

Reply to Anonymous Referee #2 regarding the paper
submitted to Ocean Science entitled “ Eddy Surface
properties and propagation at Southern Hemisphere western
boundary current systems”

G. S. Pilo et al.

June 30, 2015

This paper gives an overview of some eddy statistics in the 3 Southern Hemisphere western boundary current systems using Chelton’s global eddy dataset. The authors make the case that the role played by eddies in these systems is dynamically important, and therefore that analysis of the statistics of these eddies can contribute to our understanding of the circulation. In general I found the manuscript well-written (subject to a number of minor grammatical/ spelling mistakes which I have tried to correct below) and the figures very well presented. However, I am concerned that the extent of the analysis is somewhat shallow. The authors need to do more to connect their understanding of eddy statistics with the dynamics of these regions. The best example of such a connection is Figure 6, which I found very illuminating. But I think the authors can do more. Details below.

R: We thank the referee for the detailed review. His/her suggestions were valuable for the overall improvement of the manuscript. As suggested, we extended the analysis by adding new figures and improving the discussion section. Considering all reviewers’ comments we

added the following analyses to the new version of the manuscript:

- Mean Eddy Kinetic Energy (EKE) maps for all three systems.
- Eddy density maps.
- Mean eddy amplitude maps.
- Mean eddy propagation maps.

We also added new discussions on the following matters:

- Comparison of mean EKE, and eddy density, radius and amplitude spatial distribution.
- Eddies not propagating into continental shelves.
- Brazil Current System northward eddies advected by the Malvinas Current.
- Further discussion on eddies' propagation patterns.

In this document, our reply to the referee's specific comments is in normal font, whereas the reviewers' specific comments are displayed in **bold** font. New paragraphs added to the manuscript are copied here in *italic*.

1) Can these statistics be used to investigate the mean transport, or temporal variability, of Agulhas leakage or Tasman Leakage?

Estimates of leakage can be given by transport calculation based on 3D eddy resolving models (e.g. Speich et al., 2002; Biastoch et al., 2009; van Sebille et al., 2012; Cetina-Heredia et al., 2014), and hydrographic measurements (e.g. Rosell-Fieschi et al., 2013; Le Bars et al., 2014). Studies on such matter show that a proper estimate of eddy-driven transport requires not only a 3D definition of the eddies, but also consideration on how much water mass content is loss due to filamentation and mixing (Beron-Vera et al., 2013).

With eddies surface characteristics only, as is the case of our manuscript, it is possible to have a rough estimate of eddy volume. Let's first consider mean eddy radii of Agulhas Rings and Tasman Sea eddies to be 120 km and 70 km when they cross south of Africa (41°S) and south of Tasmania (45°S), respectively (Figure 5). If we consider these eddies as lense-type (which can be untrue, specially for retroflection eddies) and having zero potential vorticity, we can estimate their volume (V) as follows (Nof, 1981):

$$V = \frac{\pi f_0^2 r_0^4}{16g'} \quad (1)$$

where

$$g' = g \frac{\rho_2 - \rho_1}{\rho} \quad (2)$$

where f_0 is the Coriolis parameter, r is the eddy radius, g' is the reduced gravity and ρ_1 and ρ_2 are the density of upper and lower water layers. We can consider $\rho_{AC1} = 24.0 \text{ kg/m}^3$; $\rho_{AC2} = 27.2 \text{ kg/m}^3$; $\rho_{EAC1} = 24.8 \text{ kg/m}^3$; and $\rho_{EAC2} = 27.4 \text{ kg/m}^3$ according to Rykova et al. (submitted). Considering the eddies are in a 1,5 layers model we have an approximate eddy volume of $1.2 \times 10^{13} \text{ m}^3$ for Agulhas Rings and $2.0 \times 10^{12} \text{ m}^3$ for Tasman Sea eddies. Considering these rings propagate at 5×10^{-5} and 2×10^{-5} m/s (Figure 7 in the new version of the manuscript), we have a leakage of $6.1 \times 10^5 \text{ Sv}$ and $4.0 \times 10^4 \text{ Sv}$ for each individual Agulhas Ring and Tasman Sea eddy, respectively. These values are more than 4 orders of magnitude larger than the ones from the literature ($O(1) \text{ Sv}$; Garzoli and Goni, 2000; van Sebille et al., 2012). This is only a rough estimate and does not account for eddy mixing and water entrainment, heat loss, or filamentation. Also, our estimates are based on punctual measurements of eddy radius and mean propagation speed, and do not consider eddy changes within the Cape Basin. Considering the uncertainties of this measurement, an analysis of the temporal variability would also be limited by the

method.

Agulhas Leakage estimates were summarised by Lutjeharms (2006) (Figure 1). The Agulhas Leakage temporal variability depends on the number of rings shed per year. Garzoli and Goni (2000) show the leakage varying from $1 \times 10^6 \text{ m}^3/\text{s}$ to nearly $40 \times 10^6 \text{ m}^3/\text{s}$ between 1993 and 1997. A recent studie also shows that the Agulhas leakage has an important interannual variability, but there has been no substantial trend over the last 20 years (Le Bars et al., 2014).

Table 6.5. Estimates of inter-ocean volume transports south of Africa by ring translation⁵¹⁶. Sv is $10^6 \text{ m}^3/\text{s}$. Results obtained by Lutjeharms and Cooper (1996)⁵⁵ are for Agulhas filaments.

Authors	Flux/ring [Sv]	Reference	Date
Olson and Evans (1986) ⁵⁴	0.5–0.6	T > 10 °C	November–December 1983
Duncombe Rae et al. (1989) ⁵⁴³	1.2	total	April–May 1989
Gordon and Haxby (1990) ⁴⁶⁴	1.0–1.5	T > 10 °C	May 1987
	2.0–3.0	total	May 1987
McCartney and Woodgate-Jones (1991) ³⁸⁵	0.4–1.1	total	February–March 1983
Van Ballegooyen et al. (1994) ¹²⁹	1.1	T > 10 °C	February–March 1987
Byrne et al. (1995) ⁹⁵	0.8–1.7	1000 db	10 cruises in the 1980s
Clement and Gordon (1995) ⁵³⁷	0.45–0.90	1500 db	May 1993
Duncombe Rae et al. (1996) ⁵²⁰	0.65	total	June 1992; May–October 1993
Lutjeharms and Cooper (1996) ⁹³	0.10	total	November 1983; December 1992
Goni et al. (1997) ⁵¹⁷	1.0	T > 10 °C	September 1992–December 1995

Figure 1: Table extracted from Lutjeharms (2006) summarizing estimates of the Agulhas Leakage.

Tasman Leakage estimates range from $3.8 \pm 1.3 \text{ Sv}$ (Rosell-Fieschi et al., 2013) to $4.2 \pm 4.3 \text{ Sv}$ (van Sebille et al., 2012). Using an eddy resolving global ocean model van Sebille et al. (2012) show large variability in the Tasman leakage on sub-weekly and inter-annual scales, but no trend between 1983 and 1997.

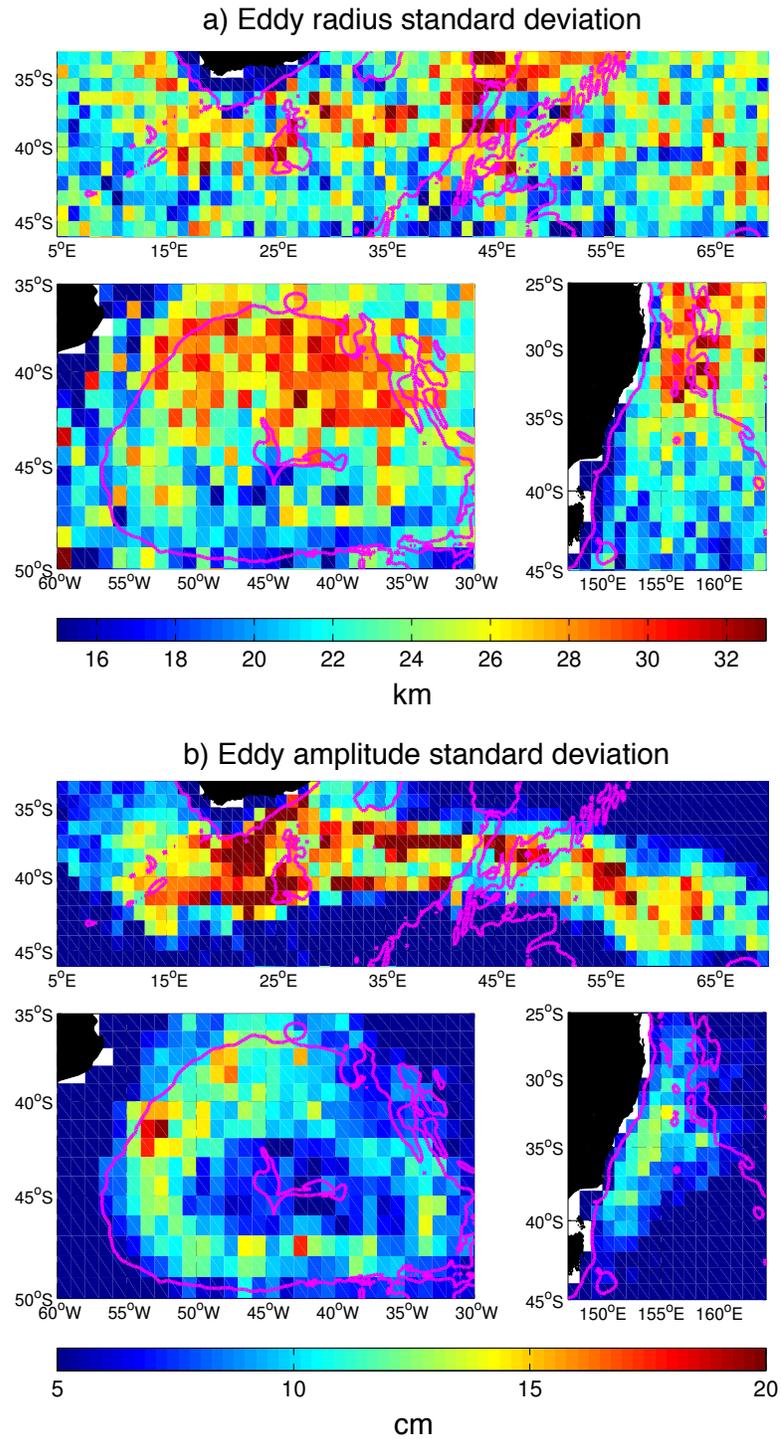
As we can see from previous works, we overestimate both leakages per eddy by more than four orders of magnitude. This is due to the uncertainties of a method based only on surface

characteristics, as previously mentioned. We agree that eddies contribution on both the Agulhas and the Tasman Leakage is a relevant topic, however it is not the goal of this study. For us to estimate these leakages we would need to evaluate the full structure of the eddies, as well as take into account all process that would affect the eddies volume and changes in its inner water mass properties.

2) Is there time-variability in eddy properties which may allow identification of forcing of the eddies, or the effect of eddies on local circulation features such as the Zapiola gyre?

We thank the Referee for the comment. To give insight on eddies' radius and amplitude time variability we calculated these properties standard deviations within each $1^{\circ}\times 1^{\circ}$ grid cell for the entire time series, as described in the Data and Methods section of the revised manuscript and copied below:

“ Eddy mean and standard deviation (STDev) radius and amplitude maps are built after gridding each WBC region onto $1^{\circ}\times 1^{\circ}$ cells. We then consider the radius and amplitude of all eddy-like features (lifetime > 4 weeks) that occur in each cell to calculate both mean and STDev values for that cell. This analysis is performed throughout the entire time series (Oct/1992–Apr/2012). To test for significance of mean values we perform a non-paired t-test with 95% confidence level. To determine eddies with mean radius and amplitude larger (smaller) than the mean within that system we perform a right (left) tail test. ”



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Figure 2: Standard deviation of a) radii (km) and b) amplitude (cm) of eddy-like features (lifetime > 4 weeks) in the AC, BC and EAC Systems in a $1^\circ \times 1^\circ$ grid. Magenta lines indicate the 4000, 3000 and 2000 m isobaths, respectively.

We added a new subsection to the Results section, as follows:

“ Maps of eddies’ radius and amplitude STDev give us further insight on these properties spatial patterns of temporal variability (Figure 4). ”

“ Eddy radius STDev spatial distribution shows no evident pattern in the AC System (Figure 4a). However, spatial patterns similar to eddy mean radius emerge both in the BC and the EAC Systems. In the BC System cells with high standard deviation values cluster in the northeast domain of the basin. In the EAC System most of the variability happens in the current’s retroflexion region. ”

“ Eddy amplitude STDev spatial distributions for all systems are similar to the eddy mean amplitude distribution (Figure 4b). Here, cells with high STDev values are associated with the AC, the BC and the EAC retroflexions. ”

And to the Discussion as follows:

“ Maps of eddy properties STDev spatial distributions may give further insights on external forcing acting on eddies. For example, high STDev values might be caused by eddies significantly altering their size within those cells. Eddies can increase in size due to merging (e.g. Cresswell, 1982), feeding on instabilities and energy conversions (e.g. Mata et al., 2006). Conversely, eddies can decay by loss of balance in the upper ocean (sub-mesoscale instabilities; e.g. Drijfhout et al., 2003), lateral entrainment (e.g. Cheney and Richardson, 1976), bottom stress (de Steur and van Leeuwen, 2009), interaction with internal waves (Polzin, 2010) damping by air-sea fluxes (e.g. Villas Bôas et al., 2015) and generation of Rossby waves (McDonald, 1998; van Sebille et al., 2010). Amplitude high STDev values we see close to the BC and EAC retroflexions (38°S and 31°S, respectively) indicate that the eddies occurring there are not only large anticyclonic retroflexion eddies, but a large range of eddies’ sizes. The high values also suggest that these eddies might be highly interacting

with each other or with the mean flow.

“ Regions with radius and amplitude small STDev values suggest that a) local eddies have always the same size, or b) there is no significant energy conversion between the eddies and the mean flow in those locations (i.e. no growing nor fading). Cells with small STDev values occur north and south of the ARC, the centre of the Zapiola Drift, and the Tasman Sea. ”

We also looked at the eddy time-variability along its propagation (i.e. in a lagrangian sense), founding it to be an interesting question and approached the issue by considering a particular case of AC System eddies into the South Atlantic (Figure 3). To tackle the referee’s question on eddy property time-variability we here describe our results on Agulhas Rings’ properties change.

AC System eddies show an increase in eddy radius and a decrease in eddy amplitude as they propagate (Figure 3). We have several theories to explain these results, being some of them related to external forcing acting on the eddies.

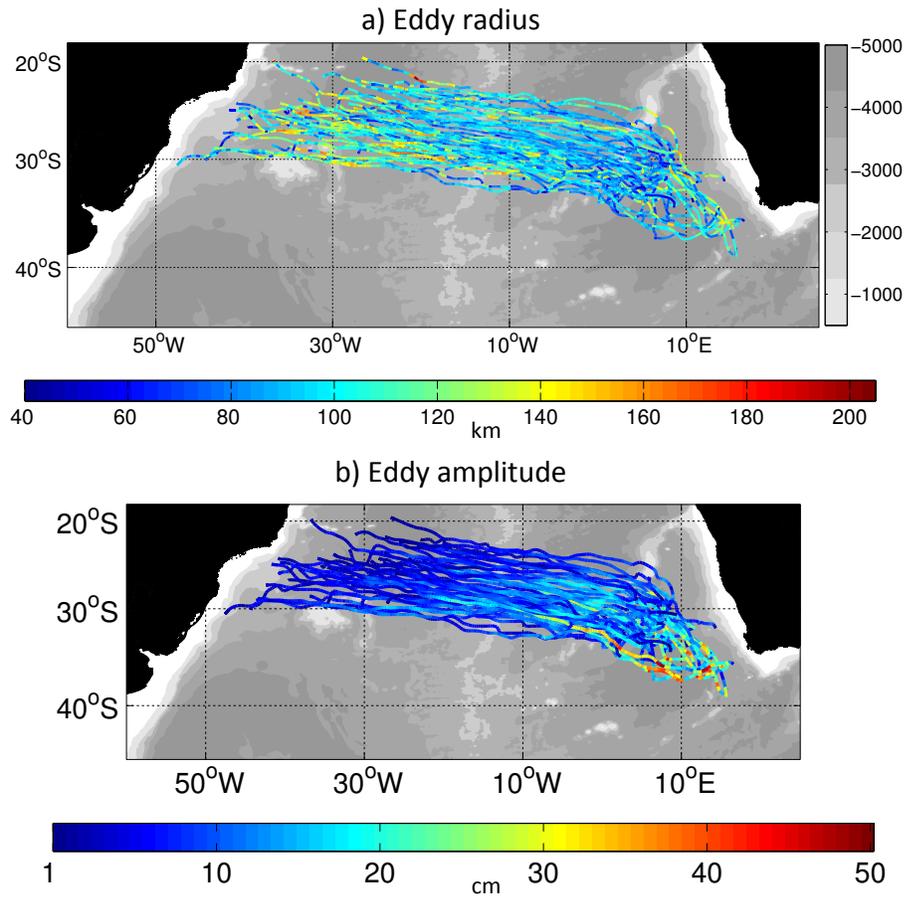


Figure 3: Agulhas Rings crossing the South Atlantic. Colours change according to a) eddy radius, and b) eddy amplitude at each time step (7 days). These eddies were first identified between 25°S and 45°S and 10°E and 21°E.

As Agulhas Rings propagate across the Atlantic they change their radius and amplitude. However, these changes are opposite: while we see a significant decay in eddies' amplitude, we see a significant increase in eddies' radius as they overcome the Mid-Atlantic Ridge (Figure 3).

The eddies' radius increase across the South Atlantic is of 2.6×10^{-2} km/day (considering only significant trends with confidence interval $>95\%$). In a comparison between different eddy identification and tracking methods J. M. A. Souza (personal communication, Nov 12 2012) also found an increase in Agulhas Rings radius as they propagated in the South Atlantic, but this was not reported in their work (Souza et al., 2011). The authors identified an eddy radius increase rate of 5.45×10^{-2} km/day along their Atlantic crossing. This value has the same order as the one found in our work.

The eddies' amplitude decrease is of -1.4×10^{-2} cm/day, and their initial amplitude is reduced by 86% as they reach their final stage. This $\sim 85\%$ amplitude reduction is also showed by Byrne et al. (1995) and Souza et al. (2011). Both works use altimetry data to identify eddies as they propagate away from the Cape Basin. Souza et al. (2011) shows an eddy amplitude decay rate of -9.33×10^{-5} cm/day.

Expected direct relations between amplitude (A), rotation speed (U) and vertical length (L) are different than the one found here. According to eddies' governing equations of potential vorticity and momentum conservation in cylindrical coordinates (Nof, 1981), lense-type eddies vertical length (H) and rotation speed are given by:

$$H = \frac{f_0^2(r_0^2 - r^2)}{8g'} \quad (3)$$

$$U = -\frac{f_0 r}{2} \quad (4)$$

where f_0 is the Coriolis Parameter, r_0 and r are eddy radius values, g' is the reduced gravity and H is given by $H = A + \xi$ for lens-type eddies, where ξ is the displacement of the inferior isotherm. Therefore, H and r^2 are directly proportional, and H is directly proportional

to the eddies' amplitude A . However, these direct relations are not observed in the results presented here. Several processes may be affecting these eddies' characteristics, as we will now elaborate.

1. The interaction with bottom features at shallower depths may cause eddies squeezing, (i.e. eddy radius increase and H decrease) in order to maintain their potential vorticity (Cushman-Roisin and Beckers, 2006). However, that is not the case for the Agulhas Rings in matter, because they present larger radii when reaching deeper oceanic regions, as the Brazil Basin (Figure 3). Nevertheless, the radius increase is always observed after the rings cross the Mid-Atlantic Ridge. The effect of the ridge cannot be disregarded, nevertheless we cannot sustain that the ridge is in fact squeezing the eddies.
2. The presence of a strong pycnocline could have the same effect on eddies as a shallow bottom, causing their squeezing. Still, that is not the case for the studied region. We see the increase in Agulhas Rings radius in the centre of the South Atlantic Subtropical Gyre. There, the pycnocline presents higher depths due to surface high pressure forcing and Ekman transport convergence. Therefore, squeezing due to stratification can also be ruled out.
3. The increase in eddies' radius could also be explained by eddy merging. However, during this interaction, eddies may alter their structure for a period of time (Nof, 1988; Cushman-Roisin, 1989) hindering the identification mechanism to keep track of Agulhas Rings after the merging event (Chelton et al., 2011). Therefore, if eddies are merging, they might be abandoned by the tracking algorithm, and the merging event would not explain the radius increase.
4. The meridional displacement of an eddy can cause an increase in its radius. This

is because the Rossby Radius of Deformation (R_D) is larger in lower latitudes and the minimum eddy radius is given by $R_D 2\sqrt{2}$ (Azevedo, 2009). However, the eddy with higher radius increase rate (0.58 km/week) propagates quasi-zonally, translating roughly along the 30°S parallel. Furthermore, one of the only four rings with significant radius decrease propagates equatorward, moving across $\sim 6^\circ$ of latitude.

5. A possible explanation for an increase in eddy radius and decrease in eddy amplitude may be the identification method combined with the altimetry sampling resolution. After crossing the Mid-Atlantic ridge, the eddies' amplitudes are close to the altimeter resolution limit (1–2 cm rms). This limiting resolution might be causing the increase in radii measurements when compared to these values reported east of the Mid-Atlantic Ridge. As mentioned, J. M. A. Souza (personal communication, Nov 12 2012) found an increase in Agulhas Rings' radius in the South Atlantic as well. However, this increase only occurred in eddies identified by the same identification and tracking method used by Chelton et al. (2011) (the one used to build the eddy dataset used in our study). All these hypotheses may raise the question: are the Agulhas Rings' radius increasing in the South Atlantic due to a challenge to the identification method or due to a real phenomenon?

As presented above, the time-variability in eddy properties is a very complex analysis and requires a more focused investigation. This investigation should possibly combine different types of datasets (altimetry and hydrography) as well as eddy-resolving model outputs.

3) Are the temporal trends matching the southward progression of WBC systems?

It has been shown that the poleward migration of Southern Hemisphere western boundary

currents can affect eddies behaviour. At the EAC System, Cetina-Heredia et al. (2014) show a significant increase in southward transport inside and outside eddies between 1980 and 2010 in a global eddy-resolving model output (Ocean Forecast for the Earth Simulator - OFES). The authors associate this transport increase due to intensification of both the EAC poleward flow and the EAC Extension flow. In their study the EAC does not penetrate further south, but separates more often at southernmost latitudes within the known separation region. Matear et al. (2013) report an increased eddy activity in a climate change scenario in global eddy-resolving model (Ocean Forecasting Australian Model - OFAM).

At the AC System the Agulhas Leakage response due to poleward shift of the westerlies is still in debate. Previous studies report an increased leakage (e.g. Biastoch et al., 2009; Beal et al., 2011; Loveday et al., 2015). However, Durgadoo et al. (2013) reports a decrease in the Agulhas Leakage due to a westerly poleward shift in an eddy permitting model. The decrease would happen due to the redistribution of momentum input by the winds.

It is known that the Brazil-Malvinas Confluence has a southward displacement between $0.39^\circ/\text{decade}$ and $0.81^\circ/\text{decade}$ (Goni et al., 2011; Lumpkin and Garzoli, 2011; Combes and Matano, 2014). Although Goni et al. (2011) reported a southward shift of the EKE in the region, no studies have explored the BC eddies' behaviour due to westerlies increase.

To look at temporal trends related to the southward displacement of WBCs we would have to determine which eddies within each region were shed by the current. We found it to be very difficult to determine which eddies were directly shed by the WBCs retroreflections just based on D. Chelton's global eddy dataset. For that, we would have to go back to Maps of Sea Surface Height and investigate the origin at each of the eddies identified within that region, which was not the scope of the study. Nevertheless, we tried to look at this

matter by selecting anticyclonic eddies first identified close to the currents' retroflection region and applying a radius threshold - to select larger eddies. However, we are not fully confident that this approach was successful. We could not differentiate, without a doubt, eddies shed by the retroflection meander and other eddies. We agree with the referee that this is a relevant matter for a future study, specially when it comes to BC eddies.

4) Relating properties to more easily attainable metrics, such as eddy kinetic energy.

We agree that the comparison between the amount of eddies, their mean radius and amplitude, and the system's mean EKE is of great interest. We performed that comparison on request of Referee #1 as well (Figure 4, now added to the manuscript a Figure 2). Mean EKE maps were built after Aviso's Reference Series Maps of Absolute Geostrophic Velocities between Jan/1993 and Dec/2010.

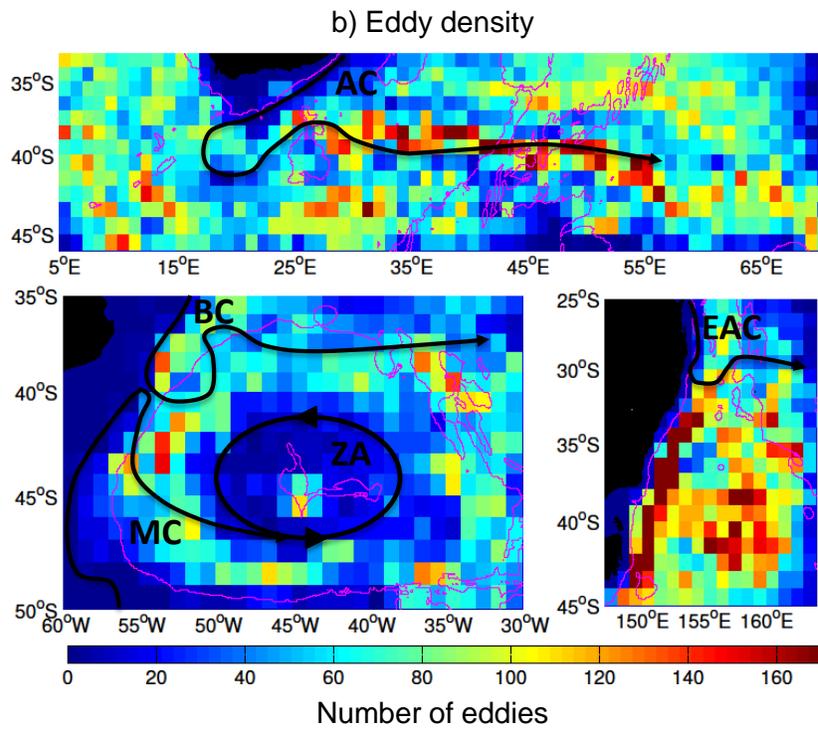
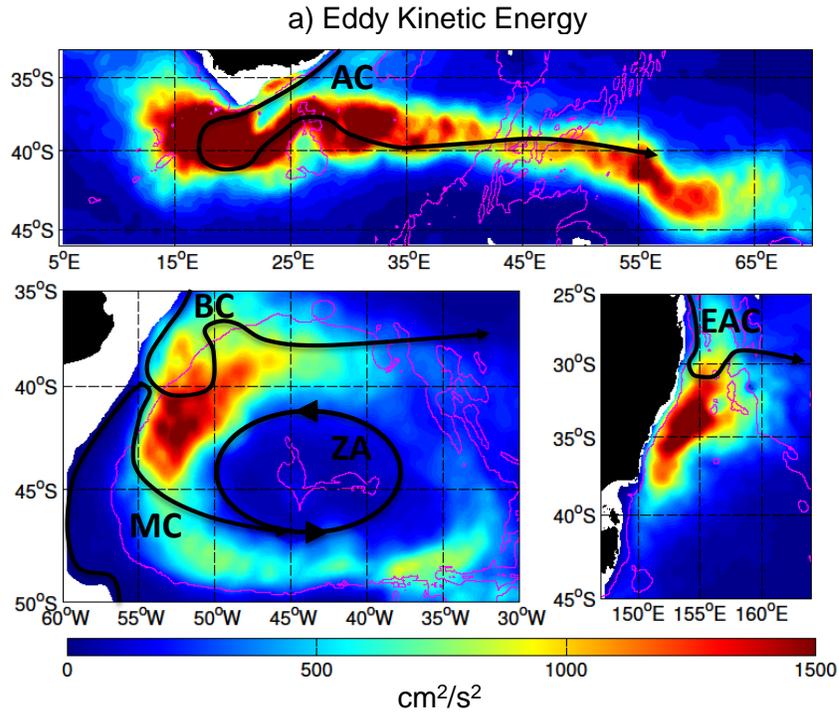


Figure 4: a) Map of mean Eddy Kinetic Energy built after Aviso's Sea Surface Height dataset (1993-2011), and b) map of eddy density built after Chelton et al (2011) global eddy dataset.

These new results revealed that regions of high mean EKE are not necessarily associated with regions of high eddy density. In turn, high mean EKE is associated with eddies' amplitude (Figure 5, edited after requests from the review group led by J. Williams; this figure is now Figure 3 in the manuscript). A clear example is the EAC System, where high number of eddies (~ 90 eddies per cell; Figure 4b) occur over the entire domain and specially high values (>140 eddies per cell) along the southeast Australian coast. However, the high EKE occurs close to the EAC retroflection regions, due to the retroflection itself, its meanders and eddies. There, we find eddies with significantly higher amplitudes (~ 25 cm).

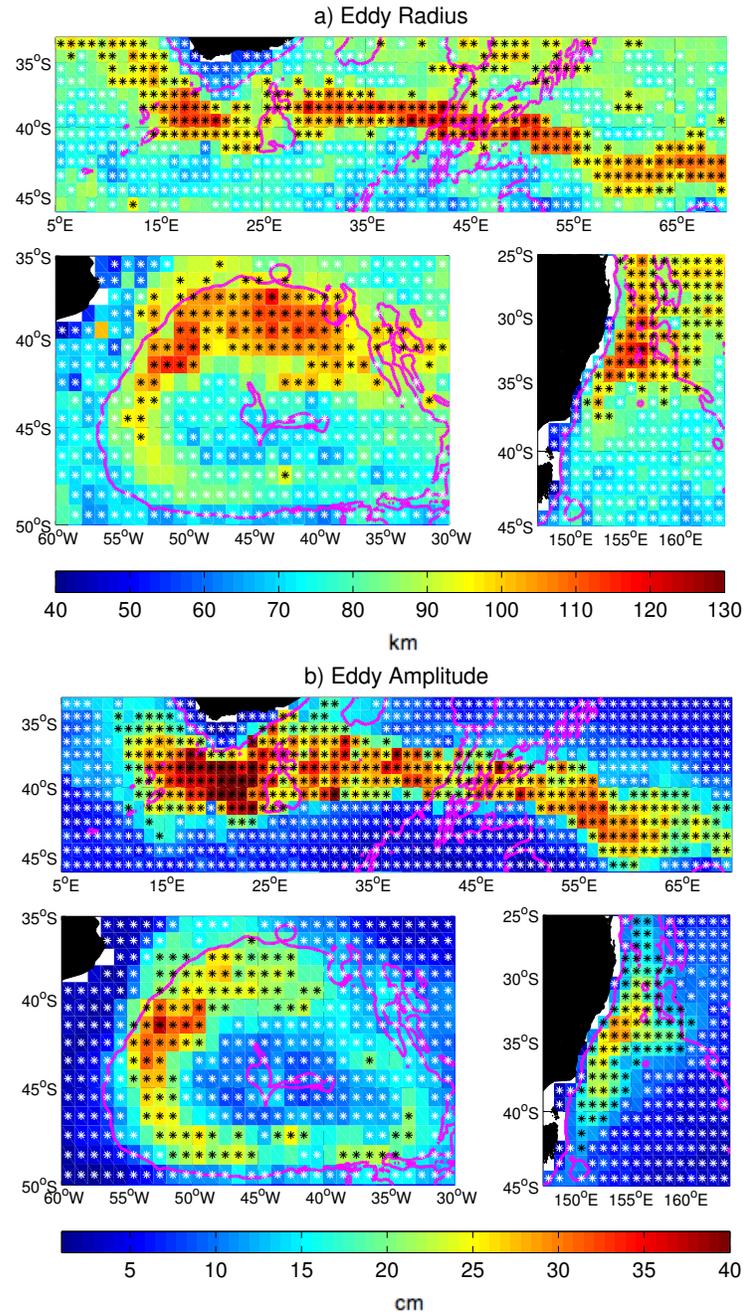


Figure 5: Mean a) radii (km) and b) amplitude (cm) of eddy-like features (lifetime > 4 weeks) in the AC, BC and EAC Systems in a $1^\circ \times 1^\circ$ grid. Magenta lines indicate the 4000, 3000 and 2000 m isobaths, respectively.¹⁷ White (black) dots indicate cells with values significantly smaller (higher) than the system mean. (Figure requested by J. Williams et al in their review process of this manuscript.)

Maps of eddy density for both polarities (not shown) display similar patterns at the AC and EAC System. In the BC System polarity differences occur mainly in the inner part of the Zapiola Drift. Here, a high number of cyclonic eddies (~ 100 eddies) occur over the Zapiola Rise. This polarity difference has already been reported by Saraceno et al. (2009). Therefore, considering the overall similarities between cyclonic and anticyclonic density distribution we decided to combine polarities and add only one figure to the manuscript (Figure 4b).

The maps of mean EKE and eddy density were added to the manuscript as Figure 2. We added two new subsections to the Results section of the manuscript, where we describe EKE and eddy density distribution, and eddy radius and amplitude distribution, allowing the reader to compare these figures together. The text added to the first subsection is as follows:

“ The EKE is a measurement of mesoscale activity within a region. Therefore, one would expect regions with high EKE to be associated with an increased number of eddies. With that in mind, we look at both mean EKE maps and eddy density maps of the three systems (Figure 2a and 2b, respectively). While high mean EKE is associated with the WBCs retroflection regions, high eddy density seems not to be the case.

In the AC System high mean EKE values occur in the AC retroflection ($\sim 17^\circ E, 37^\circ S$) and expand further west, reaching the Cape Basin. In this system the ARC also displays high EKE values along its path. Here, the meandering performed by the current when encountering the Agulhas Plateau ($26^\circ E, 40^\circ S$) becomes evident. High eddy density patterns do not agree with the EKE distribution in this system, with eddies occurring over the entire region. Cells with low eddy density occur both to the north and to the south of the ARC.

In the BMC System high mean EKE values occur in the BC retroflection ($\sim 52^\circ W$, $40^\circ S$) and contouring the Argentine Basin, as previously shown by Fu (2006). High eddy density patterns do not agree to the mean EKE distribution in this system. High density cells occur in the outer portions of the basin and over the Zapiola Rise, a bathymetric feature in the centre of the Argentine Basin ($45^\circ W$, $45^\circ S$) that rises 4700 m below the surface (Ewing, 1964). This Basin has depths exceeding 6000 m in its southwestern part (Saunders and King, 1995). This high eddy density over the Zapiola Rise was previously shown by Saraceno and Provost (2012) to be due to the presence of cyclonic eddies that enter the Zapiola Drift. This drift is an anticyclonic flow that dominates the Argentine Basin circulation (Miranda et al., 1999), flowing around the Zapiola Rise.

In the EAC System high mean EKE values occur to the south of the EAC retroflection ($\sim 157^\circ E$, $31^\circ S$) extending to the southern end of Australia's mainland. However, a band of high eddy density cells expand further south, reaching Tasmania. Eddies also occur over the entire Tasman Sea, and not only close to the eastern Australian shelf break, as suggested by the mean EKE map. ”

And the discussion of maps of EKE, and eddy density, radius and amplitude distribution was added to the Discussion section as follows:

“While eddy density maps are valuable to show locations of major eddy activity, they can be misleading. Eddy density maps consider the numbers of eddies identified within each grid cell along the entire time period. However, they do not consider if an identified eddy is still the same eddy or not. Therefore, a stationary eddy can be counted more than once, evasively suggesting a higher abundance of eddies in that particular grid cell. The fact that a group of grid cells has a high density does not necessarily means that it is a significant region of eddy formation. In the case of the EAC retroflection region, despite the local shedding and

meandering, eddies also remain “trapped” for long periods of time, interacting with each other (Mata et al., 2006), and therefore increase eddy density per cell. This could also be the case for the BC System, considering eddies seem to be retained within the Argentine Basin boundaries.

In all three systems, eddies with radius larger than 115 km occur close to the WBCs retroflections. This value corroborates with retroflection eddies radii of the AC current (120 – 324 km; Lutjeharms, 1981), the BC current (35 – 150 km; Lentini et al., 2006), and the EAC current (100–150 km; Nilsson and Cresswell, 1981; Bowen et al., 2005). The mechanisms responsible for eddies’ segregation according to radius size seem to act similarly in both cyclonic and anticyclonic eddies. These mechanisms are more complex than would be expected based only on the relation between latitude and the first baroclinic Rossby radius of deformation.

We show that high mean EKE regions in all systems are more related to eddies’ amplitude than to eddies’ abundance. In the AC System, eddies with large radius and large amplitude occur in the same regions of high mean EKE (i.e. the AC retroflection and the ARC). Conversely, in the BC and the EAC Systems large radius eddies are not necessarily spatially distributed as the mean EKE field. In these systems, eddies with significantly large radius occur in the northern domains (BMC region and Coral Sea, respectively), while high mean EKE concentrates in the currents’ retroflection regions. Furthermore, in these systems high mean EKE values are associated with large amplitude eddies. Hence, large radius’ eddies are not necessarily the most energetic ones. ”

5) Investigating the extent to which they can use eddy decay rates to characterise barotropicity of eddies.

Although still debatable, it has been suggested that eddies may decay due to loss of balance

in the upper ocean (sub-mesoscale instabilities; e.g. Drijfhout et al., 2003), lateral entrainment (e.g. Cheney and Richardson, 1976), bottom stress (de Steur and van Leeuwen, 2009), interaction with internal waves (Polzin, 2010) damping by air-sea fluxes (e.g. Villas Bôas et al., 2015), and generation of rossby waves (McDonald, 1998; van Sebille et al., 2010). From all these mechanisms, eddies' barotropicity is more relevant when it comes to energy loss due to bottom stress and wave generation at rough bottom topography (M. Nikurashin, personal communication 5 June 2015). This is because highly barotropic eddies are more likely to have significant velocities near the bottom. We can estimate an eddy depth based on its amplitude (equation 3). However, if the eddy is a non-lense type (Figure 6) and the upper layer thickness is unknown, we cannot really say if the eddy is in contact with the ocean's bottom or not.

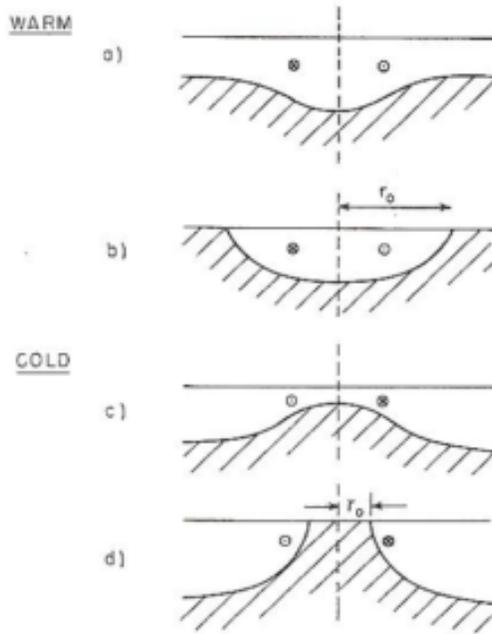


Fig. 1. Sketches of possible solution geometries. Dashed line represents center, lower layer fluid is indicated by crosshatching, and currents are shown.

Figure 6: Figure extracted from Flierl (1979)

Wunsch (1997) shows that the surface EKE measurement from satellite altimetry is dominated by the first baroclinic mode. This energy partitioning is different from the water column average EKE, where the ratio of EKE found in the barotropic and first baroclinic modes is ~ 1 . The author shows that altimetric measurements are directly reflecting the movement of the main thermocline and that the altimeters see very little barotropic kinetic energy. Therefore, relating eddy decay inferred from altimetry data and eddy barotropicity could be an unachievable task. In turn, barotropic energy conversion can be estimated from altimetry (Mata et al., 2006).

The balance between barotropic and first baroclinic modes in an eddy is another point to be considered. The balance between these modes is given by dissipation near the surface (M. Nikurashin, personal communication 5 June 2015). Therefore, if the dissipation process is unknown - as is the case for our study based on a global eddy dataset - we cannot say how barotropic or baroclinic an eddy is.

In summary, even if we estimate an eddy decay rate - as we did in reply to comment #2 for the Agulhas Rings -, we still cannot say how much of the eddy energy is projected onto the barotropic or baroclinic modes. For that, we must know the eddy's horizontal speed vertical structure. Therefore, a future study using an eddy-resolving model output or hydrographic data would be more suitable to answer the referee's suggestion.

Recent advances have been made regarding this subject. Rykova et al. (submitted) shows how much of WBCs canonical eddies horizontal velocity is projected onto the barotropic and first baroclinic modes. The authors show that eddies from the BC are the most barotropic from all WBC eddies, while EAC eddies are the most baroclinic. Also, Pilo et al. (submitted) show that EAC eddies velocity change from the first baroclinic mode to the barotropic mode as the eddy propagate and decrease in amplitude.

6) Eddy amplitude and rotation speed are highly correlated, as one might expect based on geostrophy alone. Are one of these redundant?

We agree that eddy rotation speed is redundant, considering they are calculated after eddy amplitude. We removed the rotation speed histogram of Figure 5 and also changed binning intervals for both eddy amplitude and radius, as also requested by Anonymous Referee #1 (Figure 7).

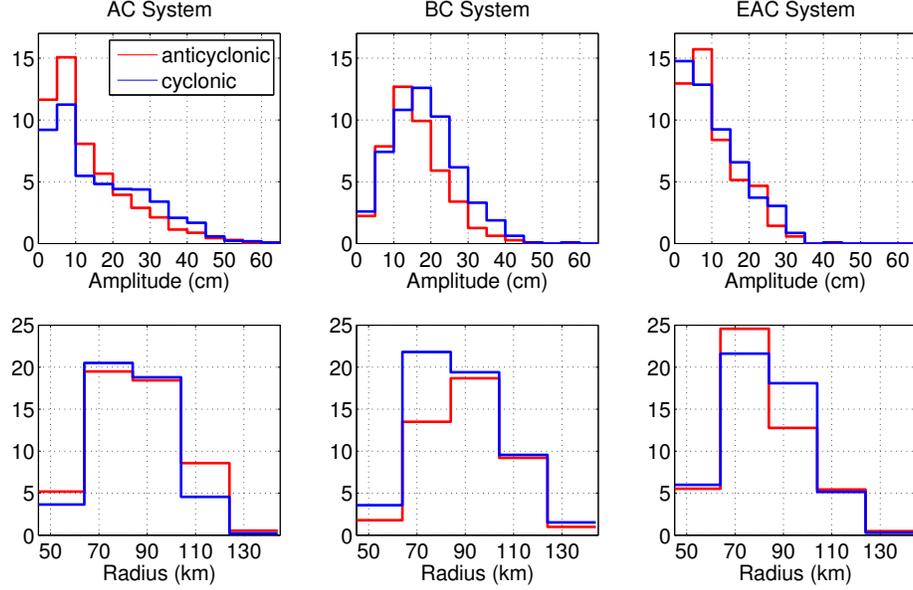


Figure 7: Histograms of amplitude and radius for AC, BC and EAC System eddies.

However, on their review of our discussion manuscript, J. Williams *et al.* suggested the addition of 2D amplitude contour plots. We agree with the reviewers that such plots are more meaningful than the histograms. Therefore, we chose to omit the histograms and add the amplitude spatial distribution to the manuscript (Figure 5). Different from the original eddy radius spatial distribution figure (Figure 6 in the original manuscript) we chose to merge cyclonic and anticyclonic eddies. The found general distribution pattern is the same for both, not justifying a polarity segregation.

The discussion regarding this new figure is copied in our reply to comment #4 in the current document.

7) Much is made of the difference between cyclonic and anticyclonic eddies in the histograms, but it is not clear that these differences are statistically significant. A more in-depth analysis of whether these differences are important

would be a useful addition.

We agree that the differences between cyclonic and anticyclonic eddies both in the histogram and in Table 1 are not significant. As mentioned above we removed the histograms. We also narrowed our discussion on Table 1. The next paragraph was added to the Results section:

“For completion purposes we show eddies’ mean properties in Table 1. Differences in eddy properties are not significant between cyclonic and anticyclonic eddies in all three systems (with some standard deviation values as large as the mean values). The similarities between cyclonic and anticyclonic eddies is due to the large range of eddies investigated. Eddies with radii spanning from 40 km to 130 km were included in the analysis.

Anticyclonic eddies from the AC System are the longer lived ones from all systems, due to their propagation across the South Atlantic. The small number of eddies propagating south of Tasmania do not increase the mean lifetime of EAC System anticyclonic eddies.

We draw attention to BC System eddies’ shorter mean lifetime and larger mean amplitude when compared to the other systems. These differences occur because AC and EAC System eddies lose their amplitude as they live and propagate across long distances (e.g. Souza et al., 2014, for the Agulhas Rings). This is evidenced if we calculate AC and EAC System eddies amplitudes considering only eddies with lifetime shorter than 17 weeks (being 17 weeks the mean lifetime of BC System eddies). Young AC System eddies have a mean amplitude of 13.8 cm compared to 8.4 cm for all eddies; and young EAC eddies have a mean amplitude of 11.5 cm compared to 8.9 cm for all eddies. The mean amplitudes of these young AC and EAC eddies are more comparable to the 17.3 cm mean amplitude of BC eddies. ”

8) Minor Typos

We thank the referee for the thorough review of the paper. Below, we copy the referee's **minor typos**, followed by our response in regular font.

- **Abstract, line 4: on → in.**

We thank the referee and corrected the typo.

- **line 6: local → the local.**

We thank the referee and corrected the typo.

- **Abstract, line 7: Main → The main**

We thank the referee and corrected the typo.

- **Abstract, line 15: anticyclonics → anticyclonic eddies**

We thank the referee and corrected the typo.

- **p. 137, line 19 & 22: after → using**

We thank the referee and corrected the typo.

- **p. 138, line 1: persisting → persistent**

We thank the referee and corrected the typo.

- **p. 138, line 2: unorganized → disorganized**

We thank the referee and corrected the typo.

- **p. 139, line 4: Heigh → Height**

We thank the referee and corrected the typo.

- **p. 140, several locations: particularity → inaccuracy?**

We thank the referee and changed the term to “aspects”.

- **p. 142, line 15-16: propagate → propagating**

We thank the referee and corrected the typo.

- **line 18-19: intraseazonal → intraseasonal**

We thank the referee for the correction. This sentence was edited out of the improved manuscript.

- **p. 146, line 16: isopicnals → isopycnals**

We thank the referee and corrected the typo.

- **p. 146, line 18: especulate → speculate**

We thank the referee and corrected the typo.

- **p. 148, line 17: unanswerd → unanswered**

We thank the referee and corrected the typo.

- **p. 148, line 20: restrained → constrained**

We thank the referee and corrected the typo.

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