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**Key Points:**

- Eddies dissipate as they approach the Agulhas Current
- Eddies affect Agulhas Current velocities
- Eddies can cause meanders in the Agulhas Current

**Supporting Information:**

- Supporting information S1

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# Observed eddy dissipation in the Agulhas Current

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**Abstract** Analyzing eddy characteristics from a global data set of automatically tracked eddies for the Agulhas Current in combination with surface drifters as well as geostrophic currents from satellite altimeters, it is shown that eddies from the Mozambique Channel and south of Madagascar dissipate as they approach the Agulhas Current. By tracking the offshore position of the current core and its velocity at 30°S in relation to eddies, it is demonstrated that eddy dissipation occurs through a transfer of momentum, where anticyclones consistently induce positive velocity anomalies, and cyclones reduce the velocities and cause offshore meanders. Composite analyses of the anticyclonic (cyclonic) eddy-current interaction events demonstrate that the positive (negative) velocity anomalies propagate downstream in the Agulhas Current at 44 km/d (23 km/d). Many models are unable to represent these eddy dissipation processes, affecting our understanding of the Agulhas Current.

## 1. Introduction

Variability in the northern Agulhas Current is influenced by both cyclonic and anticyclonic mesoscale eddies, originating from the Mozambique Channel and south of Madagascar (hereafter referred to as source region eddies) and which propagate toward the offshore edge of the Agulhas Current [*Schouten et al.*, 2002; *Harlander et al.*, 2009; *Backeberg and Reason*, 2010; *Collins et al.*, 2014]. Past studies focused on the influence anticyclonic eddies have in destabilizing the current's trajectory and thus triggering cyclonic meanders known as Natal Pulses [*de Ruijter et al.*, 1999; *Schouten et al.*, 2002; *Tsugawa and Hasumi*, 2010]. These pulses have been shown to propagate poleward along the offshore edge of the Agulhas Current [*van Leeuwen et al.*, 2000; *Backeberg et al.*, 2008], occasionally affecting the Agulhas retroflection dynamics, by causing an upstream retroflection of the Agulhas Current [*Lutjeharms and van Ballegooyen*, 1988], thereby affecting the leakage of warm and salty waters into the South Atlantic Ocean [*Biastoch et al.*, 2008; *Loveday et al.*, 2014]. In contrast, the impact of cyclonic eddies on the dynamics of the Agulhas Current is less known. Indeed, the need for improved understanding of such interactions has been highlighted by *Zhai et al.* [2010] and *Rouault and Penven* [2011].

The mesoscale eddy circulation in the Mozambique Channel and south of Madagascar is complex, and both cyclonic and anticyclonic eddies regularly propagate from these source regions toward the Agulhas Current. However, the mechanisms for eddy entrainment and their dissipation in the Agulhas Current are not well understood. The region is poorly observed and numerical models tend to exaggerate the frequency and scales of eddies approaching the Agulhas Current. This is further evident by the eddy kinetic energy (EKE) distribution of eddy-resolving models [*Backeberg et al.*, 2014; *Durgadoo et al.*, 2013; *Loveday et al.*, 2014], where higher levels of EKE have been observed further from the coast than satellite altimetry observations suggest [*Penven et al.*, 2006; *Biastoch et al.*, 2008].

Globally, western boundary currents are known to be sinks for ocean-eddy energy [*Zhai et al.*, 2010], and conventionally, anticyclonic and cyclonic eddies interacting with a wall are known to propagate poleward and equatorward, respectively, along a continental shelf [*Shi and Nof*, 1993, 1994]. These studies did not, however, account for the presence of a western boundary current. A study by *Nof* [1999] has shown that as an eddy interacts with a meridional boundary, it remains almost stationary and gradually dissipates as a result of an

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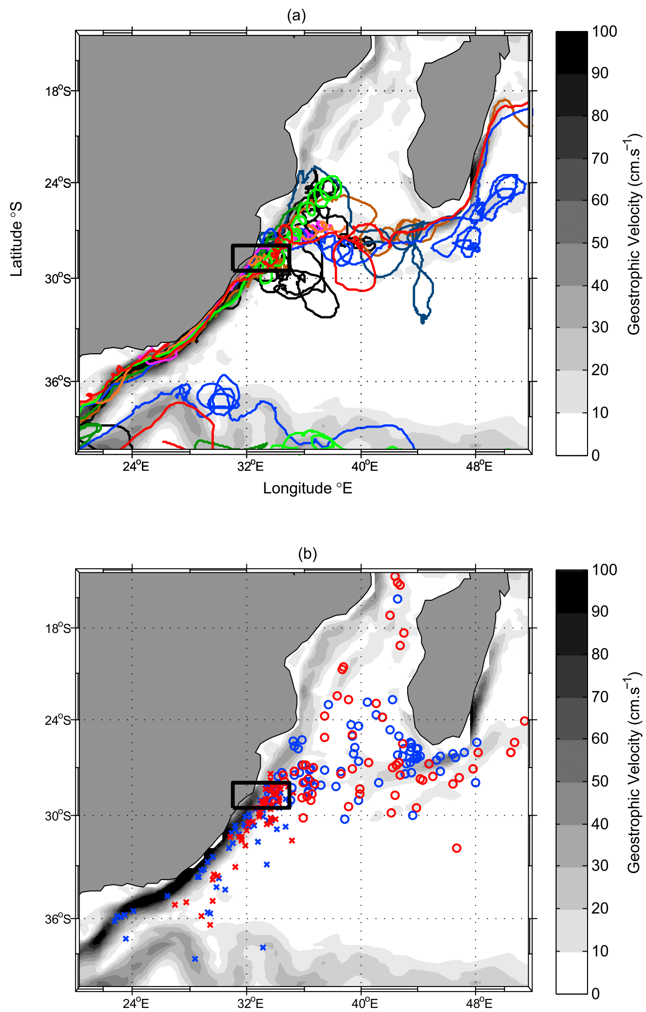


**Figure 1.** (a) The trajectories of surface drifters (color) passing through the black box between October 1992 and April 2002. (b) Formation (circles) and termination (crosses) sites of all cyclonic (blue) and anticyclonic eddies (red) passing through the black box overlaid on the mean geostrophic current derived from the satellite altimetry observations between October 1992 and April 2012.

equatorward leakage of water from the eddy until it can no longer be defined as an eddy. *Nof* [1999] also highlighted that an eddy propagating toward such a boundary loses one third of its open ocean velocity as a result of increased bottom friction. *Nof* [1999] shows that eddies slow down as they propagate toward a western boundary, but they suggest that water leakage from an eddy interacting with a continental boundary would be very difficult to detect because it would be occurring at depth. One might consider that the eddy-topography interaction is relatively small, as the western boundary currents present a significant barrier through which the eddies need to break in order to feel the bathymetry. Figure 2 suggests that eddies passing through the region 28–29.5°S and 31–35°E have dissipated at 32.9°E, before reaching the landward side of the core of the current which is at 32.2°E. Frequent interactions between deep oceanic eddies and the northern region of the Agulhas Current make this area an ideal natural laboratory to study the evolution of source region eddies as they approach and interact with a major western boundary current.

This paper aims to build on previous eddy dissipation studies using a global (altimetry-based) data set of automatically tracked eddies in combination with in situ surface drifter data and altimetry-derived geostrophic currents.

## 2. Data and Methods

Eddy characteristics from a global (altimetry-based) data set of automatically tracked eddies [*Chelton et al.*, 2011] (http://cioss.coas.oregonstate.edu/eddies/) were analyzed for the Agulhas Current region between 24–52°E and 15–35°S for the period of October 1992 to April 2012.

The automatic eddy-tracking algorithm used to estimate these eddy characteristics is applied to weekly, 0.25° resolution, gridded maps of sea surface height (SSH). In this data set, eddies are defined as having an SSH amplitude of at least 1 cm and must consist of closed SSH contours containing a minimum of 8 and a maximum of 1000 pixels (SSH data points). Additionally, a criterion of the Chelton method is that SSH must range between −100 cm and +100 cm. Once identified, the algorithm calculates different properties of the eddy such as position (longitude and latitude), direction of rotation, amplitude, radii, and circum-averaged speeds over a 7 day interval. In this study, only eddies passing through the northern sector of the Agulhas Current, defined by *Grundlingh* [1983] and *Lutjeharms* [2006] to be 28–29.5°S and 31–35°E, were considered (black box in Figure 1). Surface current velocities in this region are known to exceed 1.3 ± 0.3 m/s [*Grundlingh*, 1980].

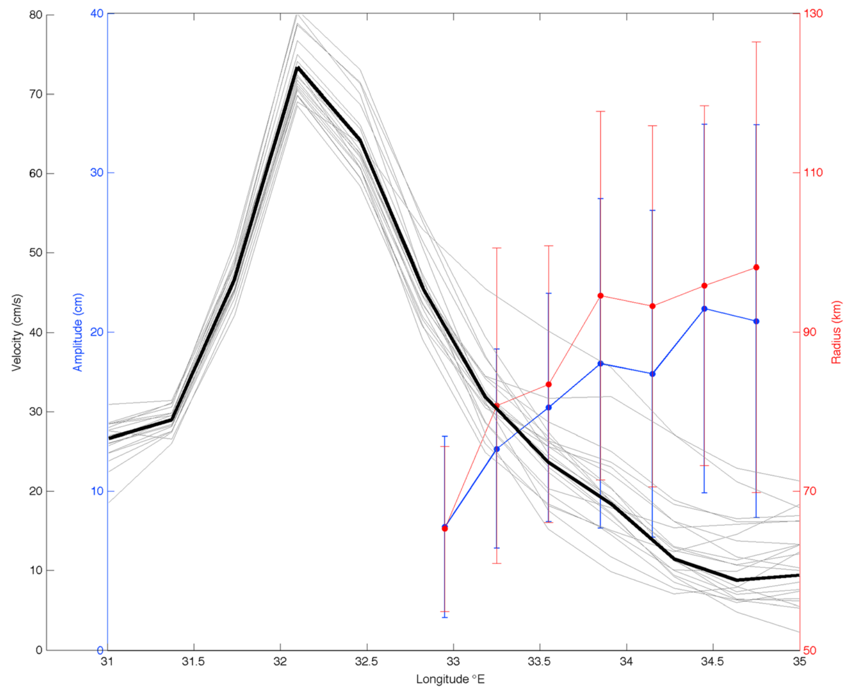


**Figure 2.** The meridional mean and standard deviation of the radii (red) and amplitudes (blue) of eddies as they approach the Agulhas Current meridional mean of 28–29.5°S indicated by the black line. Annual meridional mean velocities of the Agulhas Current are shown by thin grey lines.

The eddy tracks were thoroughly checked for errors against sea level anomaly data and corrected where necessary (Text S1 and Figures S1 and S2 in the supporting information). Eddy parameters used in this study were determined from altimetry data—which are known to have limitations near the coast [*Bouffard et al.*, 2010; *Chelton et al.*, 2011]. Hence, to further validate the accuracy of eddy characteristics in the northern Agulhas Current where the current flows close to the coastline, the eddy termination sites were compared to in situ surface drifter observations from the Global Drifter Program (Figure 1). Nine drogued drifters, which were entrained into eddies and subsequently moved into the Agulhas Current between into the black box from 1993 to 2011, were studied.

To illustrate the effect of the Agulhas Current on approaching eddies, the formation and termination positions of all cyclonic and anticyclonic eddies passing through the black box (Figure 1) were overlaid on the mean geostrophic current derived from altimetry observations for the period of October 1992 to April 2012 (Figure 1b).

The long-term and annual mean meridional geostrophic velocity profiles from 31 to 35°E, together with the corresponding meridional mean eddy amplitudes and radii, are shown in Figure 2.

In order to quantitatively analyze how eddies interact with the Agulhas Current, its offshore position and velocity (along the transect extending between 30.0–32.4°S and 30.95–34.4°E; see black line in Figure 4) were determined using the method described in *Krug et al.* [2014]. The resultant offshore position and current velocity anomaly time series are shown in Figure 3. Observations in the altimetry data where cyclonic and anticyclonic eddies interact with the Agulhas Current are represented by the blue and red vertical lines, respectively. Events in which an eddy interacted with the Agulhas Current were defined as the minimum distance between the eddy's edge and the concurrent position of the current. In this study, an eddy is considered to interact with the Agulhas Current if its edge was $<50$ km from the current core.

A composite analysis was performed so as to quantify the average change to the current during an Agulhas Current-eddy interaction event (Figure 4). The mean velocity anomaly where all anticyclonic (Figure 4a1) and cyclonic (Figure 4b1) eddies interact with the Agulhas Current was calculated, and composite maps for the weeks following the eddy-current interaction events were calculated for weeks 1 and 3 (anticyclonic eddy

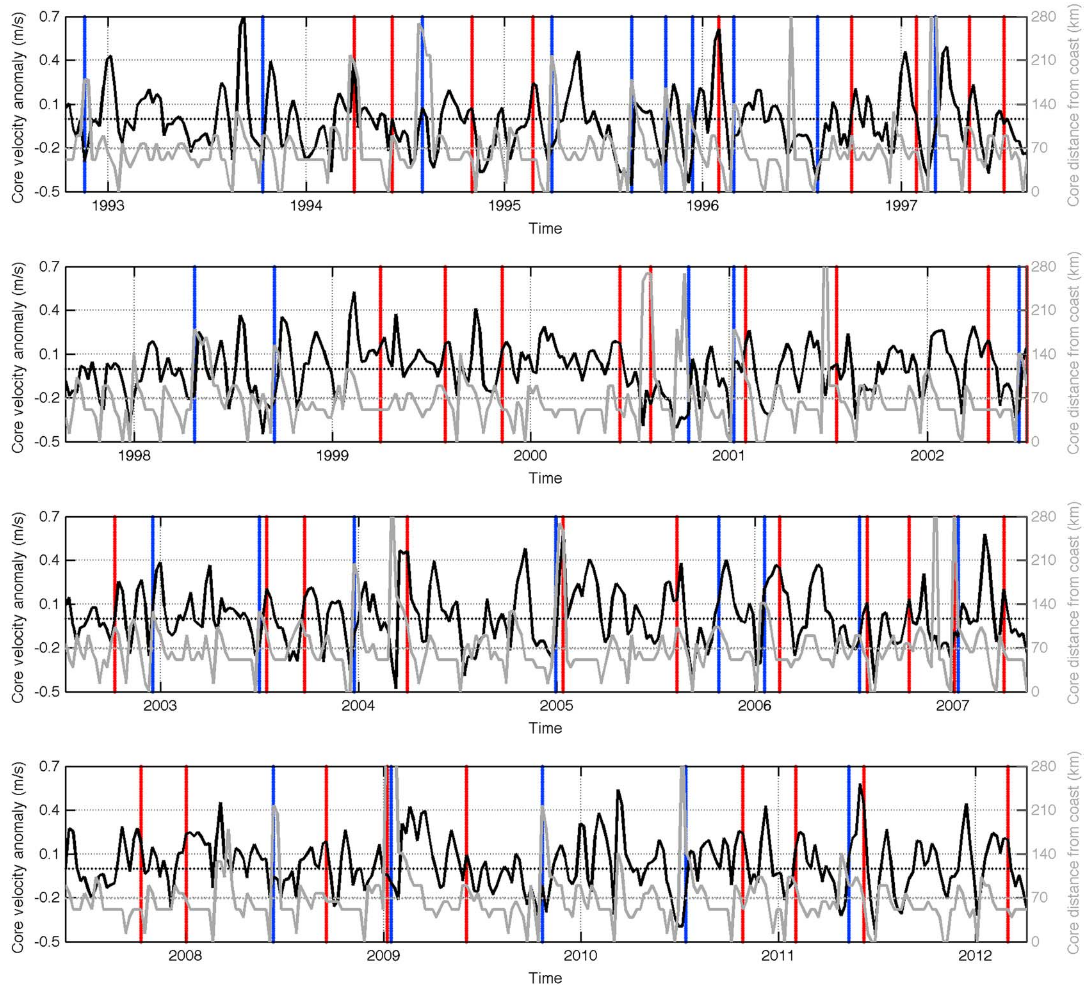


**Figure 3.** The time-averaged velocity anomaly of the Agulhas Current core (black), with the distance of the Agulhas Current core from the coast (grey) and cyclonic (blue) and anticyclonic (red) eddies interacting with the Agulhas Current core from (a) 1992–1997, (b) 1997–2002, (c) 2002–2007, and (d) 2007–2012. The position of the zero anomaly in Agulhas Current velocity is shown (black dotted line), as well as the mean distance of the Agulhas Current core from the coast (grey dotted line).

interaction; Figure 4a2 and 4a3) and as a result of faster propagation speeds for weeks 6 and 15 (cyclonic eddy interaction; Figure 4b2 and 4b3).

## 3. Results and Discussion

Surface drifters were used to highlight the entrainment of mesoscale eddies into the Agulhas Current (Figure 1a). On approaching the Agulhas Current, rotating drifter trajectories very quickly become linear, indicating their entrainment into the fast flowing Agulhas Current. The position of the eddy termination sites for eddies moving through the same region (red crosses; Figure 1b) shows that eddies forming in the Mozambique Channel and south of Madagascar (blue circles) are no longer tracked, shortly after arriving at the Agulhas Current—providing evidence of eddy dissipation. This also indicates that the eddy characteristic data set [*Chelton et al.*, 2011] is able to accurately determine eddy characteristics as they approach the Agulhas Current.

Considering all eddies that pass through the black box between 1992 and 2012 (Figure 1a), it is evident that those arriving at the Agulhas Current originate predominantly from the Mozambique Channel and the South East Madagascar Current (Figure 1b). Approximately five eddies propagate into the black box annually. A maximum of 22% of the eddies reach further south each year. Increasing the width of the black box, to capture these offshore eddies, does not alter the results of our study. Although more eddies are captured in a

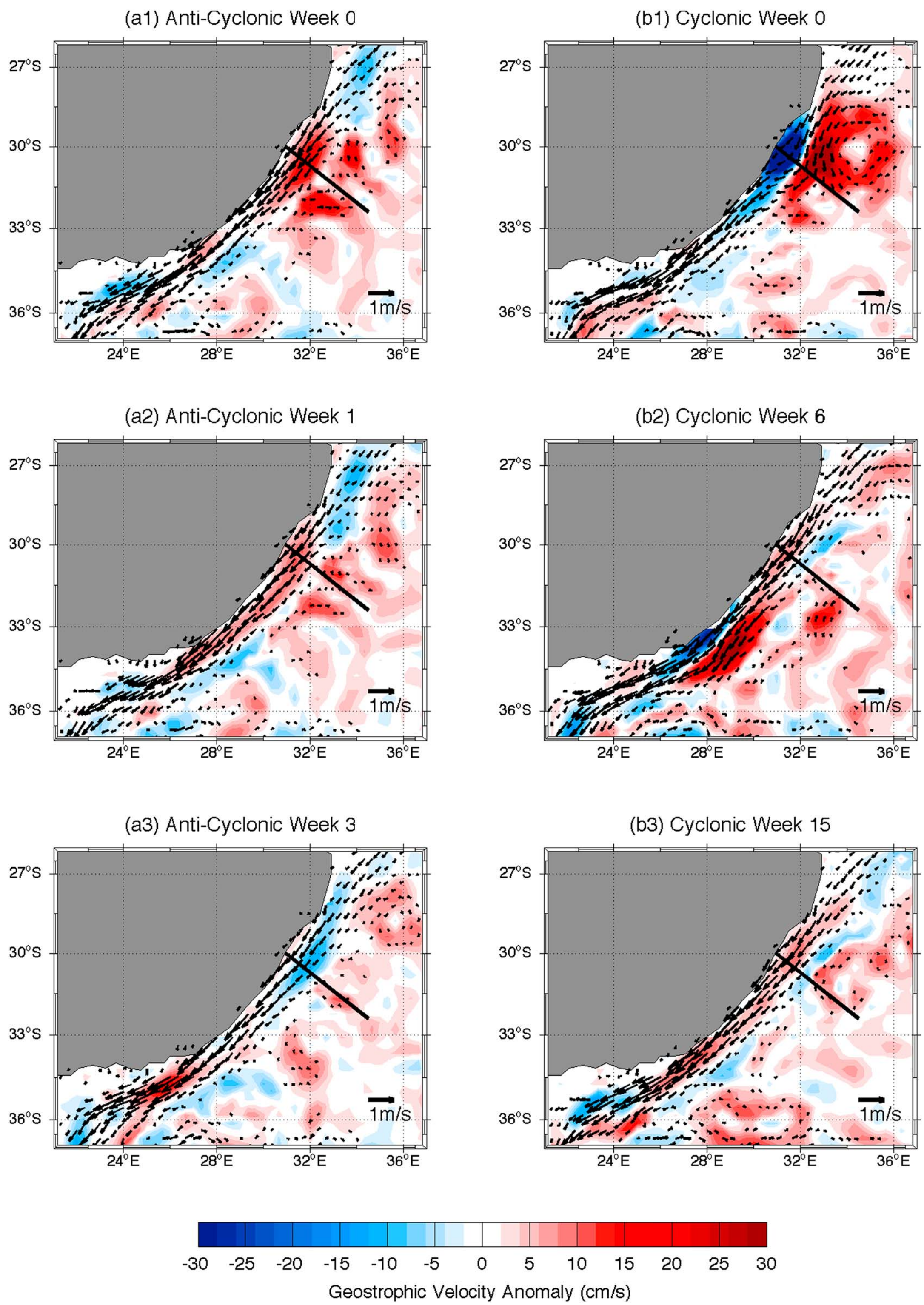


**Figure 4.** (a1) The mean velocity anomaly of the Agulhas Current when an anticyclonic eddy is present based on 61 anticyclonic eddies detected from 1992 to 2012 and the resulting effect on the Agulhas Current (a2) 1 week and (a3) 3 weeks later. (b1) The mean velocity anomaly of the Agulhas Current when a cyclonic eddy is present based on 71 cyclonic eddies detected from 1992 to 2012 and the resulting effect on the Agulhas Current (b2) 6 weeks and (b3) 15 weeks later. The transect across which the Agulhas Current core properties were studied, 30°S, 30.95°E to 32.4°S, 34.4°E, is shown by a thin black line. The black vectors indicate the absolute geostrophic velocity greater than 10 cm/s and show the direction of flow.

bigger box, it is still found that the eddies still dissipate upon approaching the Agulhas Current further south. Additionally, a larger box also captured eddies that did not interact with the Agulhas Current—many of these eddies propagate southwestward before dissipating upon interaction with other eddies. We chose to keep the box small as we wanted to examine only those eddies that propagated into the Agulhas Current. There is no significant seasonality to the arrival of the eddies at the Agulhas Current; however, wavelet analysis revealed that there is a significant signal of variability in the Agulhas Current velocities at a time period of approximately 6 weeks to 3 months. This is most likely caused by mesoscale eddies (Text S2 and Figure S3).

A total of 132 source region eddies approached the Agulhas Current at the black box between October 1992 and April 2012 of which 61 eddies were anticyclonic and 71 eddies were cyclonic. The dissipation of eddies upon approaching the Agulhas Current is evident in the mean zonal geostrophic velocity profile, the zonal mean eddy amplitudes, and radii from 31 to 35°E (Figure 2). The figure illustrates that eddies decrease in amplitude and radius upon approaching the Agulhas Current between 28 and 29.5°S. They reach their minimum dimensions at around 33°E, where Agulhas Current velocities are approximately 45 cm/s. Between 35°E and 33°E, the mean radius of the eddies decreases from $97.82 \pm 22.98$ km to $65.28 \pm 10.38$ km and the mean amplitude decreases from $20.87 \pm 12.39$ cm to $7.75 \pm 5.69$ m. The mean decrease in amplitude and radii is most pronounced when eddies are within ±100 km proximity of the Agulhas Current. The sizes of the eddies before they interacted with the Agulhas Current are found to be in agreement with eddy radii of 50–200 km in the existing literature [*Schouten et al*., 2002; *de Ruijter et al*., 2004; *Ridderinkhof et al*., 2013; *Halo et al*., 2014a, 2014b]. These results suggest that eddies dissipate upon approaching the Agulhas Current due to eddy-current interactions. While we are confident that the eddy characteristics are accurately captured in the data set (Figure 1), it should be noted that the data set does not necessarily track eddies close to the coast and that eddies may exist for longer than the automated eddy-tracking algorithm suggests.

The results showing eddy dissipation are in agreement with the previous findings [*Zhai et al*., 2010], which show western boundary currents to be eddy energy sinks. An investigation into the influence of all eddies on the velocities and position of the Agulhas Current core was also undertaken for the transect 30°S, 30.95°E to 32.4°S, 34.4°E (Figure 4) by tracking the maximum current velocity and its offshore position (red vertical lines in Figure 3). The time mean satellite-derived geostrophic current velocity and distance offshore at this latitude was found to be 0.91 m/s and 68.71 km. On average an anticyclonic eddy interacting with the Agulhas Current increases the velocity by $0.16 \pm 0.17$ m/s and shifts the current to $100.31 \pm 78.92$ km from the coast. (All of the mean changes associated with anticyclonic and cyclonic eddies observed here are significant at the 95% confidence interval using a Student's *t* test). At first our results appear to contradict a study by *Leber and Beal* [2014], which shows that although transport is maintained during a meander of the Agulhas Current, the current widens and its core velocity decreases by 70 cm/s. However, their case study was much further south of the transect 30°S, 30.95°E to 32.4°S, 34.4°E and was caused by an eddy that did not propagate within 50 km of the Agulhas Current core along this transect and therefore was not included in this study. Examination of anticyclonic eddy-current interactions in the altimetry indicates the vortex to become stretched (elongated) until it is eventually entrained into the Agulhas Current (Text S3 and Figure S4). These results differ from the existing literature, which shows the dissipation of anticyclonic (cyclonic) eddies through the gradual equatorward (poleward) leakage of water resulting from eddy interactions with a boundary [*Shi and Nof*, 1993, 1994; *Nof*, 1999]. It is also assumed that any leakage from the eddies in this study would be swept poleward, by the Agulhas Current. Associated with this entrainment and dissipation is a momentum transfer, whereby velocities of the Current appear to increase. This is in agreement with the suggestion by *Tsugawa and Hasumi* [2010] that the Agulhas Current speed increase is due to the transfer of barotropic energy from the anticyclonic eddies.

In contrast, cyclonic eddies interacting with the Agulhas Current (blue vertical lines in Figure 3) are associated with a decrease of its velocity by $0.13 \pm 0.16$ m/s and an offshore shift to $144.73 \pm 84.98$ km from the coast. (All of the mean changes associated with anticyclonic and cyclonic eddies observed here are significant at the 95% confidence interval using a Student's *t* test). Similarly, examination of individual eddy-current interactions shows the leading equatorward flow of a cyclonic eddy to become weaker as it approaches the Agulhas Current. This is likely due to horizontal shear of the opposing flow. Observations of these interactions frequently showed the formation of cyclonic meanders in the Agulhas Current or Natal Pulses. In contrast to existing literature which states that Natal Pulses are triggered by the interaction of an anticyclonic eddy with the Agulhas Current [*de Ruijter et al*., 1999; *Schouten et al*., 2002; *Tsugawa and Hasumi*, 2010], our results show that cyclonic eddy interaction results in an ever larger meander. Additionally, on seven occasions the cyclonic eddies interacting with the Agulhas Current (Figure 3) have anticyclonic eddies located to their east-northeast, suggesting the presence of dipole eddies similar to those documented in *Ridderinkhof et al.* [2013].

The composite analysis of eddy-current interaction events in Figure 4 shows the mean effect of anticyclonic and cyclonic eddies on the Agulhas Current (Figures 4a1 and 4b1, respectively). A consistent increase in the current velocity is noticeable when an anticyclonic eddy interacts with the Agulhas Current with the positive anomaly propagating downstream to about 26°E, 35°S at a rate of 44 km/d (Figure 4a2 and 4a3), where after the signal is lost. For cyclonic eddy-current interaction events, the mean velocity core of the Agulhas Current consistently decreases close to the coast but has a strong positive velocity anomaly on the offshore edge of the current. The composite map (Figure 4b1) shows that a larger anticyclonic eddy lies to the northeast of the smaller cyclonic eddy, indicating the consistent presence of dipole eddy pairs during cyclonic eddy-current interactions. The negative inshore and positive offshore velocity anomalies propagate downstream at 23 km/d to 24°E, 36°S (Figure 4b2 and 4b3), where the signal is lost. In both cases it is evident that a transfer of momentum occurs with the velocity anomalies propagating downstream at different speeds.

## 4. Conclusion

Using a combination of an eddy-tracking data set with in situ surface drifter observations and altimetry-derived geostrophic currents, it has been shown that both cyclonic and anticyclonic source eddies dissipate upon approaching the Agulhas Current. On average the eddy dissipation process commences when eddies are within ±100 km of the Agulhas Current. Their entrainment into the Agulhas Current affects its mean velocity and offshore position through a transfer of momentum, with anticyclonic eddies consistently increasing the Agulhas Current velocity by $0.16 \pm 0.17$ m/s. In contrast, entrainment of cyclonic eddies results in a decrease in velocity by $0.13 \pm 0.16$ m/s and shifting the current up to $144.73 \pm 84.98$ km offshore. These eddies propagate downstream at rates of 44 km/d (anticyclonic) and 23 km/d (cyclonic).

Finally, the observed eddy interaction and dissipation process described in this study are poorly represented in many numerical models [e.g., *Backeberg et al*., 2014; *Durgadoo et al*., 2013; *Loveday et al*., 2014]. In these models, eddies propagate from the source regions to the Agulhas retroflection as a train of successive eddies. This suggests that energy dissipation processes affecting the variability of the Agulhas Current are not adequately resolved in numerical models and may result in an incorrect estimation of the transport associated with the Agulhas leakage. Consequently, an inaccurate parameterization of these models, through poor representation of eddy entrainment processes, may have further implications on the links between source region eddies and mesoscale variability within in the Agulhas Current, its retroflection, and the exchange of heat and salt between the Indian and South Atlantic Ocean basins and thus global climate.

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