), where the continental shelf widens, the Agulhas Current detaches from the coastline and becomes increasingly unstable (Paldor and Lutjeharms 2009). Barotropic and/or baroclinic instabilities lead to the development of shear-edge eddies on the inshore side of the current (Tedesco et al. 2019). The presence of these shear-edge features modifies the circulation on the Agulhas Bank and drives local upwelling that contributes to the nutrient enrichment of surface waters

(Goschen et al. 2015; Malan et al. 2018). Northward of Gqeberha, the Agulhas Current is more stable. Its path shows remarkably little variability, follows the continental slope closely, and remains confined within  $\pm 15$  km of its mean position. The stability of the northern portion of the Agulhas Current has been attributed to topographic steering induced by the steep continental slope (Paldor and Lutjeharms 2009). The occasional passage of cyclonic frontal eddies perturbs the current from its mean path (Figure 1) (Roberts et al. 2016; Guastella and Roberts 2016; Heye et al. 2022; Burgher et al. 2025).

Cold core cyclonic frontal eddies were first identified in the Gulf Stream from current-meter records showing reversals that could not be associated with wind stress or tidal forcing (Lee 1975; Lee and Mayer 1977). Thanks to their cold SST signature in satellite infrared images, they have since been observed along the inshore edge of all western boundary currents systems, including the Agulhas Current (Krug and Penven 2011; Burgher et al. 2025), the Gulf Stream (Lee 1975; Gula et al. 2016), the Kuroshio Current (Liu et al. 2017; Kasai et al. 2002), the East Australian Current (Roughan et al. 2017; Schaeffer et al. 2017), and the Brazil Current (Calil et al. 2021; Rocha and Simoes-Sousa 2022).

The classic model of a cyclonic frontal eddy involves cyclonic circulation and an uplift of isopycnals in the core. This uplift can inject cool, nutrient-rich deep water into the surface euphotic layer, stimulating primary production. The snapshot of modeled sea-surface temperature in Figure 1 shows their distinctive cold core at the surface, surrounded by warm Agulhas Current water, forming sharp thermal fronts between the warm boundary current and the cool cyclonic frontal eddy.

Cyclonic frontal eddies are important dynamical features that drive cross-shore transport (Guastella and Roberts 2016; Pivan et al. 2016) and vertical mixing (Schaeffer et al. 2017; Roughan et al. 2017; Ribbe et al. 2018; Malan et al. 2020), influencing coastal circulation (Heye et al. 2022) and the distribution of nutrients and sediments along the continental shelf (Van der Vaart and de Ruijter 2001; Bryden et al. 2005). Their boundaries are associated with strong horizontal and vertical velocities that lead to intense frontal regions (Barabinot et al. 2024). Using a very high-resolution model ( $\Delta x \approx 300$  m), Gula et al. (2016) identified submesoscale structures within cyclonic frontal eddies in the Gulf Stream that enhance vertical transport in the eddy core and may contribute to productivity within the cyclones and the surrounding continental shelf.

Due to their close proximity to the coast, frontal eddies are efficient mechanisms for entraining, trapping, and transporting coastal water, pollution, nutrients, and larvae within their cores, redistributing them along the coast (Kasai et al. 2002). Heye et al. (2022) showed that cyclonic frontal eddies in the KZN Bight increase particle retention time within Marine Protected Areas (MPA), which can greatly impact the coastal regions. Coastal areas within and downstream of the KZN Bight have received little attention despite the presence of numerous MPAs. The green boxes in Figure 1 mark four MPAs, which are named, from north to south: uThukela, Aliwal Shoal, Protea Banks, and Pondoland. Aiming to ensure sustainable marine resource use and biodiversity preservation, MPAs are intended to have positive impacts on ecosystems and nearby communities (Kasai et al. 2002; Mitarai et al. 2009; Sowman

and Sunde 2018; Mann-Lang et al. 2021). However, connectivity between MPAs can be a double-edged sword: the transport of nutrient-rich, larva-laden waters enhances phytoplankton growth, species richness, and abundance (Kasai et al. 2002; Mitarai et al. 2009), while the transport of plastics and pollutants can have severely negative effects on ecosystem health (Robinson et al. 2017; Hatzonikolakis et al. 2022). Understanding MPA connectivity is therefore vital for effective management and enforcement (Schleyer et al. 2018; Peer et al. 2022). Although the Agulhas Current may initially appear to form a dynamical barrier separating coastal waters from the open ocean and the South Indian Subtropical Gyre, instabilities and cyclonic frontal eddies inshore of the current likely play a key role in mediating both connectivity among MPAs and environmental conditions over the continental shelf.

The KwaZulu-Natal (KZN) Bight is an embayment situated between Richards Bay in the north and Durban in the south (Figure 1). Where the coastline recedes near Richards Bay and the continental shelf widens, a region sheltered from the Agulhas Current is formed. The embayment is characterised by variable flow dynamics, and at the transition between the offshore Agulhas Current and the inshore KZN Bight waters, strong horizontal shear exists (Roberts et al. 2016; Heye et al. 2022). The formation of frontal eddies is initiated when the mean flow (here, the Agulhas Current) becomes unstable, resulting in meanders that form from mixed barotropic and baroclinic instabilities propagating in western boundary currents (Oey 1988; Bowen et al. 2005; Gula et al. 2015; Tedesco et al. 2019). Frontal eddies form and are shed through the transfer of mean energy from the jet to eddy kinetic energy. In baroclinic flows, mean potential energy is transferred due to density differences, whereas in barotropic instability, mean kinetic energy is transferred due to horizontal shear. Tedesco et al. (2019) confirmed that barotropic instabilities dominate in generating frontal eddies in the southern Agulhas Current at Algoa Bay (embayment between Gqeberha and Kenton-on-Sea) and we assume that similar dynamics are at play here. The growth and decay of these structures are strongly influenced by topography.

Frontal eddies are typically short-lived ( $< 4$  weeks) and are characterised by diameters ranging from 10 - 100 km (Lee 1975; Roughan et al. 2017; Burgher et al. 2025). Eddy translational (i.e., propagation of the eddy core) and tangential (i.e., rotational around the eddy core) velocities have been observed to range between  $0.1 - 0.8 \text{ m s}^{-1}$  and  $0.3 - 1.97 \text{ m s}^{-1}$ , respectively (Lee and Atkinson 1983; Everett et al. 2015; Guastella and Roberts 2016). Tangential velocities are generally larger than translational velocities (Nagai et al. 2015; Roughan et al. 2017) and vary across the eddy, with higher velocities along the offshore branch where it merges with the boundary current flow (Schaeffer et al. 2017). The inshore counter-flow is inhibited by the land boundary.

The translational velocities of frontal eddies in the Gulf Stream ( $0.2 - 0.8 \text{ m s}^{-1}$ ) (Lee and Atkinson 1983) and the East Australian Current ( $0.3 - 0.4 \text{ m s}^{-1}$ ) are typically faster than those in the Kuroshio ( $0.15 - 0.3 \text{ m s}^{-1}$ ) (Itoh and Sugimoto 2008) and the Agulhas Current ( $0.1 - 0.25 \text{ m s}^{-1}$ ) (Burgher et al. 2025). This is typically due to varying shelf depths (James et al. 1999).

A list of cyclonic frontal eddies observed and modeled within the KZN Bight since 2000 is presented in Table 1. Prior to the turn of the century, satellite observations and

modelling capabilities were largely limited by their spatial resolution. The result was that only the large anomalous features gained much attention. It is only since the early 2000s that satellite observations and models have had sufficient resolution to resolve finer-scale dynamics. In earlier studies, eddy properties and behaviour largely determined the terminology used (e.g., Cyclonic Swirls, Cyclonic Eddies, Durban Eddies, and Natal Pulses). Cyclonic swirls are the precursors of Natal Pulses and Durban Eddies and are therefore much smaller (Roberts et al. 2016). For instance, cyclonic swirls could develop into Durban Eddies or Natal Pulses. The distinction between the Natal Pulses and Durban Eddies has caused considerable confusion in the past. Natal Pulses continues to grow as it propagates downstream, whereas Durban Eddies are either episodically flushed away by the Agulhas Current or detach from the KZN Bight as “break-away” Durban Eddies, decreasing in size as they propagate downstream (Roberts and Nieuwenhuys 2016; Guastella and Roberts 2016; Burgher et al. 2025). This behaviour is largely dictated by the presence of an offshore mesoscale anticyclone, which pulls the Agulhas Current offshore and facilitates the growth of Natal Pulses and their downstream propagation (Tsugawa and Hasumi 2010). In the absence of such a feature, the Agulhas Current restrains the growth and migration of the frontal eddy, leading to the rapid decay of the Durban Eddies. The name Cyclonic Eddies was given to features that could not be distinguished between Natal Pulses or Durban Eddies.

| No. of frontal eddies    | Type            | Region               | Period                           | Source                       |
|--------------------------|-----------------|----------------------|----------------------------------|------------------------------|
| 4                        | Natal Pulse     | 32° S                | 1 March 1995 - 24 April 1996     | (Lutjeharms et al. 2003)     |
| 3                        | Natal Pulse     | 29°-34° S; 27°-33° E | 2 years (model outputs)          | (Tsugawa and Hasumi 2010)    |
| 3                        | Durban Eddies   | 29°-34° S            | May 2005 - July 2005             | (Roberts et al. 2010)        |
| 30 (1.6 p.a.)            | Natal Pulse     | 29°-36.5° S          | 1992-2011                        | (Krug and Penven 2011)       |
| 1                        | Natal Pulse     | 32°-35° S            | 15 June - 26 July 1998           | (Pivan et al. 2016)          |
| 10                       | Durban Eddies   | 28°-31° S            | March 2009 - September 2010      | (Guastella and Roberts 2016) |
| 4                        | Natal Pulse     | 28°-31° S            | March 2009 - September 2010      | (Guastella and Roberts 2016) |
| 2                        | Cyclonic Swirls | 27°-33° S            | 2005 - 2010                      | (Roberts et al. 2016)        |
| 3                        | Cyclonic Eddy   | 27°-33° S            | 2005 - 2010                      | (Roberts et al. 2016)        |
| 1                        | Durban Eddies   | 27°-33° S            | 2005 - 2010                      | (Roberts et al. 2016)        |
| 84 - 94 (1.5 - 2.1 p.a.) | Natal Pulses    | 29.8° - 30.7° S      | 1 September 1981 - 18 March 2021 | (Burgher et al. 2025)        |
| Undefined (4.2 p.a.)     | Durban Eddies   | 27°-33° S            | 1 September 1981 - 18 March 2021 | (Burgher et al. 2025)        |

**Table 1**  
Summary of cyclonic frontal eddies (Natal Pulses, Durban Eddies, Cyclonic Eddies and Cyclonic Swirls) observed and/or modeled in the KZN Bight from 2000 to present.

The size, intensity, and frequency of Natal Pulses and Durban Eddies also differ markedly. Natal Pulses are large (approximately 170 km in diameter) and rare, occurring about 1.6 - 2.1 times per year (Krug and Penven 2011; Burgher et al. 2025). In extreme cases, Natal Pulses can propagate past Gqeberha, where they may influence the Agulhas Leakage, a process known to contribute to the global overturning circulation (Krug and Penven 2011).

The smaller and more frequent Durban Eddies typically occur between the Agulhas Current and Durban (Figure 1). This semi-permanent cyclonic eddy does not exhibit a clear seasonal signal and new eddies form every 4 - 7 days (Roberts et al. 2016; Guastella and Roberts 2016; Burgher et al. 2025), which is consistent with other frontal eddies observed inshore of the Gulf Stream (Glenn and Ebbesmeyer 1994; Churchill and Gawarkiewicz 2009), the East Australian Current (Roughan et al. 2017; Ribbe et al. 2018), and the Kuroshio (Itoh and Sugimoto 2008; Cheng et al. 2020). Moreover, their horizontal spatial scales are similar to frontal eddies studied in other major western boundary current systems, varying between 40 - 90 km (Guastella and Roberts 2016; Roughan et al. 2017; Cheng et al. 2020). Due to their small spatial scales and the inherent challenges of sampling and observing inshore regions of western boundary currents, rigorous analyses of Durban Eddies remain limited and challenging (Burgher et al. 2025). Further detailed analysis of fine-scale Durban Eddies in the KZN Bight is needed to better understand their dynamics and influence on shelf circulation where numerous MPAs have been designated

In this study, we investigate the occurrence, evolution, and dynamical characteristics of Durban Eddies along the inshore edge of the Agulhas Current using a high-resolution ocean model. We employ an eddy-tracking algorithm to identify and quantify eddy activity, combined with particle-tracking experiments to examine transport pathways. Furthermore, we use potential vorticity and Richardson number diagnostics to assess the mechanisms driving vertical mixing and the role of these eddies in modulating shelf-slope exchange processes in the KZN Bight and downstream towards Gqeberha.

## 2 Materials and Methods

### 2.1 Model Description

This study uses the Coastal and Regional Ocean COmmunity (CROCO) modelling system (Debreu et al. 2012), in its version v1.1 (<http://www.croco-ocean.org>). CROCO is a free-surface, terrain-following  $\sigma$ -coordinate model with split-explicit time stepping and with Boussinesq and hydrostatic approximations (Shchepetkin and McWilliams 2003, 2005). The advection scheme is third-order upstream biased, which reduces dispersion errors, essentially enhancing precision for a given grid resolution (Shchepetkin and McWilliams 1998). The diffusive part of the advection scheme is rotated along the isopycnal surfaces to avoid spurious diapycnal mixing (Lemarié et al. 2012; Marchesiello et al. 2009). Adaptive open boundary conditions combine outward radiation and nudging towards prescribed external boundary conditions (Marchesiello et al. 2001). Additional eddy viscosity is added in the sponge layers at open boundaries, where it increases smoothly over several grid points.

## 2.2 Model Configurations

The modelling strategy employs a one-way nesting approach using CROCO, with a high-resolution 1 km grid embedded within a 3 km parent grid to resolve frontal eddies inshore of the Agulhas Current (Figure 1). The configurations are referred to as CYC-3KM and CYC-1KM for the 3 km and 1 km grids, respectively. The CYC-3KM domain spans the broader southeast African coastline ( $38.0 - 26.5^\circ$  S,  $21.0 - 41.5^\circ$  E), capturing key features of the Agulhas Current system while excluding regions such as the retroflection to avoid unnecessary complexity. The child configuration, CYC-1KM ( $27.5 - 37^\circ$  S,  $22 - 40^\circ$  E), receives boundary conditions from CYC-3KM without feedback (visible along its border in Figure 1) and includes sponge layers of 15 grid cells to ensure smooth downscaling. Both configurations use 75 vertical levels, with enhanced resolution near the surface using stretching parameters of  $h_{\text{cline}} = 300$  m,  $\sigma_s = 7$  and  $\sigma_b = 2$ . Bathymetry was interpolated from the global Shuttle Radar Topography Mission dataset (SRTM30') at 30-arc second resolution (Becker et al. 2009).

The minimum coastal depths are set to 75 m and 10 m for CYC-3KM and CYC-1KM, respectively. In order to avoid pressure gradient errors induced by terrain-following  $\sigma$  coordinates with steep bathymetry, the interpolated bathymetry is smoothed where the steepness of the topography ( $r_s = \Delta h/h$ ) exceeds 0.25 (Beckmann and Haidvogel 1993).

The CYC-3KM and CYC-1KM are bulk-forced (Fairall et al. 2003) with the ERA5 inter-annual fifth-generation atmospheric reanalysis (Hersbach et al. 2020) produced by the European Center for Medium-Range Weather Forecasts (ECMWF), with an hourly sampling and a spatial resolution of 31 km. Current feedback was disabled in the configurations since it can act to dampen the eddies (Renault et al. 2020). Vertical mixing in the boundary layers and in the interior of the model is resolved using the K-profile parameterisation (Large et al. 1994).

The initial and lateral boundary conditions were derived from the global eddy-resolving ocean and sea-ice reanalysis (GLORYS12), based on the Nucleus for European Modelling of the Ocean (NEMO) framework, with a horizontal resolution of 9 km (Lellouche et al. 2021). This allows to feed the model with mesoscale variability coming from its source regions - Mozambique Channel and the South East Madagascar Current de Ruijter et al. (2004); Ridderinkhof et al. (2013); TERNON et al. (2014).

All results presented in this study are derived from the daily mean outputs of CYC-1KM. The CYC-3KM simulation was only run in order to provide a smooth transition between the lateral boundary forcing based on the GLORYS12 outputs and the CYC-1KM simulation. The latter is run from 2003 to 2010 and includes a three year spin-up period.

## 2.3 Eddy Detection and Tracking

### 2.3.1 AMEDA Eddy Detection Algorithm and its Adaptations

The Angular Momentum Eddy Detection and Tracking Algorithm (AMEDA) is a hybrid eddy detection method that uses kinematic and geometric flow properties to detect eddies in space and time (Le Vu et al. 2018). The code was re-written in Python

for the purpose of this study and adapted for the detection of frontal eddies inshore of the Agulhas Current within CYC-1KM. The AMEDA eddy detection algorithm follows four steps: (1) computation of the Localized and Normalized Angular Momentum (LNAM); (2) computation of the Localized Okubo-Weiss parameter (LOW); (3) detection of potential eddy centers; (4) computation of the two-dimensional horizontal stream function later used to confirm the existence of an eddy and determine its size and intensity.

- **Step 1: Computation of LNAM**

The algorithm computes LNAM at each grid point of the domain referred to by its vector  $\mathbf{X}$  (Mkhinini et al. 2014; Le Vu et al. 2018):

$$\text{LNAM}(\mathbf{X}) = \frac{L}{S+B} \quad \text{with} \quad \begin{cases} L = \left( \sum_j (\mathbf{X}_j - \mathbf{X}) \times \mathbf{V}_j \right) \cdot \mathbf{k} \\ S = \sum_j (\mathbf{X}_j - \mathbf{X}) \cdot \mathbf{V}_j, \\ B = \sum_j |(\mathbf{X}_j - \mathbf{X})| |\mathbf{V}_j|. \end{cases} \quad (1)$$

$L$  is the vertical component of the integral, over a squared box centered around  $\mathbf{X}$  and of size  $W$ , of the angular momentum vectors calculated at points  $\mathbf{X}_j$  relative to  $\mathbf{X}$ .  $\mathbf{k}$  is the vertical unit vector, and  $j$  the index of each grid point contained within the squared box.  $L$  is positive when the circulation within the squared box is anticlockwise and negative when it is clockwise.  $S$  and  $B$  terms used for normalizing LNAM.  $B$  is the upper bound of the integrated angular momentum. This upper bound is reached if the velocity vectors  $\mathbf{V}_j$  are all perpendicular to  $(\mathbf{X}_j - \mathbf{X})$ . The additional term  $S$  allows to distinguish hyperbolic and elliptical points. For an axis-symmetric vortex, when  $\mathbf{X}$  is the vortex center,  $S=0$  and the LNAM parameter reaches an extreme value of  $+1$  ( $-1$ ) for anticlockwise (clockwise) rotation. In the case  $\mathbf{X}$  lies within a region of hyperbolic flow,  $S$  ends up being large, which reduces the LNAM value. LNAM can therefore be interpreted as a normalized spatial average over all nodes  $\mathbf{X}_j$  of their angular momentum relative to  $\mathbf{X}$ .

- **Step 2: Computation of LOW**

The algorithm computes a local spatial average value of the Okubo-Weiss parameter (LOW) at each point  $\mathbf{X}$  (Okubo 1970). This parameter (Eq. 2) measures the difference between the sum of the squares of normal strain ( $S_n$ ) and shear strain ( $S_s$ ) and the square of relative vorticity ( $\zeta$ ). As for LNAM, to limit the detection of any spurious numerical features and reduce noise, it is averaged over the same squared box of width  $W$  used to calculate LNAM (Eq. 3).

$$\text{OW} = s_n^2 + s_s^2 - \zeta^2 \quad \text{with} \quad \begin{cases} s_n^2 = \frac{\partial u}{\partial x} - \frac{\partial v}{\partial y} \\ s_s^2 = \frac{\partial v}{\partial x} + \frac{\partial u}{\partial y} \\ \zeta^2 = \frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \end{cases} \quad (2)$$

$$\text{LOW}(\mathbf{X}) = \frac{1}{n} \sum_j \text{OW}(\mathbf{X}_j), \quad \begin{array}{l} n \text{ being the number of grid points} \\ \text{within the squared box centered of width } W \\ \text{centered at } \mathbf{X}. \end{array} \quad (3)$$

- **Step 3: Detection of potential eddy centers**

Potential eddy centers are defined as extrema of LNAM located in regions dominated by vorticity over strain. A minimum and maximum threshold values are therefore imposed for LNAM and LOW respectively (Eq. 4).

$$\begin{aligned} |\text{LNAM}(\mathbf{X})| &> \text{LNAM}_{thr} \\ \text{LOW}(\mathbf{X}) &< \text{LOW}_{thr} \end{aligned} \quad (4)$$

The added dynamical criteria on the Okubo-Weiss parameter has been widely used in the past to detect surface eddies from satellite altimetry or model data (Penven et al. 2005; Halo et al. 2014). Its combination with the angular momentum, a conservative dynamical quantity, facilitates the detection and tracking of small-scale eddies that may not exhibit a strong sea-surface height signal. Here, this second criteria also prevents AMEDA from detecting an eddy centre in a region characterized by large deformation.

- **Step 4: Eddy classification**

This step finalizes the detection of eddy centers, finds its edges and provides its intensity. This is achieved after computing the horizontal two-dimensional stream function  $\Psi(x, y)$  from the integration of the horizontal velocity components ( $u, v$ ) over the same squared region used to spatially average the LNAM and LOW parameters (Eq. 5).

$$\psi(x, y) = \int_{y_e}^y u(x_e, \eta) d\eta - \int_{x_e}^x v(\xi, y_e) d\xi \quad (5)$$

This integration assumes the flow is horizontally non-divergent and that the circulation is zero at eddy centers detected in the previous step ( $\Psi(\mathbf{X}_e) = 0$ , with  $\mathbf{X}_e(\mathbf{x}_e, \mathbf{y}_e)$  the vector position of a potential eddy center).

To be classified as an eddy center, the selected node  $\mathbf{X}_e$  must be surrounded by a closed contour of  $\Psi$  (in  $\text{m}^2\text{s}^{-2}$ ).  $\Psi$  can then be interpreted as the volume transport per cross-sectional unit depth of water around the eddy center. Once an eddy center is identified, the algorithm determines its intensity and outer edge. The eddy intensity is defined by the average azimuthal velocity  $\overline{V}_\theta^{max}$  over the closed contour of  $\Psi$  that maximizes the absolute value of the circulation  $C$  (Eq. 6).

$$\begin{aligned} \text{MAX}[C_C] &= |\int_{C_{max}} \vec{v} \cdot d\vec{l}|, \quad \text{with } C_{max} \text{ the contour line of } \Psi_{max} \\ \text{MAX}[C_L] &= \overline{V}_\theta^{max} \mathcal{L}_{max}, \quad \text{with } \mathcal{L}_{max} \text{ the length of the contour line } C_{max}. \end{aligned} \quad (6)$$

The outer edge of the eddy is then defined slightly beyond the contour line of  $\Psi_{max}$ , as the closed contour line of the stream function where the average azimuthal velocity is equal to  $0.97 \times \overline{v}_\theta^{max}$ . An ellipse is then fitted to this contour to estimate eddy orientation and its major and minor axes.

Some adaptations and tuning of the AMEDA parameters were implemented to ensure seamless detection of the frontal eddies at different life stages (generation, maturation, propagation and dissipation) within the coastal band. The LNAM and LOW

were only computed over a 150 km-wide coastal band in order to prevent the masking of inshore eddies by offshore mesoscale dynamics.  $LOW_{thr}$  was set to  $-5 \times 10^{-9} s^{-2}$ . Nevertheless, the width  $W$  of the squared box used to compute LNAM, LOW and  $\Psi$ , as well as the  $LNAM_{thr}$  were varied from 20 km to 100 km in 20 km intervals, and from 0.7 to 0.86 in intervals of 0.02 respectively at each detection attempt. Additional post-processing was then required to remove duplicate detections and nested eddies. In such cases, smaller eddies embedded within larger ones were removed, potentially excluding submesoscale features. This was a necessary trade-off for an exhaustive eddy detection algorithm. Finally, to avoid discontinuities in the stream function  $\Psi$ , for each integration of the stream function within a square box with land points, the coastal value of the stream function was kept fixed and set to the one of the nearest coastal grid point relative to the eddy center.

### 2.3.2 Tracking Routine

The AMEDA eddy tracking algorithm uses a cost function (C) that measures the physical similarity between two eddies e1 and e2, each detected at two different time steps. This cost function is based on the eddies displacement  $D$ , size  $r_v$ , and intensity  $v_\theta$ , and relative vorticity  $\zeta$ . In AMEDA, this cost function incorporates a time-evolving normalization and an additional term giving more weight to recent detections in case eddy characteristics are equal (Le Vu et al. 2018). Since our study region is coastal and relatively small, few eddies were detected per day in our simulation. Therefore, a simpler tracking algorithm was adopted, based on the cost function (Eq.7) used by Penven et al. (2005):

$$C_{e1,e2} = \sqrt{\left(\frac{\Delta D}{D_\theta}\right)^2 + \left(\frac{\Delta r_v}{r_{v\theta}}\right)^2 + \left(\frac{\Delta \zeta}{\zeta_\theta}\right)^2} \quad (7)$$

The  $\Delta$  operator denotes the difference between the tracked eddy (e1) and the candidate eddy (e2). The subscript  $\theta$  refers to the maximum values used to normalise the cost function.

### 2.4 Lagrangian Particle Tracking

The offline tracking algorithm Pyticles allows to track fluid water particles released within a time varying flow (Gula et al. 2014). Pyticles uses a fourth-order explicit Runge-Kutta time-stepping scheme to advect particles without additional diffusion. Particle velocities are interpolated in both time and space from daily model outputs using linear interpolation in time and the vertical, and bilinear interpolation in the horizontal. The particles are purely passive, meaning that their spatio-temporal distributions are solely dependent on the three-dimensional ocean currents.

To illustrate the fate of water particles embedded within a Durban eddy, particles were seeded within one frontal propagating eddy detected within our simulation. Particles were seeded between the surface down to 1000 m depth when the eddy was at its peak intensity. The particles were tracked forward and backward in time in order

to infer the evolution of the eddy properties during its life cycle. A total of  $\sim 1.4$  million particles were released within the eddy in order to produce robust statistics of changes of the eddy properties, and better understand the dynamics at play.

## 2.5 Potential Vorticity

Ertel’s Potential Vorticity (PV) combines rotation and stratification into a single scalar quantity (Ertel 1942). Its primary advantage lies in its link to circulation and its conservative properties (Pedlosky 1987; Müller 2006). By calculating Ertel PV, one can approximate the overall fluid flow field; positive (negative) PV corresponds to anticyclonic (cyclonic) circulation. In an inviscid and adiabatic fluid, PV is conserved along particle trajectories. However, in the ocean, this is not strictly the case, and changes in PV may be either adiabatic (due to meridional displacement) or diabatic (due to mixing or friction). In this study, PV changes are expected to be primarily diabatic, as frontal eddies do not undergo sufficient meridional displacement for planetary vorticity to contribute significantly through adiabatic processes. For instance, the change in  $f$  between Durban ( $-29.8^\circ$  S) and Gqeberha ( $-33.9^\circ$  S) is small ( $\sim 8.9 \times 10^{-6} \text{ s}^{-1}$ ).

One limitation of Ertel PV is that it is not optimal for analysing quasi-geostrophic (QG) circulation. In regions with a strong pycnocline, such as the Agulhas Current, large background stratification can mask fine-scale density variations responsible for QG dynamics. It is therefore more appropriate to recover the QG PV to isolate finer-scale processes and investigate diabatic effects (Pedlosky 1987; Müller 2006). To address this, a rescaled form of PV ( $PV_{rescaled}$ ) is used (Morel et al. 2019, 2023).  $PV_{rescaled}$  is computed by taking into account a reference density profile that is representative of the background stratification at rest and is defined as:

$$\begin{aligned} PV_{rescaled} &= (\nabla \times \mathbf{U} + \mathbf{f}) \cdot \nabla Z(\rho, t) \\ &= \nabla \cdot ((\nabla \times \mathbf{U} + \mathbf{f})Z(\rho, t)) \end{aligned} \quad (8)$$

where  $\mathbf{U}$  is the velocity field,  $\mathbf{f}$  is the Earth’s rotation vector (whose vertical component defines the Coriolis parameter  $f$ ), and  $Z(\rho, t)$  is a function of potential density  $\rho$  evolving in time  $t$ .  $Z(\rho, t)$  corresponds to the vertical position of density along a reference profile that evolves in time  $\rho^*(z, t)$  and can be written as  $Z(\rho^*(z, t), t)$ .

The reference profile was computed using Lorenz’s rearranged stratification profile (Lorenz 1955; Tseng and Ferziger 2001; Morel et al. 2023). This involves constructing the probability density function of the model density field and assigning values to predefined density classes. The class intervals must be sufficiently small to avoid a staircase-like profile, which would introduce errors in  $PV_{rescaled}$ .

Using this formulation,  $PV_{rescaled}$  corresponds to the absolute vertical vorticity associated with  $f$ . At rest,  $PV_{rescaled}^{rest} = f$ . The difference between  $PV_{rescaled}$  and  $f$  defines the Potential Vorticity Anomaly (PVA):

$$PVA = PV_{rescaled} - f \quad (9)$$

Although PV corresponds to QG PV and is linked to balanced dynamics, PVA is not conserved due to the exclusion of  $f$ , which contributes to vorticity adiabatically through its meridional gradient (the beta effect). Therefore, PVA must be analysed along isopycnal surfaces. Hereafter,  $PV_{rescaled}$  is referred to as PV.

## 2.6 Richardson Number

The Richardson number (Ri) is a non-dimensional number expressing the ratio between the local stratification (Brunt-Väisälä frequency) and vertical gradient of the velocity field (Eq. 10):

$$Ri = \frac{-g\partial_z\rho}{\rho_0||\partial_z\mathbf{U}||^2}, \quad (10)$$

where  $\rho$  is the density and  $\mathbf{U}$  the velocity vector. Note that Ri is calculated at the same grid locations as PV on the Arakawa C-grid of the CROCO model. Low Ri values indicate that vertical shear dominates over stratification, promoting vertical mixing and modifying the PV field.

## 2.7 Model Evaluation

Given the dominant role of the Agulhas Current in driving inshore variability along the east coast of South Africa, it is important to demonstrate that our simulation adequately captures the main characteristics of this current. Model averages of the alongshore currents ( $v$ ) and PV over the simulated period are therefore compared with observations from the Agulhas System Climate Array (ASCA). The latter consists of a mooring array deployed along a cross-shore transect at 32° S (solid magenta in Fig. 1). The ASCA experiment provides gridded cross-sectional velocities, temperatures, and salinities between April 2016 and June 2018 (McMonigal et al. 2020; Gunn et al. 2020).

[Fig. 2 about here.]

The cross-sectional currents are perpendicular to both the model and the ASCA transect (Figures 2a and b). The mean PV from both the model and the ASCA observations was calculated using Equation 8 and is presented in Figures 2c and d.

The modeled Agulhas Current exhibits a weaker, poleward-flowing jet that does not extend as far offshore or as deep as the observations (Figures 2a and b). This is illustrated by the 0.5 m s<sup>-1</sup> velocity contour, which extends ~ 90 km offshore and to 600 m depth in the model, compared to exceeding 110 km offshore and 800 m depth in ASCA (Figures 2a and b). At deeper depths (~ 1500 m), the weak equatorward flow represented by the 0.03 m s<sup>-1</sup> velocity contour is indicative of the Agulhas Undercurrent, which is comparable between the model and the ASCA transect (Figures 2a and b).

Both the model and observations exhibit elevated cyclonic circulation along the inshore frictional boundary layer of the Agulhas Current above the 1026.6 kg m<sup>-3</sup> isopycnals, providing confidence that the modeled circulation is a realistic representation of the mean flow (Figures 2c and d).

To provide further support that the Agulhas Current is well represented in the model we compute the modeled mean volume transport to the Agulhas Current Time-series array (ACT), deployed along the same transect as ASCA. ACT provides a 34-month in situ time series of the Agulhas Current’s boundary layer transport (Beal et al. 2015). Only the time periods that overlapped between ACT and the model, 17 April 2010 to 31 December 2010, was used.

The fluctuations of the volume transport between CYC-1KM and ACT does not match up exactly due to the absence of data assimilation in the model. However, the difference in mean volume transport between the model ( $83.67 \text{ Sv} \pm 24.86$ ) and ACT ( $82.76 \text{ Sv} \pm 27.03$ ) is negligible, confirming that the modeled Agulhas Current is well captured.

Figure 2 does shows differences at depth in the mean PV field, which is more heterogeneous in the observations, including a strong patch of cyclonic circulation at 2000 m as well as anticyclonic circulation near the bottom. Considering the meandering nature of the Agulhas Current, estimated to occur approximately 8.3% of the time (McMonigal et al. 2020), which can substantially influence its mean structure, these differences can likely be attributed to the different sampling averaging period (mean over April 2016–June 2018 for ASCA and January 2005–December 2010 for the model). Nevertheless, these biases at depth are not of a major concern in our study, since we mainly focuses on the upper-ocean dynamics in the top 1000 m.

Overall, the alongshore current, inshore cyclonic circulation and the mean volume transport are well represented, providing confidence that the model can resolve the mean flow and inshore circulation with reasonable accuracy.

### 3 Results and Discussion

#### 3.1 Occurrence and Classification of Cyclonic Frontal Eddies

The poleward-flowing Agulhas Current exhibits strong variability along the east coast of South Africa. The current is characterised by a dual band of relative vorticity with opposite signs (normalised by  $|f|$ ; Figure 3). The offshore positive band is associated with the anticyclonic recirculation adjacent to the interior of the Indian Ocean subtropical gyre, arising from wind-driven Sverdrup transport and beta-plane dynamics. The intensified inshore negative vorticity band corresponds to cyclonic shear within the Agulhas Current, where lateral friction enables the dissipation and redistribution of vorticity required to balance the vorticity budget.

To classify and detect cyclonic frontal eddies, the adapted AMEDA algorithm was employed. To reduce dataset noise and enable their identification, features not classified as cyclonic eddies, with lifespans shorter than four days, or propagating past Gqeberha were excluded, thereby removing large anomalous structures and filaments/fronts that may otherwise be misidentified as eddies.

A total of 366 cyclonic frontal eddies were detected over the five-year simulation, corresponding to a recurrence of approximately one eddy every 5 days. This frequency is consistent with previous observations in the KZN Bight (Guastella and Roberts 2016; Burgher et al. 2025) and other western boundary current systems (Churchill and Gawarkiewicz 2009; Roughan et al. 2017; Ribbe et al. 2018; Cheng et al. 2020),

confirming that these features are a persistent component of the inshore Agulhas Current system. Their semi-permanent occurrence suggests that they are a dominant driver of local variability.

[Fig. 3 about here.]

The density distribution compares the lifespan (in days) of all the cyclonic eddies as a function of their displacement distance (in km) (Figure 4). The eddy lifespans range from 4 to 42 days, with a mean of 5 days. The density distribution reflects a clear bimodal distribution, delineated by the vertical dashed line in Figure 4, that separates the eddies into two groups: (A) stationary eddies ( $<29$  km displacement) and (B) propagating eddies ( $>29$  km). Stationary eddies occur less frequently ( $\sim 24$  days) and have shorter lifespans ( $\sim 4$  days), whereas propagating eddies are more frequent ( $\sim 6$  days) and persist longer ( $\sim 7$  days). This distinction suggests differences in the dynamical coherence of the two groups, with stationary eddies dissipating relatively quickly, while propagating eddies maintaining structural integrity and persisting longer.

[Fig. 4 about here.]

Spatial probability distributions show that stationary eddies forms and dissipate throughout the KZN Bight with some preference offshore of Durban, the center of the KZN Bight and along the northern section of the KZN Bight coastline (Figures 5a and b). Furthermore, trajectories of the stationary eddies shows that they are confined to their site of generation with slow translation speeds ( $0.15 \text{ m s}^{-1} \pm 0.1 \text{ m s}^{-1}$ ) for the duration of their life (grey lines in Figure 6a).

Similarly, propagating eddies preferentially form offshore of Durban and the center of the KZN Bight along 500 m isobath (Figures 5c). In contrast to the stationary eddies the propagating eddies migrate southward, with a faster translation speed ( $0.18 \text{ m s}^{-1} \pm 0.9 \text{ m s}^{-1}$ ), along the coast where it tends to dissipate south of Durban (Figures 5d). The trajectories further demonstrate their downstream migration, intersecting multiple MPAs (green boxes), highlighting their potential role in coastal connectivity between the KZN Bight and downstream regions (grey lines in Figure 6b).

[Fig. 5 about here.]

The slower propagation speeds of the frontal eddies exhibited in CYC-1KM compared to observations made locally and in other western boundary currents, which typically range between  $0.15\text{--}0.8\text{ m s}^{-1}$  ([Guastella and Roberts 2016](#); [Schaeffer et al. 2017](#); [Cheng et al. 2020](#)), are expected due to the deeper shelf ([James et al. 1999](#)) and the weaker jet resolved in CYC-1KM (Figure 2). In reality, we can expect the cyclones to propagate faster and even further downstream due to the more intense jet stream and stronger coherence of the eddies.

[Fig. 6 about here.]

### 3.2 Evolution of Frontal Eddies

The evolution of eddy geometry and kinematics is shown in Figure 7. The mean minor-axis ( $\bar{a}$ ), major-axis ( $\bar{b}$ ), and radius ( $\bar{r}$ ) represent the eddy shape and size, while the mean azimuthal velocity ( $\bar{v}_\theta$ ) and amplitude ( $\bar{A}$ ) describe the circulation around the eddy and its intensity.

[Fig. 7 about here.]

Eddy sizes (5–45 km radius) are comparable with observations made locally in the Agulhas Current and in other western boundary currents, which vary between 10–100 km (Lee and Atkinson 1983; Guastella and Roberts 2016; Burgher et al. 2025; Roughan et al. 2017; Schaeffer et al. 2017; Cheng et al. 2020), thereby indicating that CYC-1KM captures the realistic spatial scales of the frontal eddies (Figure 7).

The stationary eddies are confined to the KZN Bight and are episodically flushed by the Agulhas Current (Figure 6a). They remain smaller ( $\bar{r}$  = 11–18 km) and weaker ( $\bar{v}_\theta$  = 0.1–0.45 m s<sup>-1</sup>;  $\bar{A}$  = 2–7.5 cm), reaching peak intensity around day 5 before rapidly dissipating due to interaction with the Agulhas Current (Figure 7).

In contrast, propagating eddies are larger ( $\bar{r}$  = 18–28 km) and more intense ( $\bar{v}_\theta$  = 0.35–0.73 m s<sup>-1</sup>;  $\bar{A}$  = 4–17.6 cm), reaching maturity around day 21 before gradually decaying downstream (Figure 7). Their stronger azimuthal velocities enhance coherence, allowing them to persist longer and travel further. This was shown in more detail using observations and an analytical framework by Barabinot et al. (2024) when investigating the boundaries of eddies.

The converging major and minor axes over time reveal a transition from an elliptical to a more circular structure (dashed and dotted lines in Figure 7a). The snapshots in Figure 3 show the evolving geometry clearly. This has been observed by Guastella and Roberts (2016) inshore of the Agulhas Current, who found that the alongshore axis tends to be longer (30–45 km) than the cross-shore axis (20–25 km). Our modelling analysis indicates that this transition occurs more rapidly in stationary eddies due to their weaker coherence, as reflected by their lower intensity. In contrast, propagating eddies retain elongated structures for longer owing to their stronger coherence, allowing sustained interaction with the background Agulhas Current (Figures 7b and c).

To better understand the characteristics of frontal eddies, we focus our analysis on a long-lived propagating eddy case study in the following section. This case is used to illustrate how such eddies influence coastal circulation and vertical mixing. Given the frequent occurrence of frontal eddies in the KZN Bight, we assume similar dynamics across events.

### 3.3 A Long-Lived Eddy Case Study

The case study focuses on the life cycle of the 37-day, long-lived propagating eddy shown at the surface in Figure 3 and along a vertical section through its core in Figure 8, illustrating its generation, maturation, migration, merging, and dissipation phases. These phases are defined based on the temporal evolution of its size and

intensity, as presented in Figure 9a. The dashed grey lines indicate the phase timings and correspond to the snapshots in Figures 3 and 8.

Consistent across all cross-shore transects in Figure 8 is the intense cyclonic circulation exhibited by the frontal eddy, especially at the surface where PV and PVA exceed  $-7.5$ . The cyclonic circulation is accompanied by uplift of isopycnals (grey and black contours) in the eddy core, and due to the frontal nature of the eddy, alongshore velocities (green contours) are intensified on the offshore edge where it merges with the poleward-flowing Agulhas Current (Figure 8). Similar observations were made by Guastella and Roberts (2016) and Schaeffer et al. (2017) in the Agulhas Current and East Australian Current, however, our velocities are slower due to the weaker jet in CYC-1KM. The grey contours represent densities from  $1025.5$ – $1027.4$   $\text{kg m}^{-3}$  at  $0.1$   $\text{kg m}^{-3}$  intervals, while the black contours delineate isopycnal layers containing PV and PVA cores. The PV cores tend to remain within these layers in the absence of diabatic processes (Pedlosky 1987; Müller 2006). The definition of the isopycnal layers is subjective, but here it is somewhat clear and they are defined as: **surface** ( $\rho < 1026.0$   $\text{kg m}^{-3}$ ), **subsurface** ( $1026.0 < \rho < 1026.6$   $\text{kg m}^{-3}$ ), **intermediate** ( $1026.6 < \rho < 1027.1$   $\text{kg m}^{-3}$ ), and **bottom** ( $\rho > 1027.1$   $\text{kg m}^{-3}$ ).

[Fig. 8 about here.]

[Fig. 9 about here.]

[Fig. 10 about here.]

Cyclonic circulation is intensified in the surface layer and weakens with depth, becoming negligible in the bottom layer (Figure 8). This indicates that the eddy dynamics are governed primarily by PV and PVA in the surface isopycnal layer. This is corroborated by the inversion of a PV profile for a four-layer axisymmetric vortex (Figure 9b–p).

The solution used to invert the PV profile is described in Appendix A. Figures 9b–d compare the layer thickness  $\Delta h$  and azimuthal velocity  $v_\theta$  resulting from the inversion of a PV profile of an analytical vortex and the long lived eddy case study on 3 March 2006. Panels b–d show that the analytical vortex, with slightly more intense PV, underestimated layer thickness  $\Delta h$  and azimuthal velocity  $v_\theta$ . This difference is expected, as the eddy from CYC-1KM was influenced by environmental dynamics.

Four experiments were conducted in which one isopycnal layer was injected with negative PV ( $\text{PVA} = -1.5$ ) while the others remained neutral ( $\text{PVA} = 0$ ). In all cases, the injected layer resulted in intensified azimuthal velocity  $v_\theta$  and domed isopycnals, indicated by a negative layer thickness  $\Delta h$ , consistent with PV conservation. The injected layer drove adjacent layers, producing weaker but noticeable responses.

Injection of PV in the surface layer produced strong surface-intensified circulation, while bottom-layer injection produced the strongest circulation within that layer but with limited vertical influence. Mid-layer injections produced intermediate responses.

Overall, the PV inversion tests demonstrate that enhanced PV within a layer drives circulation that influences surrounding layers, with the effect diminishing with distance. These results confirm that dominant surface PV and PVA signals are indicative of strong surface-intensified circulation that drives weaker motions below and governs the eddy dynamics.

We now analyse the evolution of the cyclonic eddy using Figures 3, 8, 9a and 10. Figure 3a shows that the eddy stemmed from an intensified band of cyclonic vorticity extending from the northern KZN Bight. Despite this strong surface vorticity, the eddy was still in its infancy ( $rv = 20$  km,  $v_\theta = 0.55$  m s<sup>-1</sup>,  $A = 10$  cm), and the PV and PVA signals associated with the eddy were relatively weak (Figure 8a and Figure 9a).

The eddy intensified and matured offshore of Durban over  $\sim 10$  days until it reached its peak intensity on 3 March 2006 ( $rv = 42.16$  km,  $v_\theta = 0.92$  m s<sup>-1</sup>,  $A = 30.25$  cm; Figure 3b and Figure 9a). At this stage, PV and PVA were concentrated in the eddy core, particularly in the surface layer. Moreover, majority of the particles seeded within the eddy originated from the Agulhas Current and aggregated within the eddy (Figures 10a and b). Note that the particle percentage within the eddy at seeding was not 100%, as some particles were seeded outside the eddy contour (Figure 9a and Figure 10b).

Once the eddy reached sufficient intensity, it detached and migrated downstream (Figures 3c and d). It lost  $\sim 42\%$  of its particles within 2 days due to the weakening of the PV structure (Figure 8e, f, Figure 9a and Figure 10c). Between 8–12 March, the eddy reached a temporary equilibrium, with relatively stable size, intensity, and particle content (Figure 9a).

At the end of the migration period, a peak in eddy size and intensity occurred on 13 March 2006 (Figure 9a). This phase is defined as the merging phase, during which a trailing filament was wrapped around the eddy, temporarily increasing its size and intensity before being absorbed ( $rv = 42.16$  km,  $v_\theta = 0.92$  m s<sup>-1</sup>,  $A = 30.25$  cm). This was evident in intensified PV and PVA signals (Figure 8g and h).

Following this interaction, the eddy weakened, and its size, intensity, and particle content decreased as it dissipated due to shear from the Agulhas Current and coastal boundary effects ( $rv = 13.17$  km,  $v_\theta = 0.31$  m s<sup>-1</sup>,  $A = 2.84$  cm; Figure 3e and Figure 9a).

### 3.4 PV Transformation, Mixing, and Coastal Impacts

We analyse the transformation of PV associated with seeded particles to infer the circulatory processes linked to the eddy (Figure 11). We compare the probability density functions of PV at the time of eddy seeding (dashed black lines) with those from the aforementioned phases within each isopycnal layer (Figure 11). The different colours represent the individual isopycnal layers (surface, subsurface, and intermediate). The bottom layer was excluded from this analysis, since the PV and PVA signals are negligible (Figure 8).

The PV transformation reflect predominantly diabatic processes, as the limited meridional displacement of particles precludes significant adiabatic PV modification (Figure 11). This does not imply that the original PV signatures are non-adiabatic,

but rather that the PV variations observed here result primarily from diabatic processes (mixing and/or friction). Therefore, time steps exhibiting greater changes in PV indicate diabatic processes that contribute to the formation, intensification, migration, merging, and decay of the eddy.

Results in Figure 11 show that the largest PV changes occur in the surface isopycnal layer. Here, the intense PV drives the eddy’s internal dynamics, as discussed in the previous section. Moreover, the greatest PV variations are observed during the eddy’s generation and dissipation phases, reflecting diabatic processes that transform the PV distribution. This is particularly noticeable at the surface when the eddy is generated and the PV distribution changes from a unimodal to a bimodal structure (Figure 11a).

[Fig. 11 about here.]

Lagrangian analysis indicates that PV originates from the frictional boundary layer of the Agulhas Current. At Richards Bay, the filament of intense cyclonic vorticity becomes unstable and submesoscale anomalies of PV coalesce together to form the eddy in the KZN Bight (Figure 12). Although the relative contributions of friction and mixing cannot be quantified explicitly, both processes likely play key roles in the formation and destruction of the eddy, as shown in the Gulf Stream (Gula et al. 2015), South Equatorial Current (Assene et al. 2020) and in idealised studies (Morel et al. 2023).

As the eddy detaches from the KZN Bight and migrates southwestward along the coast (third column in Figures 12 and 13), it is peeled apart by both the coastline and the Agulhas Current. The torn-off particles are associated with intense vorticity signals that spin up an additional smaller cyclonic eddy in its wake (fourth and fifth columns in Figure 12).

Mixing persists at all depths throughout the life cycle of the eddy. However, due to the highly stratified nature of the eddy, mixing is dampened at the surface. This is noticeable during the maturation phase (Figure 13a), when the eddy is at its peak intensity and stratification is strongest. Furthermore, during the migration (Figure 13c), merging (Figure 13d), and dissipation (Figure 13e) phases, the eddy core remains highly stratified, which suppresses mixing. At the edges of the eddy, stratification becomes weaker, and intense horizontal and vertical shear dominate (Barabinot et al. 2024), allowing mixing to persist.

Not only do the main eddy and the newly spun-up eddy drive strong vertical mixing along the coast, where numerous MPAs are designated, but the combination of eddies (the original eddy, the newly spun-up eddy, and the newly generated eddy offshore of Durban) also creates a countercurrent that flows equatorward and recirculates particles back into the KZN Bight (Figure 10d and e and the third, fourth, and fifth columns in Figure 13). This circulation promotes particle retention within the KZN Bight and adjacent MPAs which confirms earlier findings that Durban Eddies enhance coastal retention and connectivity (Heye et al. 2022). These dynamics highlight the ecological significance of cyclonic frontal eddies along the east coast of South Africa.

This is noteworthy because one might expect the eddy to detach from the KZN Bight and particles to be advected downstream and eventually removed by the Agulhas

Current as the eddy dissipates. Instead, particles are retained along the coastline and recirculated back into the KZN Bight. This behaviour is likely due to the high frequency of cyclonic frontal eddies along the coast that are either generated from the Agulhas Current or shed from larger eddies which act to retain and recirculate particles.

[Fig. 12 about here.]

[Fig. 13 about here.]

## 4 Conclusion

This study demonstrates that cyclonic frontal eddies are frequent, dynamically robust features of the inshore Agulhas Current system and play a central role in shaping coastal circulation along the east coast of South Africa. Using a high-resolution numerical model and an adapted eddy detection algorithm, we provide a continuous characterisation of Durban Eddies unconstrained by observational limitations.

The results show that these eddies originate from the inshore frictional boundary layer of the Agulhas Current, are strongly surface-intensified, and exhibit two distinct modes of behaviour: stationary and propagating. The smaller stationary eddies are confined to the KZN Bight and lack strong cohesion, leading to rapid decay of these structures. Conversely, the propagating eddies are larger, more intense, and longer-lived due to their strong cohesive structure, allowing them to transport properties downstream and interact with the coastal environment, where numerous MPAs are designated.

PV analysis highlights the dominant role of surface-layer dynamics in governing eddy structure, while Lagrangian diagnostics reveal that diabatic processes (mixing and/or friction) drive PV transformation throughout the eddy lifecycle. Interactions with the coastline and the Agulhas Current promote eddy decay, generate secondary eddies, and induce transient countercurrents that enhance particle retention along the coast and likely within the KZN Bight.

These processes have important implications for coastal connectivity and ecosystem functioning. By facilitating vertical mixing, retention, and recirculation, cyclonic frontal eddies influence the distribution of tracers, nutrients, and biological material within the KZN Bight and downstream, where MPAs are designated.

Overall, this work underscores the importance of resolving mesoscale and sub-mesoscale frontal processes inshore of western boundary current systems to better understand their physical and ecological impacts.

## Acknowledgements

The authors would like to thank Bayworld Center for Research and Education for funding this project. This work was granted access to HPC and storage resources of IDRIS (CNRS, France) under the allocations A0100107443 and A0120107443 provided by GENCI on the Jean Zay supercomputer (CSL partition).

## Declarations

- Funding: This project was funded by the Bayworld Center for Research and Education.
- Conflict of interest/Competing interests: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.
- Data availability: Data will be provided on request.
- Code availability: Code will be provided on request.

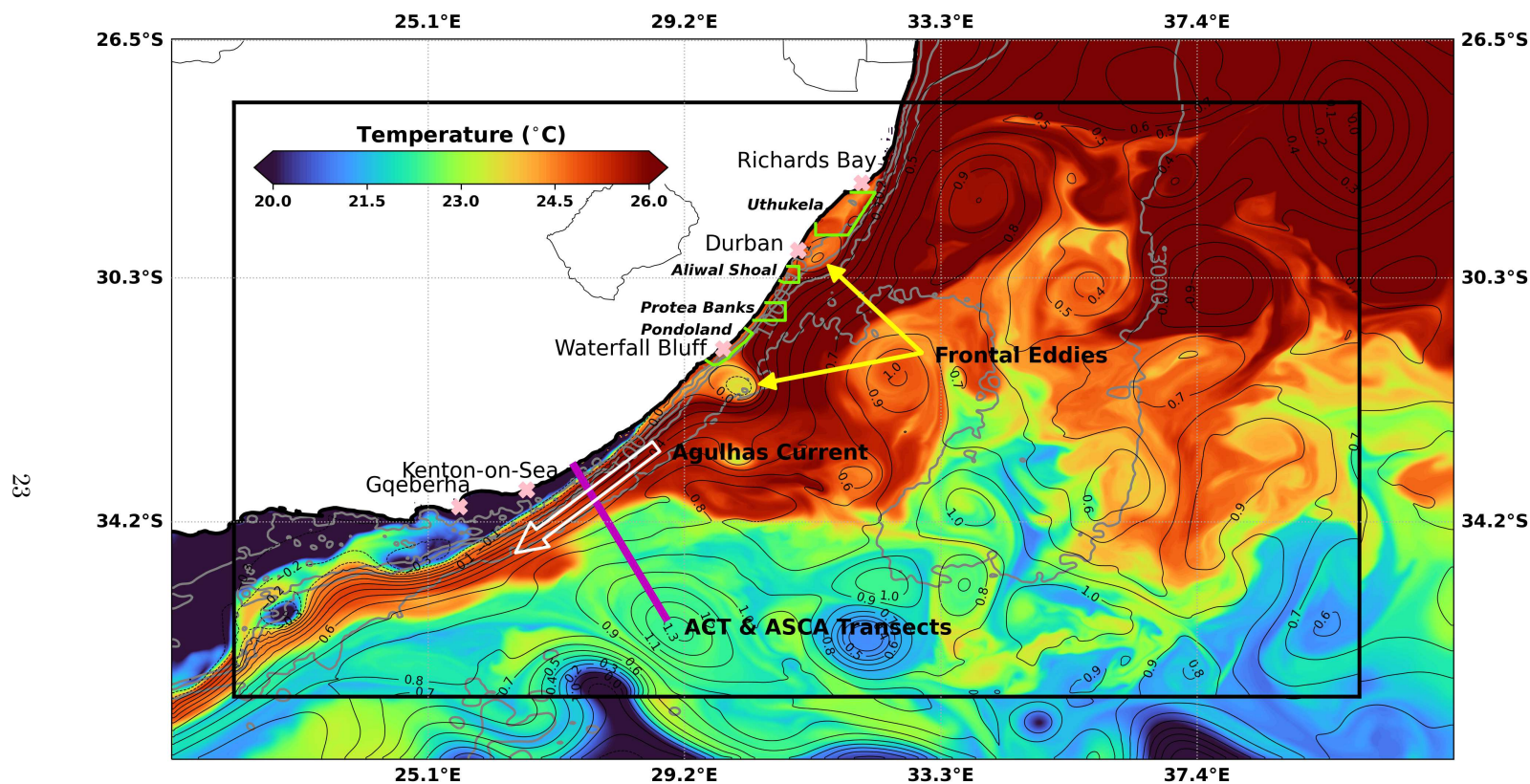


**Fig. 1** Snapshot of modeled sea-surface temperature (colour) of the east coast of South Africa. The coarser outer domain [3 km resolution] and finer inner domain [1 km resolution] are delimited by the black boxes. Contours of modeled sea-surface height [solid black at 0.1 m intervals] and sea-floor topography [solid gray -100 m, 500 m, 1000 m, and 3000 m] are superimposed. The white arrow indicates the direction of the Agulhas Current. Yellow arrows point to frontal eddies found inshore of the current. The locations of Marine Protected Areas (MPAs) are overlaid [green boxes]. Relevant coastal cities are indicated by pink crosses.

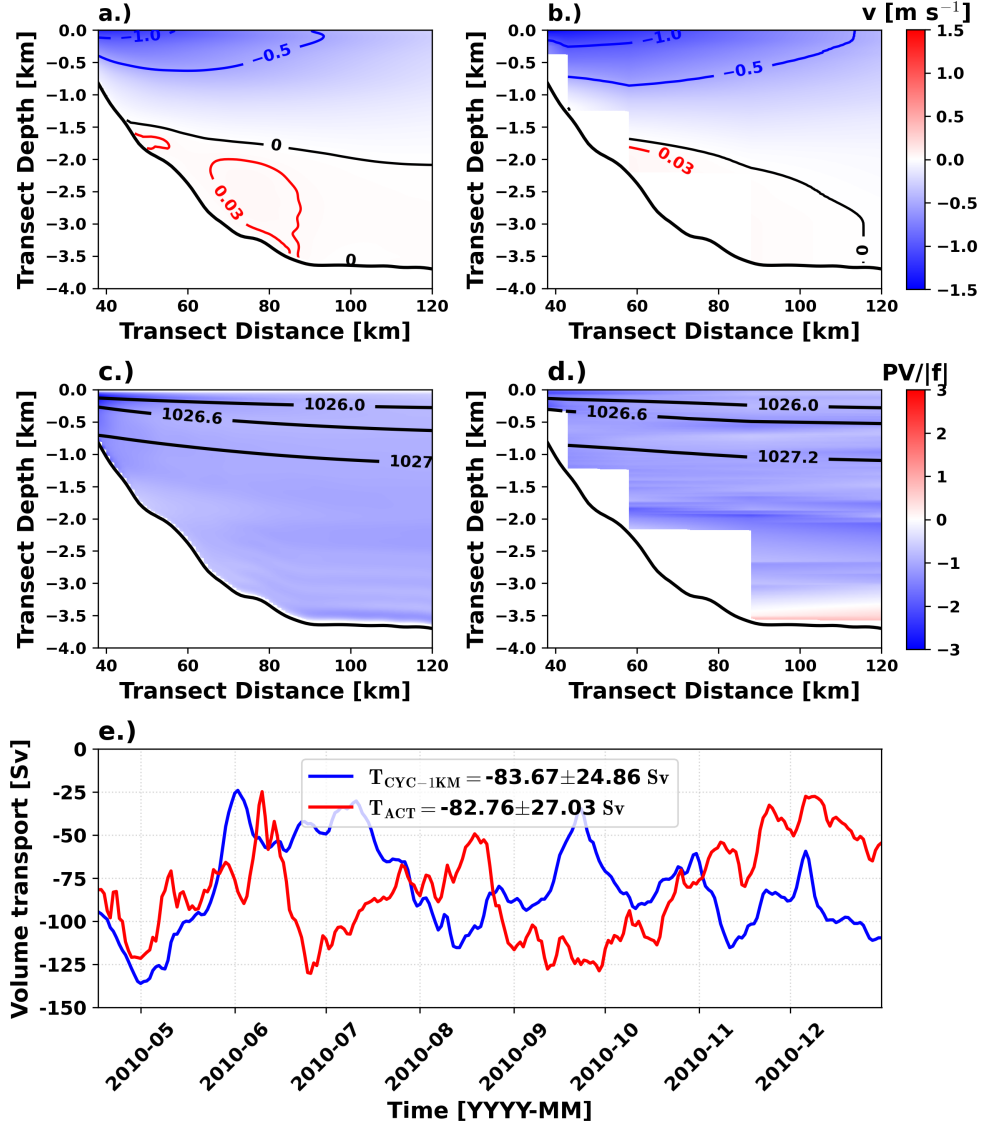


**Fig. 2** Cross-shore transect at 32°S (solid magenta in Fig. 1) of: (a-b): the mean along-shore velocity (colour) obtained in the CYC-1KM simulation (a) and observed in the Agulhas System Climate Array (ASCA) (b). Contours of the along-shore equatorward (solid red, [0.03] m s<sup>-1</sup>) and poleward (solid black, [-1.5, -1, -0.5] m s<sup>-1</sup>) flow are superimposed, as well as the separation between both (solid black) delineating the no flow contour). (c-d): the mean normalised Potential Vorticity  $PV/|f|$  (colour) simulated in CYC-1KM (c) and observed in ASCA (d). Negative (positive) PV represents cyclonic (anticyclonic) circulation. Black contours show the mean isopycnals at 1026.0, 1026.6 and 1027.2 kg m<sup>-3</sup>. (e): Time-series of the volume transport [Sv] of the modeled Agulhas Current in CYC-1KM (blue) and measured along the Agulhas Current Time-series array (ACT, red).

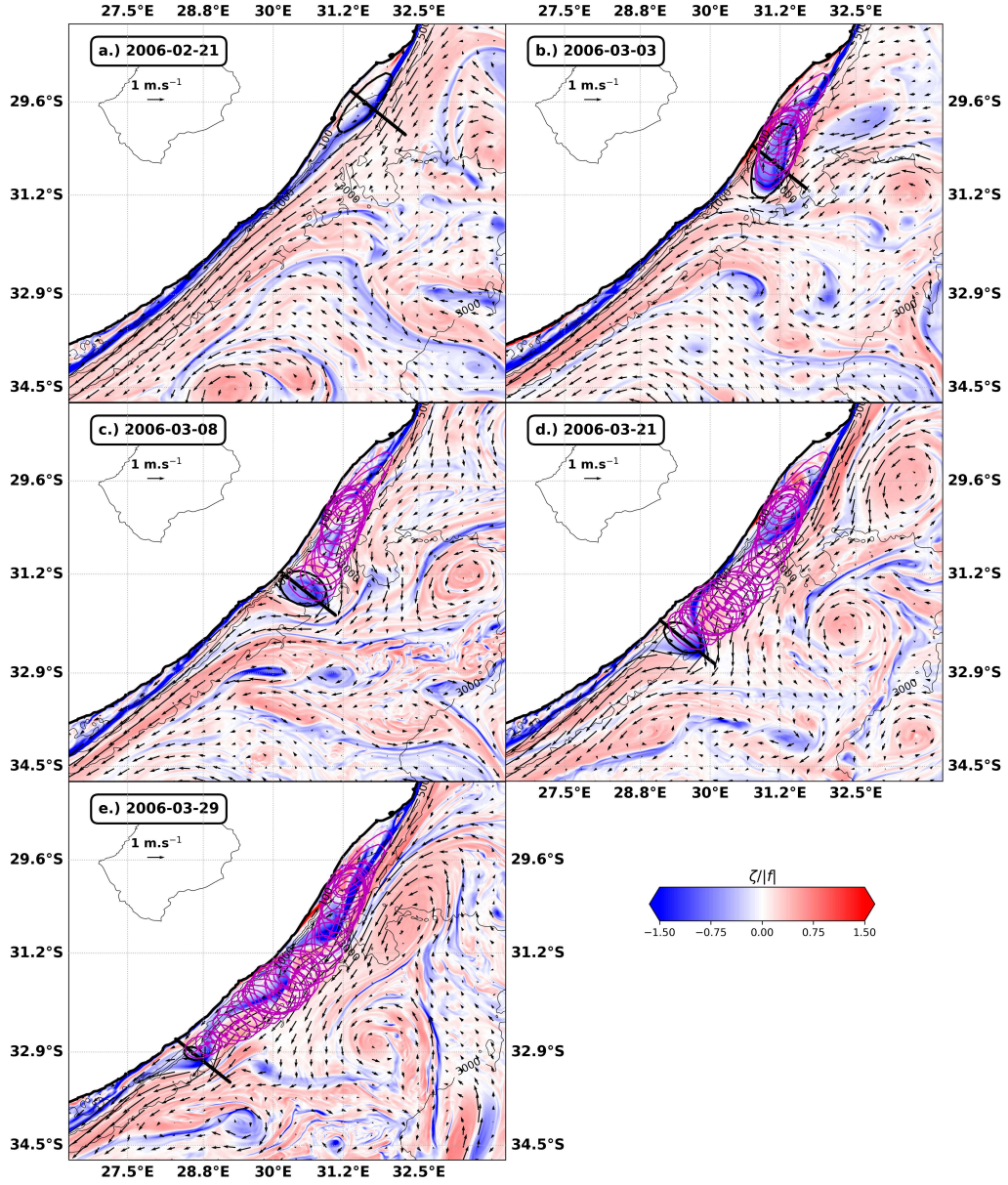


**Fig. 3** Snapshots of modeled relative vorticity, normalised by  $|f|$ , and velocities at the sea-surface of an eddy detected and tracked with the Angular Momentum Eddy Detection and tracking Algorithm (AMEDA) over a 37 day period. The ellipses and dots represents the theoretical ellipse and barycenter of the eddy fitted by the AMEDA eddy detection algorithm, where the magenta ellipses represent the track of the eddy and the black ellipse represents the instantaneous time. The cross-shore transects through the core of the eddy is shown with a black line.

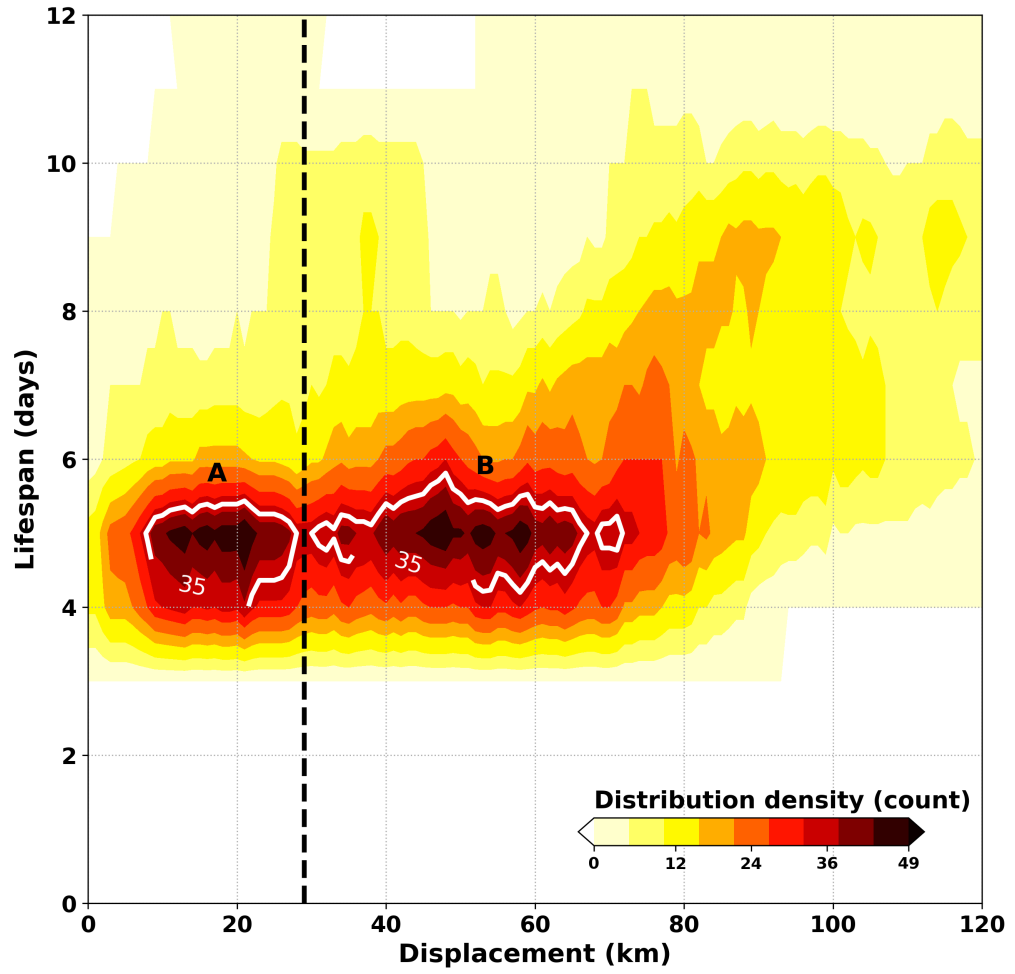


**Fig. 4** Density distribution of the life-span (days) and displacement distance (km) of all eddies detected and tracked with the Angular Momentum Eddy Detection and tracking Algorithm (AMEDA) in CYC-1KM model over 5-years. All eddies are cyclonic, have a lifespan that exceeds 3 days and are confined to the region upstream of Gqeberha. The white contour shows the 97.5 percentile and the dashed black line at 29 km indicates the threshold between the two peaks (Group A - Stationary Eddies, Group B - Propagating Eddies).

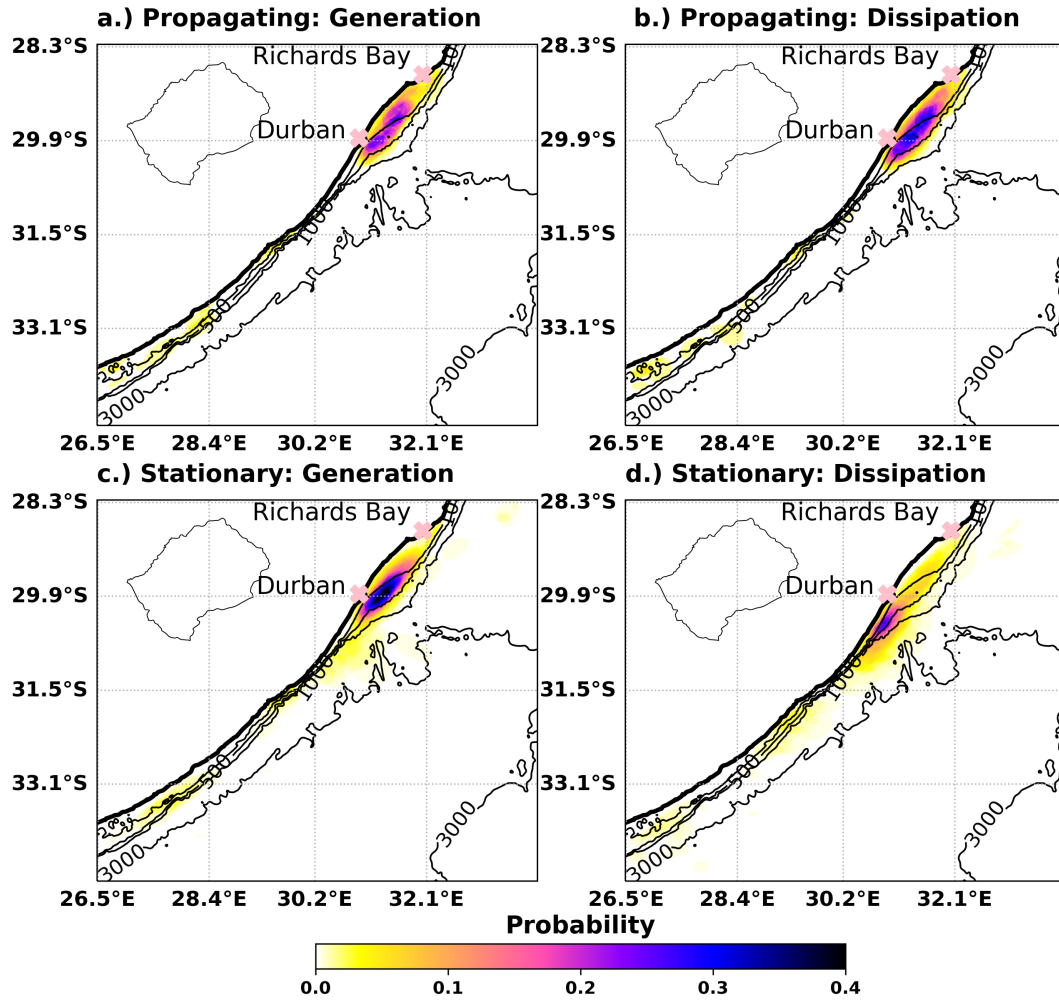


**Fig. 5** Probability density map of the generation (left) and dissipation (right) locations of the stationary (top) and propagating (bottom) eddies detected with the Angular Momentum Eddy Detection and tracking Algorithm (AMEDA) in the CYC-1KM model 5-years. All eddies are cyclonic, have a lifespan that exceeds 3 days and are confined to the region upstream of Gqeberha. Black contours show the 100 m, 500 m, 1000 m and 3000 m isobaths.

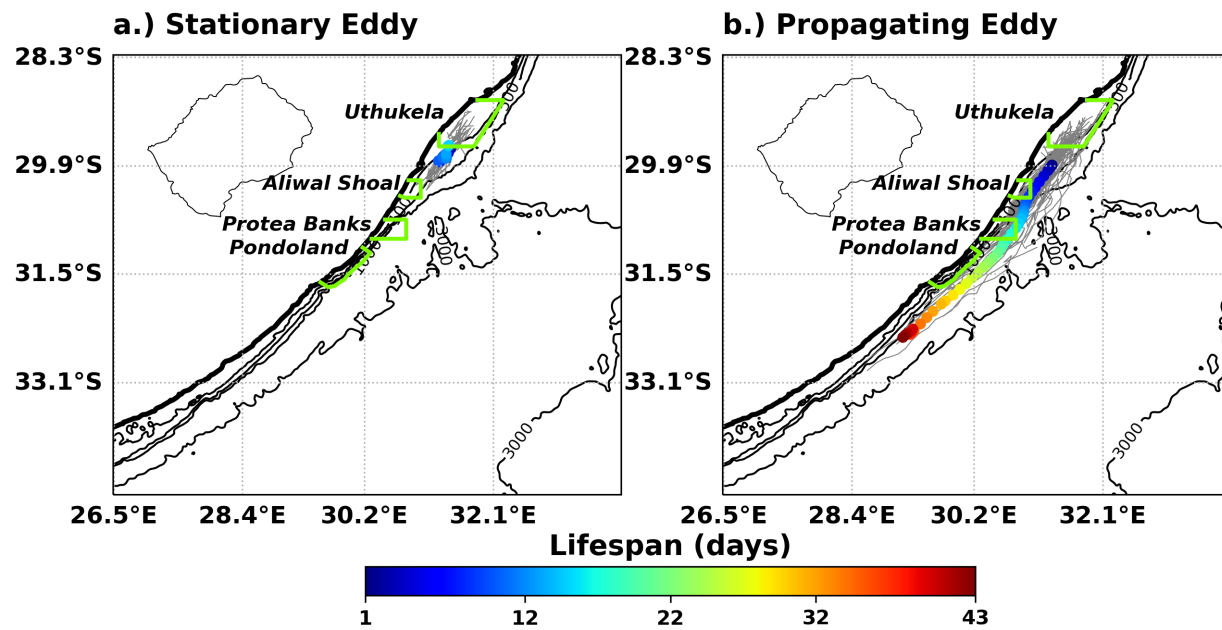


**Fig. 6** Mean stationary (a.) and propagating (b.) eddy trajectory as a function of the eddy lifespan in days (colour). Gray lines indicates trajectories of all the eddies. The 100 m, 500 m, 1000 m and 3000 m isobaths are shown in black contours and the green boxes indicates positions of Marine Protected Areas (MPAs)

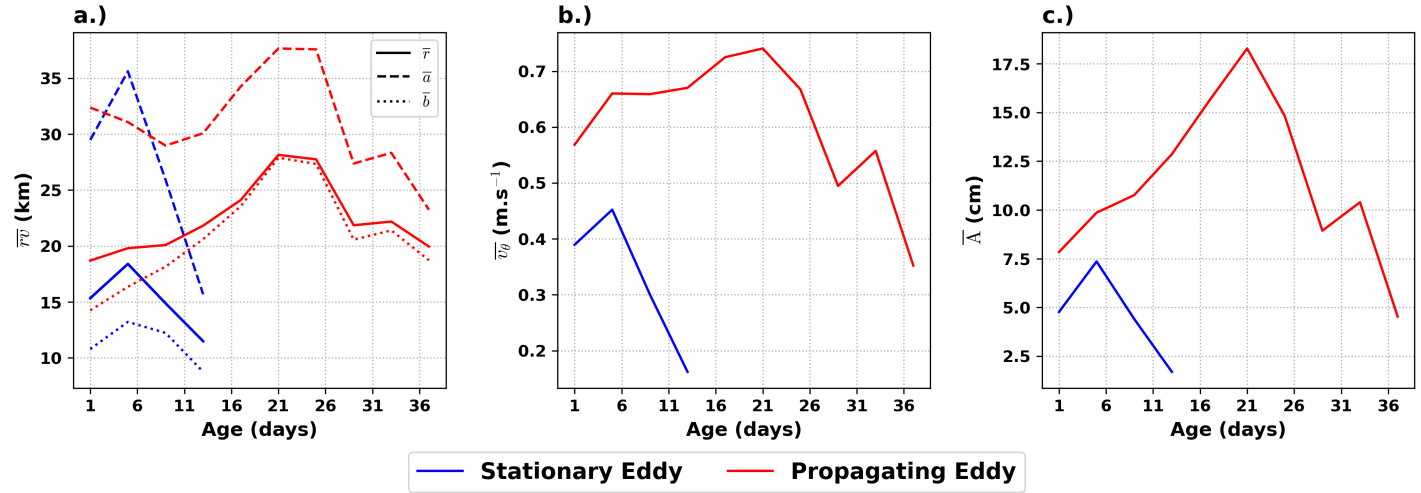


**Fig. 7** Stationary (blue) and propagating (red) eddy characteristics as a function of time in days ( $t$ ). The mean major-axis ( $\overline{a}$ ), minor-axis ( $\overline{b}$ ) and radius ( $\overline{r}$ ) are shown to indicate the evolution of the eddy size (a). The mean azimuth velocity ( $\overline{v}_\theta$ , b) and amplitude ( $\overline{A}$ , c) is indicative of the eddy intensity.

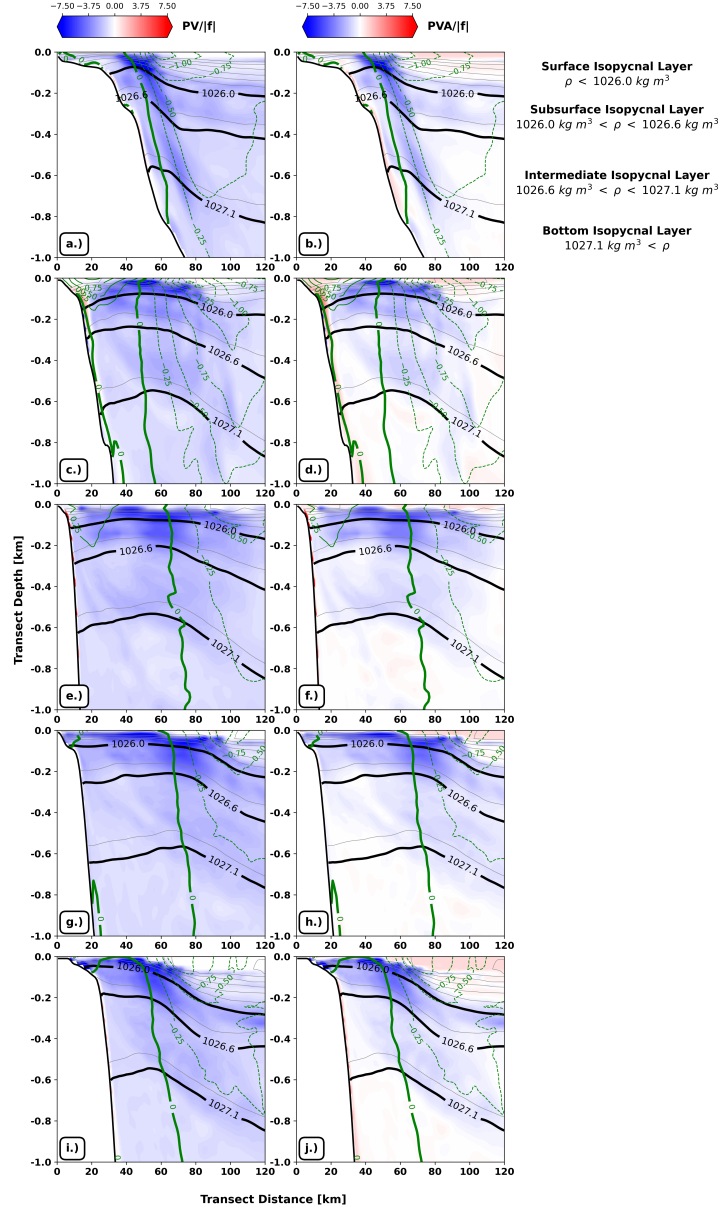


**Fig. 8** Cross-shore transect of PV (left) and PVA (right) through the core of the eddy at the corresponding times as shown in Figure 3. PV and PVA values are normalised by  $|f|$ . Thin grey contours is the densities ( $\rho$ ) from 1025.5 to 1027.4  $\text{kg m}^{-3}$  at every 0.1  $\text{kg m}^{-3}$  interval. Thick black contours represents the isopycnal layers which contains the cores of the PV and PV and are defined as: surface ( $\rho \leq 1026.0 \text{ kg m}^{-3}$ ), subsurface ( $1026.0 < \rho \leq 1026.6 \text{ kg m}^{-3}$ ), intermediate ( $1026.6 < \rho \leq 1027.1 \text{ kg m}^{-3}$ ) and bottom ( $\rho > 1027.1 \text{ kg m}^{-3}$ ) isopycnal layers. Green contours represent the alongshore velocities, where the solid (dashed) contours represent the positive (negative) velocities. The velocities are in  $0.25 \text{ m s}^{-1}$  intervals and the thick green contour is the zero velocity contour.

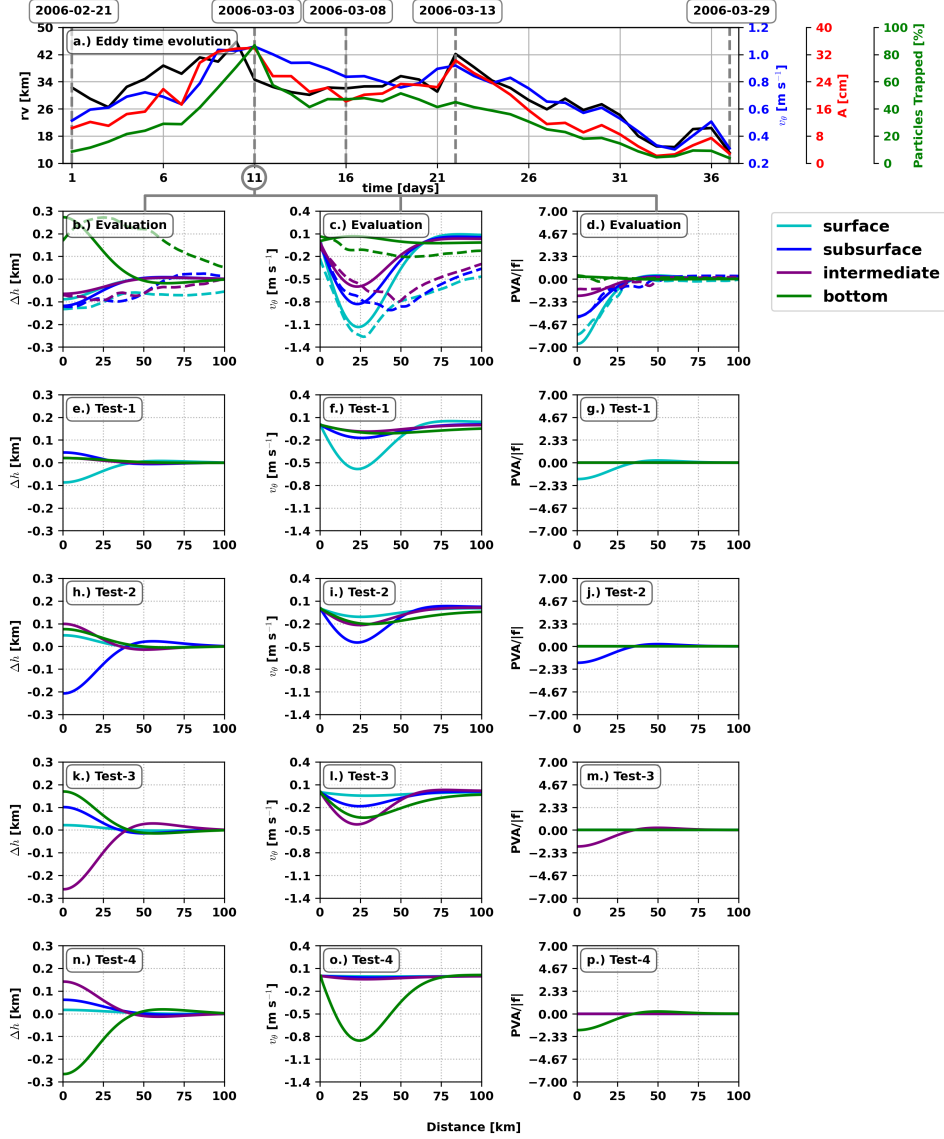


**Fig. 9** (a) Time series of the eddy radius ( $rv$ , black), azimuthal velocity ( $v_\theta$ , blue), and amplitude ( $A$ , red), as well as the percentage of particles trapped within the eddy (green), as a function of time. The vertical dashed lines indicate the generation (21 February 2006), maturation (3 March 2006), migration (8 March 2006), merging (13 March 2006), and dissipation (29 March 2006) phases of the eddy. (b–p) PVA inversion demonstrate the relationship of the PVA profile (right column) and it the change in layer thickness ( $\Delta h$ , left column) and  $v_\theta$  (center column) as a function of the distance from the vortex center. (b–d) Comparison between results obtained from inverting the PVA profile of the analytical axisymmetric vortex (solid lines) and the tracked eddy in CYC-1KM simulation (dashed lines) to evaluate the solution used for inverting the PVA field (see Appendix A). (e–p) Results from inverting the injected PVA within specific isopycnal layers: Test-1 (e–g), Test-2 (h–j), Test-3 (k–m), and Test-4 (n–p). All PVA values are normalised by  $|f|$ .

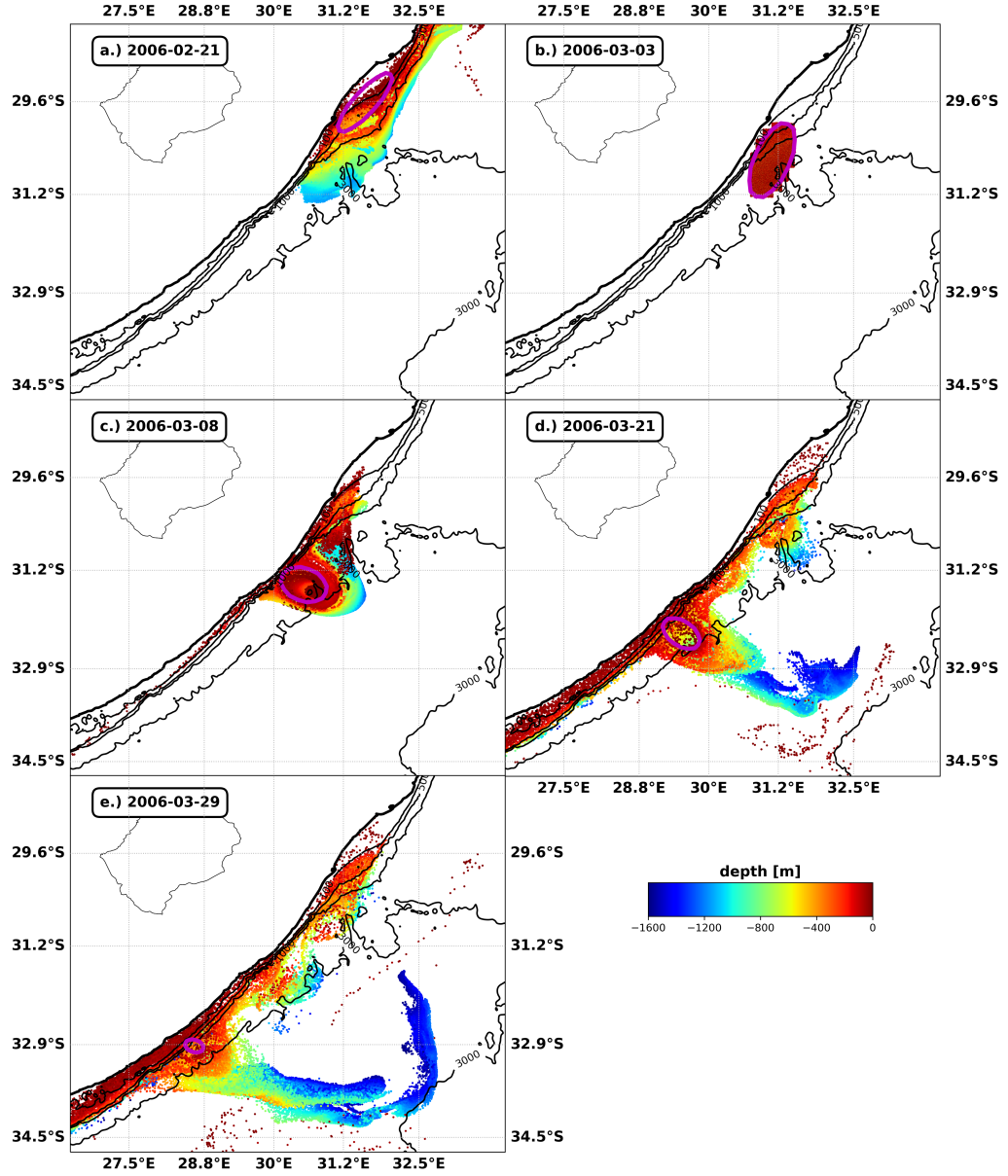


**Fig. 10** Spatial and vertical distribution of the particles seeded within the eddy case study. The snapshots correspond to the times in Figure 3. The magenta ellipses shows the position on the eddy detected with the Angular Momentum Eddy Detection and tracking Algorithm (AMEDA).

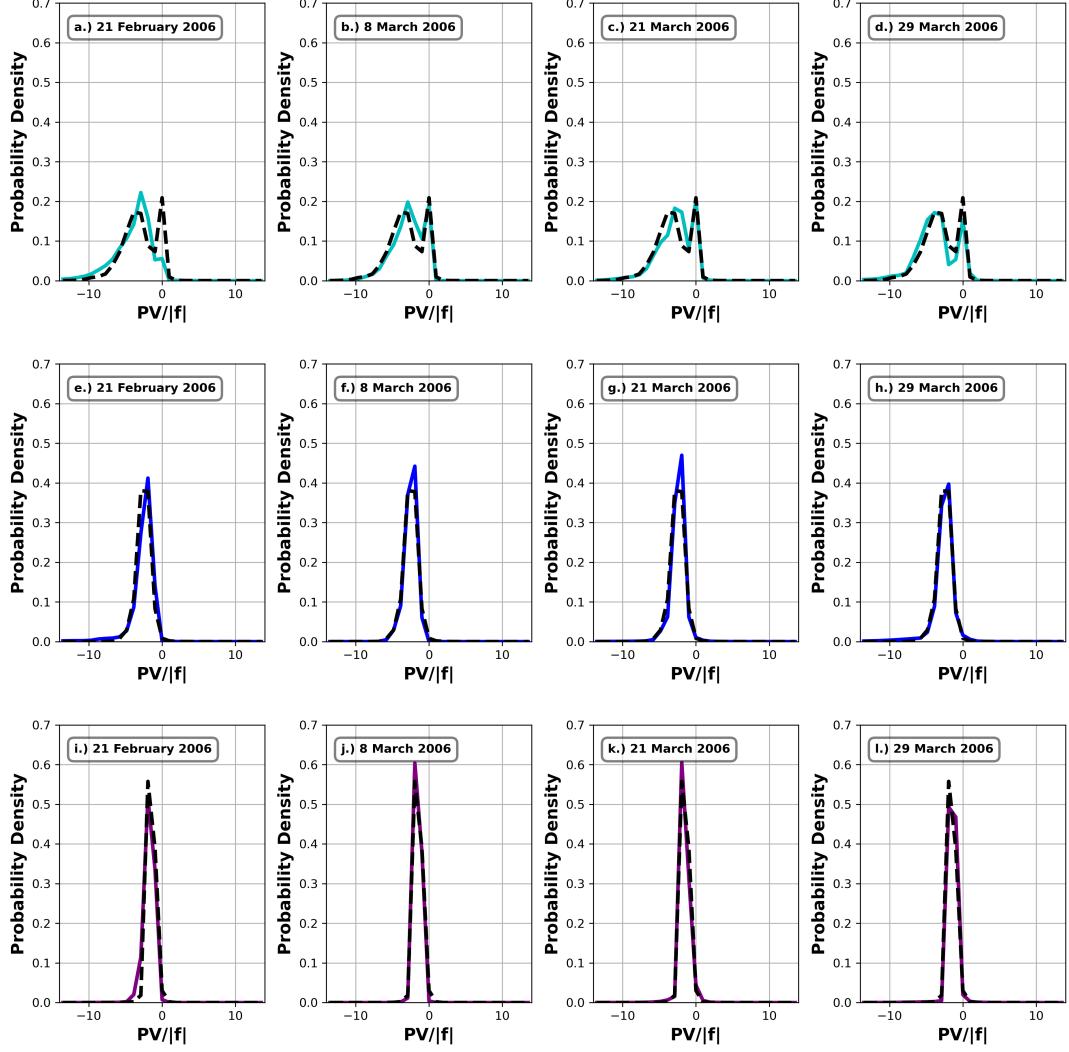


**Fig. 11** PV probability density distribution of the particles trapped within the surface ( $\rho \leq 1026.0 \text{ kg m}^{-3}$ ), intermediate ( $1026.0 < \rho \leq 1026.6 \text{ kg m}^{-3}$ ) and bottom ( $1026.6 \text{ kg m}^{-3} < \rho \leq 1027.1 \text{ kg m}^{-3}$ ) isopycnal layers and are shown with the cyan (a - c), blue (d - f) and purple (g - i) colours respectively. PV values are normalised by  $|f|$ . Dashed black line represents the PV distribution of the eddy at maturity on 3 March 2006 within its respective isopycnal layer.

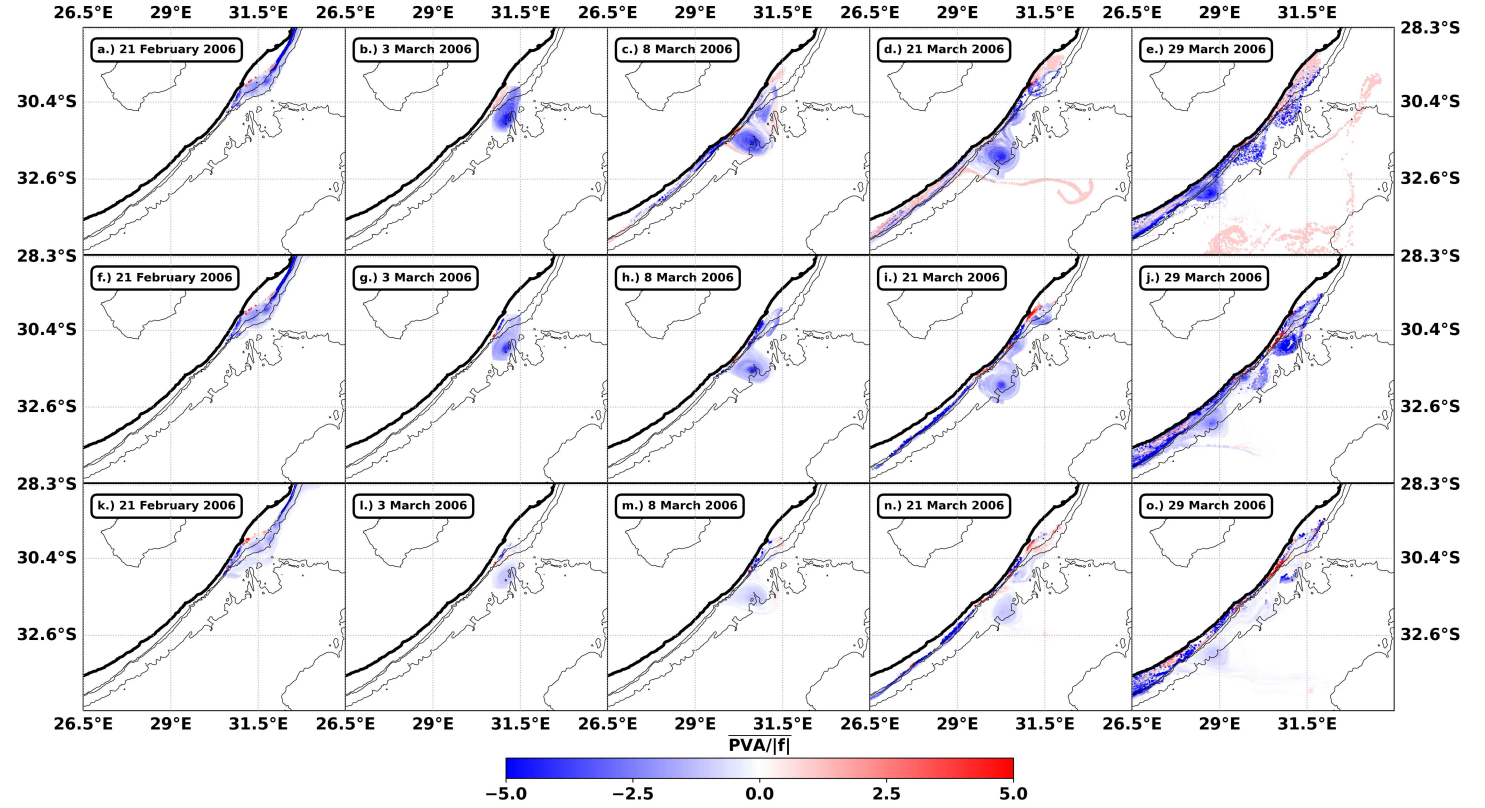


**Fig. 12** Mean Potential Vorticity Anomaly ( $\overline{PVA}$ ), in colour, of the particles seeded at the surface (top,  $\rho \leq 1026.0 \text{ kg m}^{-3}$ ), subsurface (center,  $1026.0 < \rho \leq 1026.6 \text{ kg m}^{-3}$ ) and intermediate (bottom,  $1026.6 \text{ kg m}^{-3} < \rho \leq 1027.1 \text{ kg m}^{-3}$ ) levels. PVA values are normalised by  $|f|$ . The columns represents the timestamps of the generation (21 February 2006), growth (3 March 2006), migration (8 March 2006), merging (13 March 2006) and dissipation (29 March 2006). Black contours represents the topography at 100, 500, 1000 and 3000 m depth.

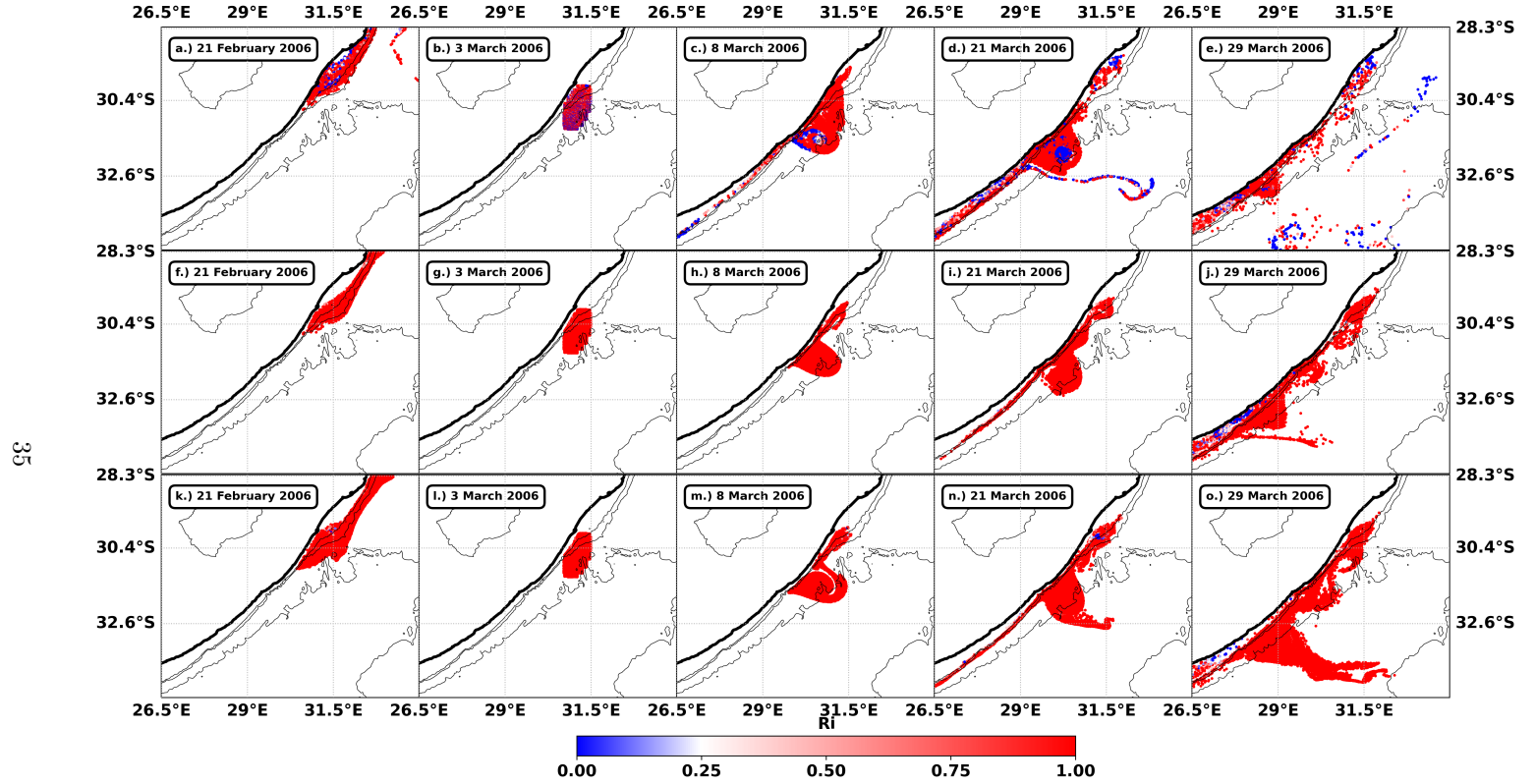


**Fig. 13** Richardson number (Ri), in colour, of the particles seeded at the surface (top,  $\rho \leq 1026.0 \text{ kg m}^{-3}$ ), subsurface (center,  $1026.0 < \rho \leq 1026.6 \text{ kg m}^{-3}$ ) and intermediate (bottom,  $1026.6 \text{ kg m}^{-3} < \rho \leq 1027.1 \text{ kg m}^{-3}$ ) levels. Where  $Ri > 0.25$  it indicates vertical mixing. The columns represents the timestamps of the generation (21 February 2006), growth (3 March 2006), migration (8 March 2006), merging (21 March 2006) and dissipation (29 March 2006). Black contours represents the topography at 100, 500, 1000 and 3000 m depth.

## Appendix A PV-Inversion

This section defines the routine and formulations used to invert the Potential Vorticity Anomaly (PV) for an analytical vortex. By inverting the PV, we can show how the isopycnal layers and the circulation within the vortex respond to the injection of PV.

The set of equations follows the methodology presented in the appendix of [Herbette et al. \(2003\)](#) closely. A N-layer ocean with a flat bottom is considered for the analytical axisymmetric vortex in cyclogeostrophic balance. The vortex is associated with a profile of PV ( $\Delta Q_k$ ). A Gaussian function is used to compute the PV distribution from a PV profile that is set at each isopycnal layer ( $k$ ). The Gaussian-like function is:

$$PVA_k = \Delta Q_k \left(1 - \frac{d^2}{rv^2}\right) \exp\left(-\frac{d^2}{rv^2}\right) \quad (\text{A1})$$

where  $\Delta Q_k$  is the maximum PV within the isopycnal layer ( $k$ ),  $d$  is the distance from the center of the vortex and  $rv$  is the radius of the vortex. By inverting the PV equation, we compute the layer thickness ( $h$ ) and azimuth velocity ( $v_\theta$ ) associated with the PV field and the analytical vortex. The system to solve is:

$$\begin{aligned} \frac{v_{\theta_k}^2}{d} + f v_{\theta_k} &= \partial_d \mathcal{M}_k \\ \mathcal{M}_1 &= g \sum_{i=1}^{i=N_c} \Delta h_i \\ \mathcal{M}_k &= \sum_{i=1}^{i=k-1} \frac{\rho_i}{\rho_k} g \Delta h_i + \sum_{i=k}^{i=N_c} g \Delta h_i \\ \zeta_k - f \frac{\Delta h_k}{H_k} &= \Delta Q_k \left(1 + \frac{\Delta h_k}{H_k}\right) \end{aligned} \quad (\text{A2})$$

where  $f$  is the Coriolis parameter,  $g$  is the Earth's gravity,  $\rho$  is the density,  $H$  is the total depth and  $\mathcal{M}_k$  is the Montgomery potential - pressure along an isopycnal surface - which can be related to the layer thickness ( $h$ ). Furthermore,  $\Delta h_k$  is the variation of the layer thickness and is defined as  $\Delta h_k = h_k - H_k$ , and  $\zeta_k$  is the relative vorticity, defined as  $\zeta_k = 1/d \partial_d (d v_{\theta_k})$ .

The quadratic term associated with the centrifugal force ( $v_{\theta_k}^2/d$ ) makes the system non-linear and its solution complex. Therefore, a numerical iterative method is used in which the quadratic term is approached in each iteration ( $n$ ) by its value at iteration ( $n-1$ ). The first step of the method ( $n=1$ ) assumes geostrophic equilibrium, and the quadratic term is omitted from the equations. Since we assume that our case is isolated and no PV is injected, we define the total PV to be zero. To overcome this constraint, we have chosen to fix  $F_k = \Delta Q_k (1 + \Delta h_k/H_k)$  instead of  $\Delta Q_k$ , therefore, we invert the following system:

$$(\mathbf{M}\nabla^2\Delta h_n)_k - f^2\frac{\Delta h_k^n}{H_k} = F_k + \frac{1}{r}\partial_d(v_{\theta_k}^2)^{n-1} \quad (\text{A3})$$

$$v_{\theta_k}^2 = \frac{1}{f}(\mathbf{M}\partial_d\Delta h)_k - \frac{(v_{\theta_k}^2)^{n-1}}{d} \quad (\text{A4})$$

where  $\mathbf{M}$  is the matrix that links the Montgomery potential ( $\mathcal{M}$ ) to the variation of the layer thickness ( $\Delta h$ ). The boundary conditions are:

$$\lim_{d \rightarrow \infty} (\partial_d \Delta h_k) = 0 \quad (\text{A5})$$

$$\lim_{d \rightarrow \infty} \left( \sum_{k=1}^{k=N} \Delta h_k \right) = 0 \quad (\text{A6})$$

$$v_{\theta_k}(d=0) = 0 \quad (\text{A7})$$

which refers to the variation of the layer thickness (Equation A5) and the sum of the variation of the layer thickness within an isopycnal layer (Equation A6) approaches zero the further away from the vortex center. Additionally, by assuming cyclogeostrophy the circulation, or  $v_\theta$ , is zero at the center of the vortex Equation A7.

The inverted system (Equations A3 & A4) with the defined boundary conditions (Equations A5, A6 & A7) leads to a linear system of partial differential equations that are solved by calculating the eigenvalues and eigenvectors of the matrix ( $\mathbf{M}$ ). The iterations are stopped when the difference between two consecutive iterations of the variation of the layer thickness is very small - less than 1 mm.

## References

- Assene, F., Morel, Y., Delpech, A., Aguedjou, M., Jouanno, J., Cravatte, S., Marin, F., Ménesguen, C., Chaigneau, A., Dadou, I., Alory, G., Holmes, R., Bourles, B., Koch-Larrouy, A.: From mixing to the large scale circulation: How the inverse cascade is involved in the formation of the subsurface currents in the gulf of guinea. *Fluids* **5**(147) (2020). DOI: <https://doi.org/10.3390/fluids5030147>
- Bryden, H.L., Beal, L.M., Duncan, L.M.: Structure and transport of the agulhas current and its temporal variability. *Journal of Oceanography* **61**, 479–492 (2005)
- Burgher, N., Braby, L., Herbette, S., Hermes, J., Roberts, M.: Characterisation of the eddy-driven variability inshore of the agulhas current using sea surface temperature observations. *Continental Shelf Research*, 105598 (2025)
- Beal, L.M., De Ruijter, W.P., Biastoch, A., Zahn, R.: On the role of the agulhas system in ocean circulation and climate. *Nature* **472**(7344), 429–436 (2011)
- Beal, L.M., Elipot, S., Houk, A., Leber, G.M.: Capturing the transport variability of a western boundary jet: Results from the agulhas current time-series experiment (act). *Journal of Physical Oceanography* **45**(5), 1302–1324 (2015). DOI: <https://doi.org/10.1175/JPO-D-14-0119.1>
- Beckmann, A., Haidvogel, B. Dale: Numerical simulation of flow around a tall isolated seamount. part i: problem formulation and model accuracy. *Journal of Physical Oceanography* (1993)
- Barabinot, Y., Speich, S., Carton, X.: Defining mesoscale eddies boundaries from in-situ data and a theoretical framework. *Journal of Geophysical Research: Oceans* **129**(2), 2023–020422 (2024)
- Becker, J., Sandwell, D., Smith, W., Braud, J., Binder, B., Depner, J., Fabre, D., Factor, J., Ingalls, S., Kim, S., *et al.*: Global bathymetry and elevation data at 30 arc seconds resolution: Srtm30-plus. *Marine Geodesy* **32**(4), 355–371 (2009)
- Bowen, M.M., Wilkin, J.L., Emery, W.J.: Variability and forcing of the east australian current. *Journal of Geophysical Research: Oceans* **110**(C3) (2005)
- Cheng, Y.-H., Chang, M.-H., Ko, D.S., Jan, S., Andres, M., Kirincich, A., Yang, Y.J., Tai, J.-H.: Submesoscale eddy and frontal instabilities in the kuroshio interacting with a cape south of taiwan. *Journal of Geophysical Research: Oceans* **125**(5), 2020–016123 (2020)
- Churchill, J.H., Gawarkiewicz, G.: Shelfbreak frontal eddies over the continental slope north of cape hatteras. *Journal of Geophysical Research: Oceans* **114**(C2) (2009)
- Calil, P.H., Suzuki, N., Baschek, B., Silveira, I.C.: Filaments, fronts and eddies in the

- cabo frio coastal upwelling system, brazil. *Fluids* **6**(2), 54 (2021)
- Debreu, L., Marchesiello, P., Penven, P., Cambon, G.: Two-way nesting in split-explicit ocean models: algorithms, implementation and validation. *Ocean Modelling* **49**, 1–21 (2012)
- Ruijter, W.P., Aken, H.M., Beier, E.J., Lutjeharms, J., Matano, R.P., Schouten, M.W.: Eddies and dipoles around south madagascar: formation, pathways and large-scale impact. *Deep Sea Research Part I: Oceanographic Research Papers* **51**(3), 383–400 (2004)
- Everett, J., Macdonald, H., Baird, M., Humphries, J., Roughan, M., Suthers, I.: Cyclonic entrainment of preconditioned shelf waters into a frontal eddy. *Journal of Geophysical Research: Oceans* **120**(2), 677–691 (2015)
- Ertel, H.: Ein neuer hydrodynamischer erhaltungssatz. *Naturwissenschaften* **30**, 543–544 (1942). DOI: <https://doi.org/10.1007/BF01475602>10.1007/BF01475602
- Fairall, C.W., Bradley, E.F., Hare, J.E., Grachev, A.A., Edson, J.B.: Bulk Parameterization of Air–Sea Fluxes: Updates and Verification for the COARE Algorithm. *Journal of Climate* **16**(4), 571–591 (2003) [https://doi.org/10.1175/1520-0442\(2003\)016<0571:BPOASF>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<0571:BPOASF>2.0.CO;2)
- Goschen, W., Bornman, T., Deyzel, S., Schumann, E.: Coastal upwelling on the far eastern agulhas bank associated with large meanders in the agulhas current. *Continental Shelf Research* **101**, 34–46 (2015)
- Gunn, K.L., Beal, L.M., Elipot, S., McMonigal, K., Houk, A.: Mixing of subtropical, central, and intermediate waters driven by shifting and pulsing of the agulhas current. *Journal of physical oceanography* **50**(12), 3545–3560 (2020)
- Glenn, S.M., Ebbesmeyer, C.C.: Observations of gulf stream frontal eddies in the vicinity of cape hatteras. *Journal of Geophysical Research: Oceans* **99**(C3), 5047–5055 (1994)
- Gula, J., Molemaker, M.J., McWilliams, J.C.: Submesoscale cold filaments in the gulf stream. *Journal of Physical Oceanography* **44**(10), 2617–2643 (2014). DOI: <https://doi.org/10.1175/JPO-D-14-0029.1>10.1175/JPO-D-14-0029.1
- Gula, J., Molemaker, M.J., McWilliams, J.C.: Gulf stream dynamics along the southeastern us seaboard. *Journal of Physical Oceanography* **45**(3), 690–715 (2015)
- Gula, J., Molemaker, M.J., McWilliams, J.C.: Submesoscale dynamics of a gulf stream frontal eddy in the south atlantic bight. *Journal of Physical Oceanography* **46**(1), 305–325 (2016)
- Guastella, L., Roberts, M.: Dynamics and role of the durban cyclonic eddy in the

- kwazulu-natal bight ecosystem. *African Journal of Marine Science* **38**(sup1), 23–42 (2016)
- Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., *et al.*: The era5 global reanalysis. *Quarterly journal of the royal meteorological society* **146**(730), 1999–2049 (2020)
- Halo, I., Backeberg, B., Penven, P., Ansorge, I., Reason, C., Ullgren, J.: Eddy properties in the mozambique channel: A comparison between observations and two numerical ocean circulation models. *Deep Sea Research Part II: Topical Studies in Oceanography* **100**, 38–53 (2014). DOI: [10.1016/j.dsr2.2013.10.015](https://doi.org/10.1016/j.dsr2.2013.10.015)
- Hatzonikolakis, Y., Giakoumi, S., Raitos, D.E., Tsiaras, K., Kalaroni, S., Triantaphyllidis, G., Triantafyllou, G.: Quantifying transboundary plastic pollution in marine protected areas across the mediterranean sea. *Frontiers in Marine Science* **8**, 762235 (2022)
- Heye, S., Krug, M., Penven, P., Hart-Davis, M.: The natal bight coastal counter-current: A modeling study. *Continental Shelf Research* **249**, 104852 (2022)
- Herbette, S., Morel, Y., Arhan, M.: Erosion of a surface vortex by a seamount. *Journal of Physical Oceanography* **33**(8), 1664–1679 (2003). DOI: [https://doi.org/10.1175/1520-0485\(2003\)033<1664:EOASVB>2.0.CO;2](https://doi.org/10.1175/1520-0485(2003)033<1664:EOASVB>2.0.CO;2)
- Itoh, S., Sugimoto, T.: Current variability of the kuroshio near the separation point from the western boundary. *Journal of Geophysical Research: Oceans* **113**(C11) (2008)
- James, C., Wimbush, M., Ichikawa, H.: Kuroshio meanders in the east china sea. *Journal of Physical Oceanography* **29**(2), 259–272 (1999)
- Kasai, A., Kimura, S., Nakata, H., Okazaki, Y.: Entrainment of coastal water into a frontal eddy of the kuroshio and its biological significance. *Journal of Marine Systems* **37**(1-3), 185–198 (2002)
- Krug, M., Penven, P.: New perspectives on natal pulses from satellite observations. *Journal of Geophysical Research: Oceans* **116**(C7) (2011) <https://doi.org/10.1029/2010JC006866>
- Lee, T.N., Atkinson, L.P.: Low-frequency current and temperature variability from gulf stream frontal eddies and atmospheric forcing along the southeast us outer continental shelf. *Journal of Geophysical Research: Oceans* **88**(C8), 4541–4567 (1983)
- Lutjeharms, J., Boebel, O., Rossby, H.: Agulhas cyclones. *Deep Sea Research Part II: Topical Studies in Oceanography* **50**(1), 13–34 (2003). DOI: [https://doi.org/10.1016/S0967-6675\(02\)00101-1](https://doi.org/10.1016/S0967-6675(02)00101-1)

- Liu, Y., Dong, C., Liu, X., Dong, J.: Antisymmetry of oceanic eddies across the kuroshio over a shelfbreak. *Scientific Reports* **7**(1), 6761 (2017)
- Lee, T.N.: Florida current spin-off eddies. In: *Deep Sea Research and Oceanographic Abstracts*, vol. 22, pp. 753–765 (1975). Elsevier
- Lellouche, J.-M., Greiner, E., Bourdalle-Badie, R., Garric, G., Melet, A., Dréville, M., Bricaud, C., Hamon, M., Le Galloudec, O., Regnier, C., *et al.*: The copernicus global 1/12° oceanic and sea ice glorys12 reanalysis. *Frontiers in Earth Science* **9**, 585 (2021)
- Lemarié, F., Kurian, J., Shchepetkin, A.F., Jeroen Molemaker, M., Colas, F., McWilliams, J.C.: Are there inescapable issues prohibiting the use of terrain-following coordinates in climate models? **42**, 57–79 (2012) <https://doi.org/10.1016/j.ocemod.2011.11.007>
- Lee, T.N., Mayer, D.A.: Low-frequency current variability and spin-off eddies along the shelf off southeast florida (1977)
- Large, W.G., McWilliams, J.C., Doney, S.C.: Oceanic vertical mixing: A review and a model with a nonlocal boundary layer parameterization. *Reviews of geophysics* **32**(4), 363–403 (1994)
- Lorenz, E.N.: Available potential energy and the maintenance of the general circulation. *Tellus* **7**(2), 157–167 (1955). DOI: <https://doi.org/10.3402/tellusa.v7i2.8796>
- Lutjeharms, J.: Three decades of research on the greater agulhas current. *Ocean Science* **3**(1), 129–147 (2007)
- Lutjeharms, J., Van Ballegooyen, R.: Anomalous upstream retroflection in the agulhas current. *Science* **240**(4860), 1770–1770 (1988)
- Le Vu, B., Stegner, A., Arsouze, T.: Angular momentum eddy detection and tracking algorithm (ameda) and its application to coastal eddy formation. *Journal of Atmospheric and Oceanic Technology* **35**(4), 739–762 (2018)
- Malan, N., Archer, M., Roughan, M., Cetina-Heredia, P., Hemming, M., Rocha, C., Schaeffer, A., Suthers, I., Queiroz, E.: Eddy-driven cross-shelf transport in the east australian current separation zone. *Journal of Geophysical Research: Oceans* **125**(2), 2019–015613 (2020)
- Malan, N., Backeberg, B., Biastoch, A., Durgadoo, J.V., Samuelsen, A., Reason, C., Hermes, J.: Agulhas current meanders facilitate shelf-slope exchange on the eastern agulhas bank. *Journal of Geophysical Research: Oceans* **123**(7), 4762–4778 (2018)

- McMonigal, K., Beal, L.M., Elipot, S., Gunn, K.L., Hermes, J., Morris, T., Houk, A.: The impact of meanders, deepening and broadening, and seasonality on agulhas current temperature variability. *Journal of physical oceanography* **50**(12), 3529–3544 (2020)
- Mkhinini, N., Coimbra, A.L.S., Stegner, A., Arsouze, T., Taupier-Letage, I., 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**(12), 8603–8626 (2014). DOI: <https://doi.org/10.1002/2014JC010176>
- Marchesiello, P., Debreu, L., Couvelard, X.: Spurious diapycnal mixing in terrain-following coordinate models: The problem and a solution. *Ocean Modelling* **26**(3-4), 156–169 (2009) <https://doi.org/10.1016/j.ocemod.2008.09.004>
- Morel, Y., Gula, J., Ponte, A.: Potential vorticity diagnostics based on balances between volume integral and boundary conditions. *Ocean Modelling* **138**, 23–35 (2019). DOI: <https://doi.org/10.1016/j.ocemod.2019.04.004>
- Mann-Lang, J., Branch, G., Mann, B., Sink, K., Kirkman, S., Adams, R.: Social and economic effects of marine protected areas in south africa, with recommendations for future assessments. *African Journal of Marine Science* **43**(3), 367–387 (2021)
- Morel, Y., Morvan, G., Benshila, R., Renault, L., Gula, J., Auclair, F.: An “objective” definition of potential vorticity. generalized evolution equation and application to the study of coastal upwelling instability. *Ocean Modelling* **186**, 102287 (2023). DOI: <https://doi.org/10.1016/j.ocemod.2023.102287>
- Marchesiello, P., McWilliams, J.C., Shchepetkin, A.: Open boundary conditions for long-term integration of regional oceanic models **3**(1–2), 1–20 (2001) [https://doi.org/10.1016/S1463-5003\(00\)00013-5](https://doi.org/10.1016/S1463-5003(00)00013-5)
- Mitarai, S., Siegel, D., Watson, J., Dong, C., McWilliams, J.: Quantifying connectivity in the coastal ocean with application to the southern california bight. *Journal of Geophysical Research: Oceans* **114**(C10) (2009)
- Müller, P.: *The Equations of Oceanic Motions*. Cambridge University Press, ??? (2006)
- Nagai, T., Gruber, N., Frenzel, H., Lachkar, Z., McWilliams, J.C., Plattner, G.-K.: Dominant role of eddies and filaments in the offshore transport of carbon and nutrients in the c alifornia c urrent s ystem. *Journal of Geophysical Research: Oceans* **120**(8), 5318–5341 (2015)
- Oey, L.-Y.: A model of gulf stream frontal instabilities, meanders and eddies along the continental slope. *Journal of physical oceanography* **18**(2), 211–229 (1988)

- Okubo, A.: Horizontal dispersion of floatable particles in the vicinity of velocity singularities such as convergences. In: Deep Sea Research and Oceanographic Abstracts, vol. 17, pp. 445–454 (1970). Elsevier
- Pedlosky, J.: Geophysical Fluid Dynamics. Springer, ??? (1987)
- Penven, P., Echevin, V., Pasapera, J., Colas, F., Tam, J.: Average circulation, seasonal cycle, and mesoscale dynamics of the peru current system: A modeling approach. *Journal of Geophysical Research: Oceans* **110**(C10) (2005). DOI: <https://doi.org/10.1029/2005JC002945>
- Pivan, X., Krug, M., Herbette, S.: Observations of the vertical and temporal evolution of a n atal p ulse along the e astern a gulhas b ank. *Journal of Geophysical Research: Oceans* **121**(9), 7108–7122 (2016). DOI: <https://doi.org/10.1002/2015JC011582>
- Paldor, N., Lutjeharms, J.: Why is the stability of the agulhas current geographically bi-modal? *Geophysical research letters* **36**(14) (2009)
- Peer, N., Muhl, E.-K., Janna, J., Brown, M., Zukulu, S., Mbatha, P.: Community and marine conservation in south africa: Are we still missing the mark? *Frontiers in Marine Science* **9**, 884442 (2022)
- Roughan, M., Keating, S., Schaeffer, A., Cetina Heredia, P., Rocha, C., Griffin, D., Robertson, R., Suthers, I.: A tale of two eddies: The biophysical characteristics of two contrasting cyclonic eddies in the e ast a ustralian c urrent s ystem. *Journal of Geophysical Research: Oceans* **122**(3), 2494–2518 (2017)
- Ridderinkhof, W., Le Bars, D., Heydt, A., De Ruijter, W.: Dipoles of the south east madagascar current. *Geophysical Research Letters* **40**(3), 558–562 (2013)
- Renault, L., Masson, S., Arsouze, T., Madec, G., McWilliams, J.C.: Recipes for how to force oceanic model dynamics. *Journal of Advances in Modeling Earth Systems* **12**(2), 2019–001715 (2020) <https://doi.org/10.1029/2019MS001715> <https://agupubs.onlinelibrary.wiley.com/doi/pdf/10.1029/2019MS001715>. e2019MS001715 10.1029/2019MS001715
- Roberts, M., Nieuwenhuys, C.: Observations and mechanisms of upwelling in the northern kwazulu-natal bight, south africa. *African Journal of Marine Science* **38**(sup1), 43–63 (2016)
- Roberts, M., Nieuwenhuys, C., Guastella, L.: Circulation of shelf waters in the kwazulu-natal bight, south africa. *African Journal of Marine Science* **38**(sup1), 7–21 (2016)
- Robinson, J., New, A., Popova, E., Srokosz, M., Yool, A.: Far-field connectivity of the uk’s four largest marine protected areas: Four of a kind? *Earth’s Future* **5**(5),

475–494 (2017)

- Rocha, C.B., Simoes-Sousa, I.T.: Compact mesoscale eddies in the south brazil bight. *Remote Sensing* **14**(22), 5781 (2022)
- Ribbe, J., Toaspern, L., Wolff, J.-O., Ismail, M.F.A.: Frontal eddies along a western boundary current. *Continental Shelf Research* **165**, 51–59 (2018)
- Roberts, M., Lingen, C., Whittle, C., Berg, M.: Shelf currents, lee-trapped and transient eddies on the inshore boundary of the agulhas current, south africa: their relevance to the kwazulu-natal sardine run. *African Journal of Marine Science* **32**(2), 423–447 (2010)
- Schouten, M.W., De Ruijter, W.P., Van Leeuwen, P.J.: Upstream control of agulhas ring shedding. *Journal of Geophysical Research: Oceans* **107**(C8), 23–1 (2002)
- Schleyer, M.H., Floros, C., Laing, S.C., Macdonald, A.H., Montoya-Maya, P.H., Morris, T., Porter, S.N., Seré, M.G.: What can south african reefs tell us about the future of high-latitude coral systems? *Marine pollution bulletin* **136**, 491–507 (2018)
- Schubert, R., Gula, J., Biastoch, A.: Submesoscale flows impact agulhas leakage in ocean simulations. *Communications Earth & Environment* **2**(1), 197 (2021)
- Schaeffer, A., Gramoulle, A., Roughan, M., Mantovanelli, A.: Characterizing frontal eddies along the east australian current from hf radar observations. *Journal of Geophysical Research: Oceans* **122**(5), 3964–3980 (2017)
- Shchepetkin, A.F., McWilliams, J.C.: Quasi-Monotone Advection Schemes Based on Explicit Locally Adaptive Dissipation **126**(6), 1541–1580 (1998) [https://doi.org/10.1175/1520-0493\(1998\)126<1541:QMASBO>2.0.CO;2](https://doi.org/10.1175/1520-0493(1998)126<1541:QMASBO>2.0.CO;2)
- Shchepetkin, A.F., McWilliams, J.C.: A method for computing horizontal pressure-gradient force in an oceanic model with a nonaligned vertical coordinate. *Journal of Geophysical Research: Oceans* **108**(C3) (2003)
- Shchepetkin, A.F., McWilliams, J.C.: The regional oceanic modeling system (roms): a split-explicit, free-surface, topography-following-coordinate oceanic model. *Ocean modelling* **9**(4), 347–404 (2005)
- Sowman, M., Sunde, J.: Social impacts of marine protected areas in south africa on coastal fishing communities. *Ocean & coastal management* **157**, 168–179 (2018)
- Tseng, Y.-h., Ferziger, J.H.: Mixing and available potential energy in stratified flows. *Physics of Fluids* **13**(5), 1281–1293 (2001). DOI: <https://doi.org/10.1063/1.1358307>
- Tedesco, P., Gula, J., Ménesguen, C., Penven, P., Krug, M.: Generation of submesoscale frontal eddies in the agulhas current. *Journal of Geophysical Research:*

Oceans **124**(11), 7606–7625 (2019)

Tsugawa, M., Hasumi, H.: Generation and growth mechanism of the natal pulse. *Journal of Physical Oceanography* **40**(7), 1597–1612 (2010). DOI: <https://doi.org/10.1175/2010JPO4347.1>

Ternon, J.-F., Roberts, M., Morris, T., Hancke, L., Backeberg, B.: In situ measured current structures of the eddy field in the mozambique channel. *Deep Sea Research Part II: Topical Studies in Oceanography* **100**, 10–26 (2014)

Vaart, P., Ruijter, W.: Stability of western boundary currents with an application to pulslike behavior of the agulhas current. *Journal of physical oceanography* **31**(9), 2625–2644 (2001)