

## RESEARCH LETTER

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## Key Points:

- Eddies in Agulhas corridor acquire material coherence away from retroflection
- Most eddies cross South Atlantic, but few pour contents on North Brazil Current
- A small fraction of these eddy contents can be traced into the Indian Ocean

## Supporting Information:

- Text S1
- Movies S1
- Movies S2

## Correspondence to:

Y. Wang,  
ywang@rsmas.miami.edu

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## Coherent water transport across the South Atlantic

Y. Wang<sup>1</sup>, M. J. Olascoaga<sup>1</sup>, and F. J. Beron-Vera<sup>2</sup>
<sup>1</sup>Department of Ocean Sciences, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA, <sup>2</sup>Department of Atmospheric Sciences, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida, USA

**Abstract** The role of mesoscale eddies in transporting Agulhas leakage is investigated using a recent technique from nonlinear dynamical systems theory applied on geostrophic currents inferred from the over two decade long satellite altimetry record. Eddies are found to acquire material coherence away from the Agulhas retroflection, near the Walvis Ridge in the South Atlantic. Yearly, one to four coherent material eddies are detected with diameters ranging from 40 to 280 km. A total of 23 eddy cores of about 50 km in diameter and with at least 30% of their contents traceable into the Indian Ocean were found to travel across the subtropical gyre with minor filamentation. Only one eddy core was found to pour its contents on the North Brazil Current. While the ability of eddies to carry Agulhas leakage northwestward across the South Atlantic is supported by our analysis, this is more restricted than suggested by earlier ring transport assessments.

## 1. Introduction

Mesoscale eddies are widely recognized as potential agents of long-range water transport [e.g., Robinson, 1983]. Agulhas rings, in particular, have long been thought as conduits for the leakage of warm and salty Indian Ocean water into the South Atlantic [de Ruijter et al., 1999; Gordon, 1986; Lutjeharms, 2006; Richardson, 2007; van Sebille and van Leeuwen, 2007] and as such contributors to the maintenance of the meridional overturning circulation in the Atlantic [Gordon, 1986; Weijer et al., 2002; Knorr and Lohmann, 2003; Peeters et al., 2004; Beal et al., 2011]. The role of rings in carrying Agulhas leakage was emphasized by Gordon and Haxby [1990], who argued that the rings, after being shed from the Agulhas retroflection as the result of occasional Indian-Ocean-entrapping occlusions, travel across the South Atlantic and pour their contents on the North Brazil Current. While this long-range transport view on rings has been challenged by the potentially important role of filaments and other forms of transport [Schouten et al., 2000; van Sebille et al., 2010a, 2010b], it remains to be tested using tools designed to unambiguously frame the structures of interest: eddies with persistent material cores. Here we extract from geostrophic currents inferred from the over two decade long record of satellite altimetry measurements of sea surface height (SSH) mesoscale coherent material eddies, investigate their life cycles, construct a time series of coherent water transport, and evaluate the significance of the obtained transport estimates. The eddies are extracted using a recently developed Lagrangian method from nonlinear dynamical systems theory [Haller and Beron-Vera, 2013, 2014]. Independent of the reference frame chosen, the method allows identification and tracking, in forward direction until the time of their demise and in backward direction to the time of their genesis, of eddies shielded by extraordinarily resilient fluid belts that defy the exponential stretching of typical fluid belts in turbulence. Such material eddies coherently transport the enclosed fluid with no noticeable leakage through the flow domain for the whole extent of their lifetimes. Eddies revealed from their Eulerian footprints, as is the case of the rings considered by Gordon and Haxby [1990], do not possess this property [Beron-Vera et al., 2013], which is critical to assess the validity of Gordon and Haxby's [1990] long-range transport view on Agulhas rings.

## 2. Methods

Haller and Beron-Vera [2013, 2014] consider exceptional material loops in turbulent flow that form the centerpieces of thin material belts exhibiting no leading order change in averaged stretching as the widths of the belts are varied. Solutions to this variational problem are material loops such that each of their subsets is stretched by a unique factor  $\lambda$  when the loops are advected from time  $t_0$  to time  $t$ . Being uniformly stretching, these  $\lambda$  loops resist the exponential stretching typical material loops experience in turbulence. Represented

as closed curves  $s \mapsto x_0(s)$ , where parameter  $s$  is periodic, the  $\lambda$  loops satisfy one of the two equations:

$$\frac{dx_0}{ds} = \sqrt{\frac{\lambda_2(x_0) - \lambda^2}{\lambda_2(x_0) - \lambda_1(x_0)}} \xi_1(x_0) \pm \sqrt{\frac{\lambda^2 - \lambda_1(x_0)}{\lambda_2(x_0) - \lambda_1(x_0)}} \xi_2(x_0). \quad (1)$$

Here  $0 < \lambda_1(x_0) \leq \lambda_2(x_0)$  and  $\xi_i(x_0) \cdot \xi_j(x_0) = \delta_{ij}$  are eigenvalues and (normalized) eigenvectors, respectively, of the right Cauchy-Green strain tensor field,  $C_{t_0}^t(x_0) := DF_{t_0}^t(x_0)^T DF_{t_0}^t(x_0)$ , a frame-invariant (or objective) measure of deformation where  $F_{t_0}^t(x_0) := x(t; x_0, t_0)$  is the flow map that associates times  $t_0$  and  $t$  positions of fluid particles, which evolve according to

$$\frac{dx}{dt} = v(x, t), \quad (2)$$

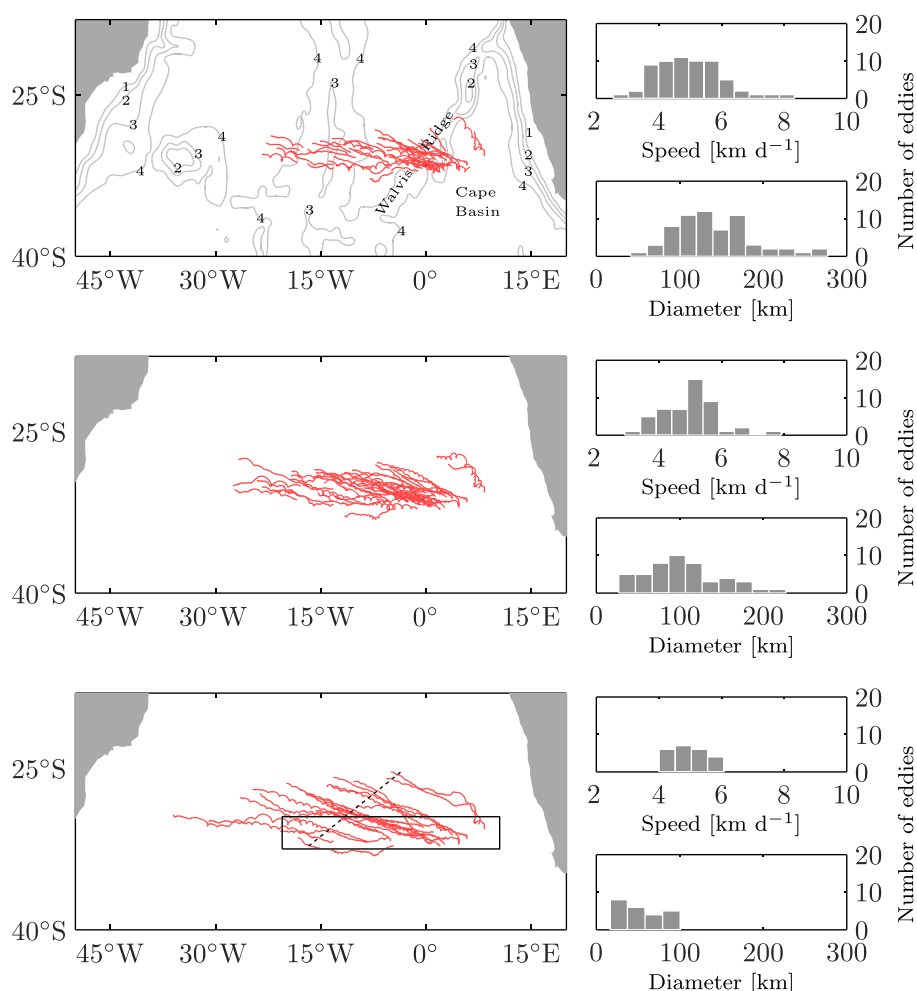
where  $v(x, t)$  is a two-dimensional velocity field. Closed curves satisfying (1) occur in families of nonintersecting limit cycles, necessarily encircling singularities of  $C_{t_0}^t(x_0)$ , i.e., points where the field is isotropic. The outermost member of a family of  $\lambda$  loops will be observed physically as the boundary of a *coherent material eddy*: immediately outside, no coherent belt may exist containing the eddy. Limit cycles of (1) tend to exist only for  $\lambda \approx 1$ . Material loops characterized by  $\lambda = 1$  reassume their initial arc length at time  $t$ . This property, along with conservation of enclosed area in the incompressible case, creates extraordinary coherence.

Coherent material eddy detection and tracking are implemented as follows (detailed algorithm steps are given in the appendix of *Haller and Beron-Vera* [2013]). (1) Fix a domain  $U$  and a time scale  $T$  over which eddies are to be identified. (2) On  $U$  set a grid  $\mathcal{G}_U$  of initial positions  $x_0$ . (3) For each  $x_0 \in \mathcal{G}_U$  integrate equation (2) from  $t_0$  to  $t = t_0 + T$ , obtaining a discrete approximation of  $F_{t_0}^t(x_0)$ . (4) Evaluate  $DF_{t_0}^t(x_0)$  using finite differences, then construct  $C_{t_0}^t(x_0)$ , and finally compute  $\{\lambda_i(x_0)\}$  and  $\{\xi_i(x_0)\}$ . (5) Locate eddy candidate regions  $V$  by isolating singularities of  $C_{t_0}^t(x_0)$  surrounded by singularity-free annular regions. (6) In each  $V$  repeat the first two steps using a finer grid  $\mathcal{G}_V$  and seek the outermost possible limit cycle of systems (1) with the aid of a Poincaré section (a limit cycle corresponds to a fixed point of the Poincaré map) starting with  $\lambda = 1$ . If no limit cycle is found for any  $\lambda$  (typically near 1), the candidate region does not contain a coherent material eddy. (7) Finally, advect the boundary of the coherent material eddy detected to track its motion.

Here we have specifically considered  $v(x, t) = gf^{-1}\nabla^\perp\eta(x, t)$ , where  $g$  is the acceleration of gravity,  $f$  stands for Coriolis parameter,  $\perp$  represents a  $90^\circ$  anticlockwise rotation, and  $\eta(x, t)$  is the SSH, taken as the sum of a (steady) mean dynamic topography and the (transient) altimetric SSH anomaly, both distributed by AVISO (Archiving, Validation, and Interpretation of Satellite Oceanographic data); specific products employed are Rio05 and DT-MSLA “all sat merged,” respectively. The mean dynamic topography is constructed from satellite altimetry data, in situ measurements, and a geoid model [Rio and Hernandez, 2004]. The SSH anomaly is provided weekly on a  $0.25^\circ$  resolution longitude-latitude grid. This is referenced to a 20 year (1993–2012) mean, obtained from the combined processing of data collected by altimeters on the constellation of available satellites [Le Traon et al., 1998]. Here the weekly SSH fields are interpolated daily, which reduces trajectory overshooting [Keating et al., 2011]. We chose  $U = [20.5^\circ\text{W}, 10.5^\circ\text{E}] \times [29.5^\circ\text{S}, 32.5^\circ\text{S}]$  (indicated by a box in Figure 1, bottom left). This domain intersects the so-called Agulhas corridor [Goni et al., 1997]. It lies sufficiently away from the Agulhas retroflexion to allow coherence to build up and is sufficiently wide, both zonally, to capture all eddies possibly shed, and meridionally, to fit the largest such eddies. We set  $T = 90, 180, \text{ and } 360$  days. This resulted in detections of eddies with maximum diameters decreasing from around 280 km to 100 km. Eddy diameters remained stable for  $T$  in the range 30–90 days; for  $T$  shorter than 30 days or longer than 360 days coherence was difficult to be revealed on any scale. Detections were carried out over 1992–2013 (nearly the entire period of available altimetry measurements) in such a way that  $U$  was filled with new eddies at each  $t_0$ , thereby avoiding defective or redundant eddy counting. We set  $\mathcal{G}_U$  and  $\mathcal{G}_V$  to be regular with square elements of roughly 1.5 and 1 km sides, respectively. All integrations were carried out using a step-size-adapting fourth-order Runge-Kutta method with interpolations obtained using a cubic scheme. In the case of (1), further care had to be taken by enforcing a unique eigenvector field orientation at each integration step.

### 3. Results

We begin by showing in Figure 1 trajectories (left column) and histograms of mean translational speeds and diameters (right column) of coherent material eddies detected from integrations with  $T = 90$  (top row),



**Figure 1.** (left column) Trajectories and (right column) mean translation speeds and diameters of coherent material eddies in the Agulhas corridor as detected from altimetry-derived velocities over 1992–2013 with lifetimes (top row) 90, (middle row) 180, and (bottom row) 360 days. (bottom left) Detection domain (solid rectangle) and the reference section used in the construction of the coherent transport time series of Figure 2 (dashed line). Selected bathymetry levels (in km) are indicated in the top left along with two relevant topographic features.

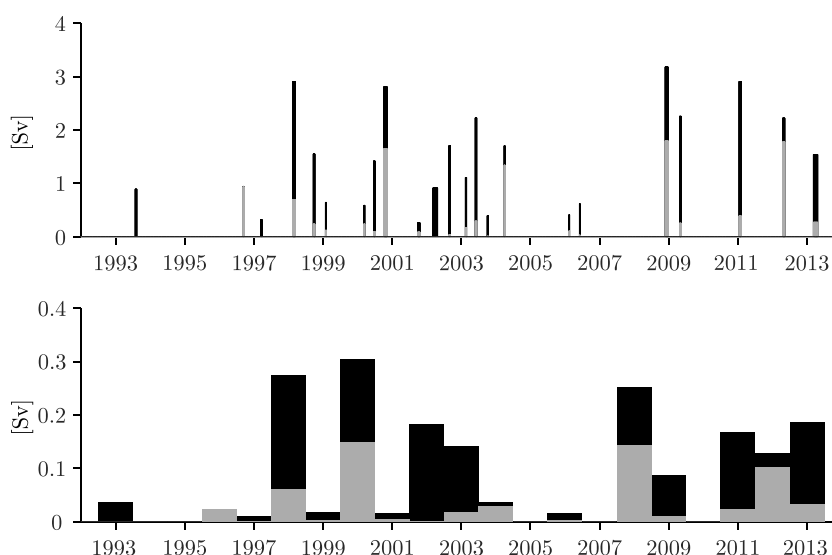
180 (middle row), and 360 (bottom row) days. A total of 59 (4), 47 (1), and 23 (0) anticyclonic (cyclonic) eddies are detected over 1992–2013. (Ignored from the analysis only are 7 (6), 3 (3), and 1 (0) anticyclones (cyclones) that take southwestward directions as these eddies are not relevant for our purposes here.) The predominance of anticyclones over cyclones signals enhanced stability for anticyclones in agreement with prior results [van Sebille *et al.*, 2010a]. Of these eddies 39, 40, and 19 are found with  $\lambda = 1$ ; for all other eddies  $\lambda$  ranges from 0.9 to 1.1. It must be realized that 180- and 360-day eddies lie inside 90-day eddies at detection time, i.e., 180- and 360-day eddies do not constitute different eddies but rather constitute 90-day coherent material eddy cores. In effect, an eddy boundary detected with a given  $T$  typically lies quite close to some member of the family of  $\lambda$  loops that fill an eddy detected with a shorter  $T$ . The detection rate is quite irregular. It varies from one to four eddies per year. This applies to 90- and 180-day eddies; it applies to 360-day eddies too when they are present, namely, all years except 1994–1995, 2004, and 2006–2007. The irregularity of the detection rate is indicative of substantial coherent material eddy episodicity rather than an artifact created by the altimetry set. Indeed, while earlier years are covered by fewer satellite altimeters than later years, gaps with no eddy detected are present in both earlier and later years. An obvious observation from the inspection of the figure is that trajectory lengths increase with  $T$  increasing from 90 to 180 to 360 days. Specifically, these increase on average roughly from 450 to 900 to 1800 km. This is accompanied by a reduction in eddy size. In effect, mean eddy diameters decrease on average approximately from 140 to 100 to 50 km. This suggests an average eddy

decay rate of  $40 \text{ km}^2 \text{ d}^{-1}$  in 360 days. Mean eddy translational speeds remain quite stable around  $5 \text{ km d}^{-1}$  (about twice the speed of long baroclinic Rossby waves) independent of  $T$ .

We now proceed to discussing transport estimates. Let  $\Sigma$  be a fixed curve and assume that it is traversed by coherent material eddies, episodically and all in the same direction. We call *coherent transport* the contribution by such eddies to the flux across  $\Sigma$  of the two-dimensional velocity supporting the eddies. For a single eddy, this function takes nonzero values over the time interval on which the eddy crosses  $\Sigma$ . To a good approximation such a function is given by a boxcar with amplitude equal to the area of the eddy divided by the length of the interval. For multiple eddies, a coherent transport time series will be given by a sequence of boxcars with different amplitudes resulting from superimposing episodic individual eddy contributions.

Figure 2 (top) shows a time series of coherent transport estimates over the period 1992–2013 obtained by considering 360-day eddies and  $\Sigma$  as indicated by the dashed segment in Figure 1 (bottom left), which is traversed by all identified 360-day eddies (and their residuals, after coherence is lost) in one direction. These eddies have the ability to carry water coherently for the longest distances and thus are the most meaningful for the transport computation. While transport as defined above is two dimensional in nature, we report three-dimensional transport values measured in Sverdrup (Sv) ( $1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$ ). These were obtained by multiplying the computed two-dimensional transport values by 1 km. With a certain degree of uncertainty [de Steur *et al.*, 2004], this value is in the range of mature Agulhas ring trapping depths inferred from float-profiling hydrography [Souza *et al.*, 2011]. A distinguishing feature of the computed transport time series is a large variability, both intraannual and interannual. Nonzero transport estimates range approximately from 0.25 to 3 Sv (about 1.5 Sv on average). These varying transport estimates are attributed mainly to varying eddy sizes. Interspersed zero transport gaps last roughly from 3 months to 3 years. These varying length gaps cannot be explained by previously reported Agulhas ring shedding rates of one ring every 2 to 3 months [Byrne *et al.*, 1995; Goni *et al.*, 1997; Schouten *et al.*, 2000; Souza *et al.*, 2011]. Rather, they are due to marked eddy episodicity. Gray-shaded bar portions in Figure 2 (top) correspond to transport of water that can be identified with leaking Indian Ocean water into the South Atlantic. The Indian Ocean water fraction carried within eddies was estimated by advecting the eddy boundaries in backward time for as long as at least 90% reversibility was attained (about 1.25 years on average) and computing the proportion of the enclosed fluid found east of  $20^\circ \text{E}$  (the longitude at which Indian Ocean and South Atlantic meet). We note that reversibility is strongly constrained by sensitive dependence on initial conditions. Also, the Agulhas retroflection typically extends west of  $20^\circ \text{E}$ . Therefore, our estimates of Indian Ocean water content should be considered as a lower bound. At least, then, the eddies are found this way to carry on average about 30% of water that can be unambiguously identified with Indian Ocean water. Accordingly, the transport of Indian Ocean water trapped inside the eddies is found to be approximately 0.5 Sv on average. Rare cases are eddies detected in mid-2002 and early 1996, which carry barely 1 and almost 99% of Indian Ocean water, respectively. The Indian Ocean water transported by these eddies is about 0.01 and 1 Sv, respectively.

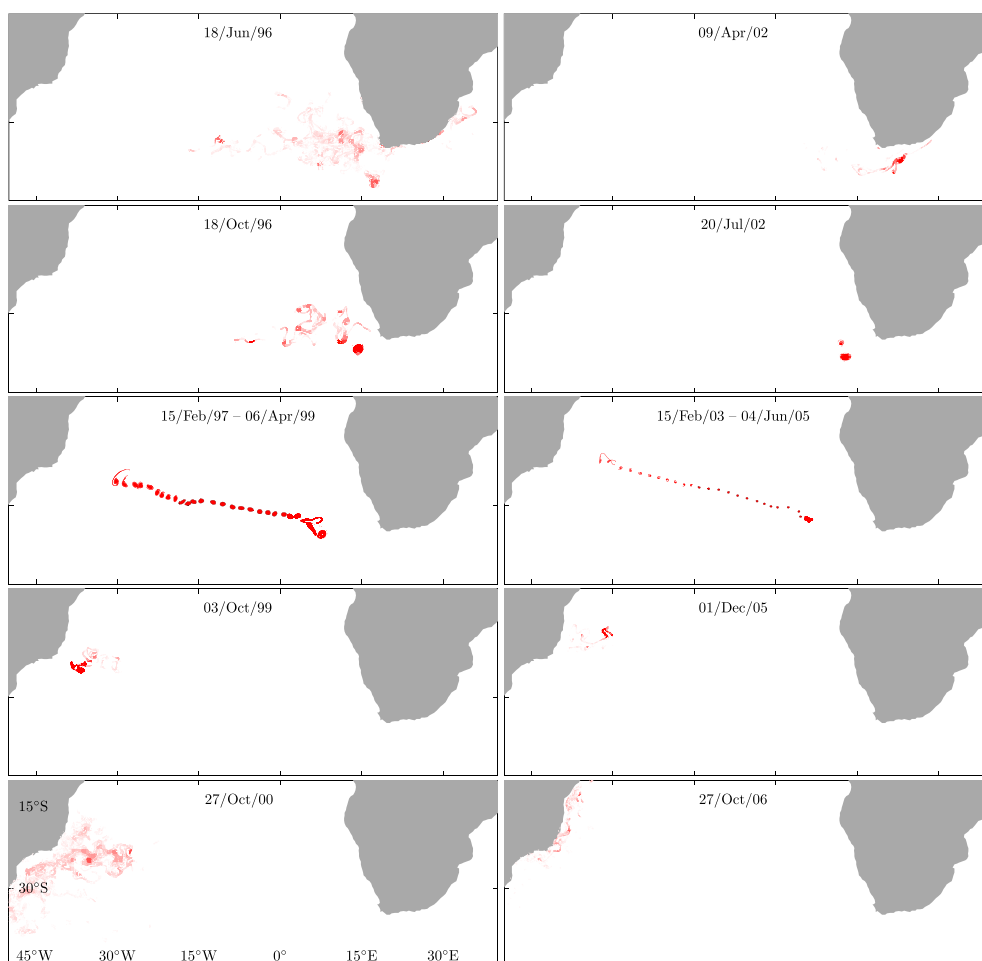
Figure 2 (bottom) shows a time series of annual coherent transport estimates computed by averaging the (instantaneous) estimates in Figure 2 (top) within each year (as in that panel, gray-shaded bar portions correspond to Indian Ocean water transport). The maximum annual transport produced by 360-day coherent material eddies is about 0.3 Sv. Our estimate is 2 orders of magnitude smaller than earlier estimates obtained as total volume of eddies detected during a given year, divided by 1 year [Garzoli *et al.*, 1999; Richardson, 2007; Dencausse *et al.*, 2011; Souza *et al.*, 2011]. This large difference might be reduced by an order of magnitude if a larger vertical extent for the eddies is assumed. Indeed, van Aken *et al.* [2003] report vertical extents of 4 km but only for very young Agulhas rings. The reason for this large discrepancy actually resides in that these earlier estimates implicitly assume that eddies whose diameters at detection time are 250 km or so can preserve material coherence over periods as long as 1 year. This cannot be guaranteed by Eulerian analysis of altimetry or the inspection of in situ and profiling-float hydrography, and drifter and float trajectories, which led to the earlier transport estimates. Truly material eddies as large as 250 km in diameter revealed from altimetry in the region of interest can be guaranteed to preserve coherence for at most 3 months. Beyond 3 months or so, eddies of this size shed filaments that typically reach the generation region or farther east. The maximum annual transport of Indian Ocean water trapped inside 360-day coherent material eddies does not exceed 0.2 Sv. This is also smaller, by 2 orders of magnitude, than annual Agulhas leakage estimates obtained from numerical simulations [Doglioli *et al.*, 2006; Biastoch *et al.*, 2009; Le Bars *et al.*, 2014]. While these Agulhas leakage estimates still lack observational support, the noted large mismatch suggests that eddies may not be



**Figure 2.** (top) Instantaneous and (bottom) annual average time series of transport produced by 360-day coherent material eddies crossing the reference section indicated by the dashed segment in the bottom left of Figure 1. Gray-shaded bar portions correspond to transport of Indian Ocean water trapped inside the eddies.

as efficient in transporting leaked Indian Ocean water across the South Atlantic as the early eddy transport estimates appear to indicate.

Finally, we turn to discussing aspects of the evolution of detected coherent material eddies. As before we focus on 360-day eddies, the most persistent of all eddies detected. Figure 3 shows snapshots of the long-term evolution of two eddies selected according to their behavior during their early and late evolution. The eddy in Figure 3 (left column) illustrates typical behavior, while the eddy in Figure 3 (right column) illustrates exceptional behavior (animations including weekly snapshots are supplied as supporting information Movies S1 and S2, respectively). The evolutions were constructed by advecting passive tracers inside each eddy boundary (indicated in black) at detection time in backward time (for as long as at least 90% reversibility was attained) and also in forward time (beyond the theoretical coherence time). The typical behavior is characterized by organization into small coherent material eddies (the specific eddy depicted in Figure 3 (left column) is approximately 90 km in diameter) from rather incoherent fluid composed of a mixture mainly of water that resides in the South Atlantic and a much smaller fraction of water traceable into the Indian Ocean. Typical coherent material eddies emerge away from the southern tip of Africa, just east of the Walvis Ridge in the South Atlantic. This genesis picture does not adhere to the commonly accepted conceptual picture in which Agulhas rings are shed from the Agulhas retroflection as a result of eventual Indian-Ocean-entrapping occlusions [Pichevin *et al.*, 1999]. Our results are more consistent with those from earlier works [Schouten *et al.*, 2000; Boebel *et al.*, 2003] reporting intense mixing in Cape Basin. But coherence eventually emerges from the mostly incoherent water resulting from this process close to the Walvis Ridge and is followed by propagation of small eddy cores with minor filamentation across the subtropical gyre. Coherence is eventually lost, the contents of the eddies are mixed with the ambient water in the vicinity of the bifurcation of the subtropical gyre, and finally transported mostly southward by the Brazil Current. Out of a total of 23 eddies detected, 15 adhere to this picture. The exceptional behavior, observed by only one eddy, is also characterized by emergence of small coherent material eddies (the particular eddy shown in Figure 3 (right column) has roughly 40 km in diameter) out of rather incoherent water, the only difference being that most of the water inside this eddy is traceable into the Indian Ocean. This is still different from the widely accepted ring genesis picture inasmuch as material coherence is not acquired immediately but rather after some time, near the Walvis Ridge. Propagation across the subtropical gyre then follows with minor filamentation until coherence starts to be gradually lost. The eddy contents mix with the surrounding water near the bifurcation of the subtropical gyre. The majority of these is then transported northward close to the coast by the North Brazil Current. This behavior most closely adheres to the scenario put forward by Gordon and Haxby [1990]. The behavior of the remaining seven eddies detected shares aspects of the two markedly distinct behaviors just described.



**Figure 3.** Snapshots of the long-term evolution of two 360-day coherent material eddies with (left column) typical and (right column) exceptional genesis and demise stages. The boundaries of the eddies while they constitute coherent material eddies are indicated in black. Indicated in red are passive tracers that completely fill these eddies during their coherent material stage.

#### 4. Conclusions

Aided by a recently developed Lagrangian technique from nonlinear dynamical systems theory, we have extracted from geostrophic velocities derived from nearly two decades of altimetry measurements a coherent transport signal across the South Atlantic through the so-called Agulhas corridor. The technique enables accurate, frame-independent identification of mesoscale eddies with cores whose material boundaries remain coherent, i.e., without showing noticeable signs of filamentation, for up to 1 year. These coherent material eddies were used in the coherent transport computation, which turned out to be smaller (by at least 2 orders of magnitude) than earlier ring transport estimates. The main reason is that those transport estimates implicitly assumed material coherence for eddies revealed from their Eulerian footsteps in the altimetry data set. Such eddies are either too large (by 1 order of magnitude) for long-range material coherence to be guaranteed or simply do not represent coherent material eddies. The portion of Indian Ocean water annually carried within the coherent material eddies was also identified and found to be small (by 2 orders of magnitude) compared to recent estimates of total Agulhas leakage based on numerical simulations. This result suggests a reduced role of Agulhas rings in transporting leaked Indian Ocean water. We also investigated the evolution of the detected coherent material eddies. We found that the conceptual picture in which Agulhas rings are shed from the Agulhas retroflection as a result of episodic Indian-Ocean-water-entrapping occlusions is, in general, not valid. Coherent material eddies tend to emerge near the Walvis Ridge from rather incoherent water, mostly residing in the South Atlantic and to a small extent traceable into the Indian Ocean. How this precisely happens is not known and is subject of ongoing investigation. The majority of the coherent material



eddies formed this way (15 out of a total of 23) was found to cross the subtropical gyre and eventually to be absorbed into the Brazil Current. However, only one eddy consisting of mainly Indian Ocean water was seen to pour its contents on the North Brazil Current. This suggests that the contribution by coherent material Agulhas rings to the global thermodynamical budget is much less significant than originally thought [Gordon and Haxby, 1990]. While we find ability of eddies to transport water over long distances, this is less important than recently argued for eddies beyond Agulhas rings based on lax assumptions about material coherence [Dong et al., 2014; Zhang et al., 2014]. Finally, explicit resolution of three-dimensional aspects of ring transport, which can be done by applying extensions of the technique employed here [Blazevski and Haller, 2014; Haller, 2014] to an ocean general circulation model, is not expected to substantively modify our results. Indeed, these may be actually more constrained by diffusion induced by submesoscale turbulence unresolved by altimetry and most models.

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