Reply to J. Williams regarding the paper submitted to Ocean Science entitled " Eddy Surface properties and propagation at Southern Hemisphere western boundary current systems"

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June 30, 2015

This paper was chosen as the subject of a journal review workshop here at the National Oceanography Centre. The following is a summary of some of the comments raised in group discussion, and does not necessarily represent the view of only myself or NOC as a whole. I hope that this proves helpful to the authors in improving their paper.

R: We greatly appreciate the detailed review and incorporated the reviewers' comments to the manuscript, thus improving its quality. The manuscript has been carefully revised in response to the reviewers' comments and suggestions; detailed responses to their comments are below. The reviewers' specific comments are in **bold** font, while our reply is in normal font. New paragraphs added to the manuscript are copied here in *italic*.

1) The authors need to make it clearer how helpful this article is and for whom. There are lots of metrics of the eddies, but what is the context of the work, exactly what questions they are attempting to answer and what new or corroborated answers are found?

We have re-structured part of the Introduction section, as follows:

"As shown above, previous studies performed eddy censuses in the three systems of interest. However, important aspects of local eddy fields remain unknown. The main questions still to be answered relate to spatial distribution and propagation of eddies within each system. In that sense, the goal of this research is to qualify AC, BC and EAC System eddies based on their surface properties (i.e. amplitude, radius, rotation speed), and investigate eddy propagation and spatial distribution.

Eddies' mean surface properties and their spatial distribution shown here help us to further understand eddies' interaction with the regional ocean circulation. Identifying eddies' mean propagation patterns helps us to establish monitoring programs (i.e. moorings location, hydrographic sampling). Also, it helps us to better understand eddies' contribution to oceanic heat and salt transports, and how eddies affect local mixing. "

2) The group was not filled with confidence that the analysis is robust. In particular, the use of standard deviations and z-tests for significance when the distributions are not normal needs justification. The methods could be set out more clearly to aid reproduction, in particular the section at the end of p147. A more thorough description of methods would permit an assessment as to whether they are correct / appropriate.
. . . fig 6 is cluttered. Are there separate black crosses and stars? Significance could be more easily seen by hashing/fading out regions of little significance.

We agree with the reviewers that another statistical analysis would be more robust. We re-calculated significantly higher and smaller eddy radii values by applying a non-paired t-test, which is more suitable for our analysis (Figure 1). This test is used to compare two populations mean property, in this case, a $1^o \times 1^o$cell mean property and the eddy mean property within that system. The non-paired t-test, despite being developed for data with gaussian distributions, can be used for datasets without normal distribution if such dataset is sufficiently large.

Further description of our methods was added to the Data and Methods section in the manuscript and is copied below.

" Eddy mean and standard deviation (STDev) radius and amplitude maps are built after gridding each WBC region onto $1^o \times 1^o$ 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. 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. "

Figure 1 shows our new results. To de-clutter the figure, as asked by the reviewers, we removed mean flow schematics and only plotted black and white stars to mark cells with large and small values - instead of both dots and stars.

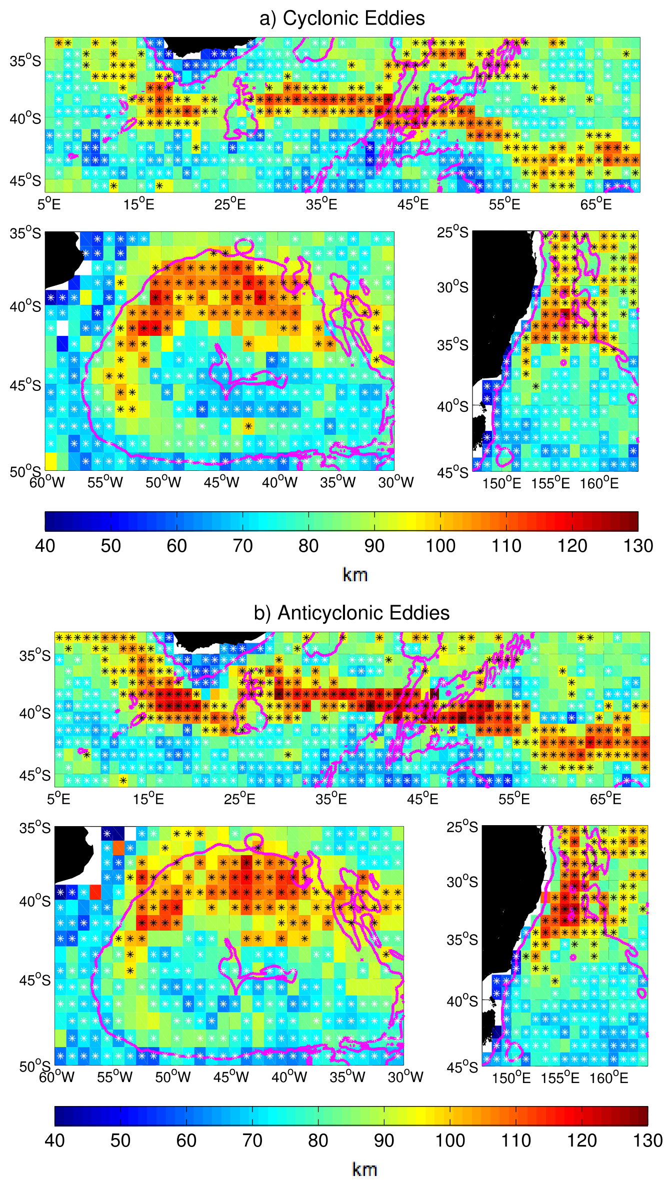

Figure 1: Mean radii (km) of a) cyclonic and b) anticyclonic eddy-like features (lifetime > 4 weeks) in the AC, BC and EAC Systems in a 1^o x 1^o grid. Magenta lines indicate the 4000, 3000 and 2000 m isobaths, respectively. White (black) stars indicate cells with values significantly smaller (higher) than the system mean.

While editing the new version of the manuscript and incorporating all the reviewers' suggestions, we chose to merge these eddy radius spatial distribution maps. Now, instead of cyclonic and anticyclonic eddies shown separately, we have a merged, both-polarity figure. As suggested by the reviewers in their 3rd comment (see below), we also performed eddy amplitude spatial distribution maps. The final figure (Figure 5, and now Figure 3 in the revised manuscript) shows both eddy radius and eddy amplitude 2D contour maps, to benefit comparison between these two properties. See more below for eddy amplitude 2D contour maps.

3) 2D contour plots for fig 5 would be more meaningful, so the reader can see eg whether the same eddies have low amplitude as low rotation speed. Figure 5 also appears to have mis-labelled axes.

We agree with the reviewers on both the relevance of 2D contour plots and the histogram.

We plotted 2D contour plots of amplitude (Figure 2) and rotation speed (Figure 3) for all three regions, considering cyclonic and anticyclonic eddies. Considering that Chelton et al. (2011) calculated rotation speed based on amplitude measurements, the spatial distribution of these properties are the same, having only different values and units. Comparing amplitude to radius spatial distribution (Figure 1), we see different patterns. The north-south segregation that occurs in eddy radius is not clear in eddy amplitude.

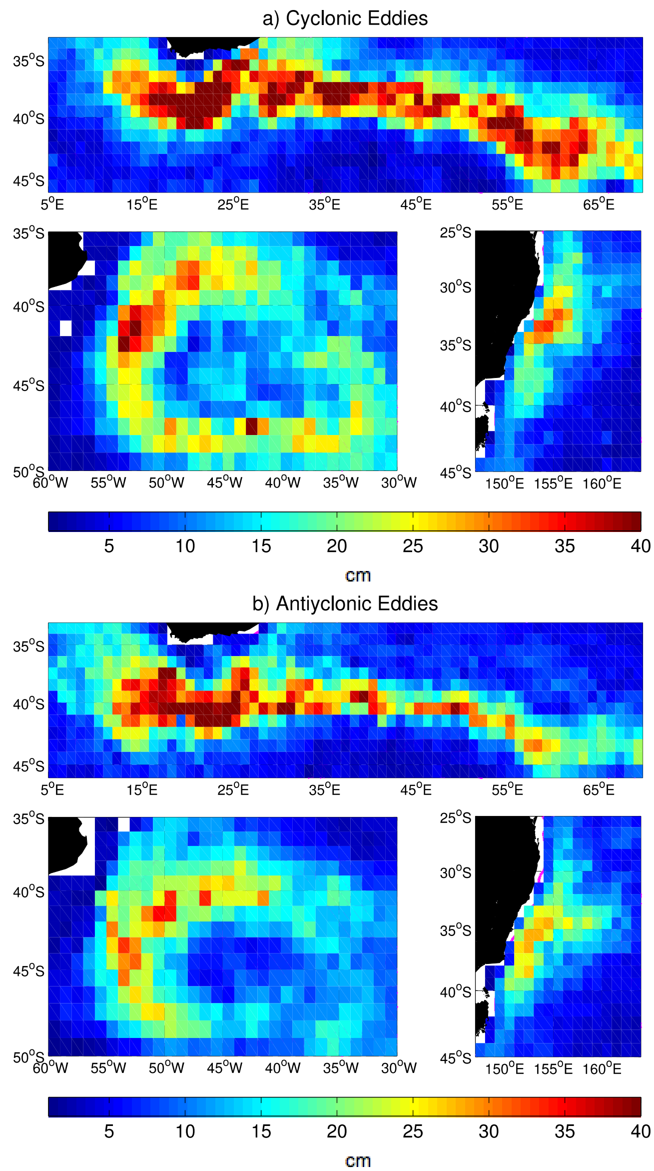

Figure 2: Mean amplitude (cm) of a) cyclonic and b) anticyclonic eddy-like features (lifetime > 4 weeks) in the AC, BC and EAC Systems in a 1^o x 1^o grid.

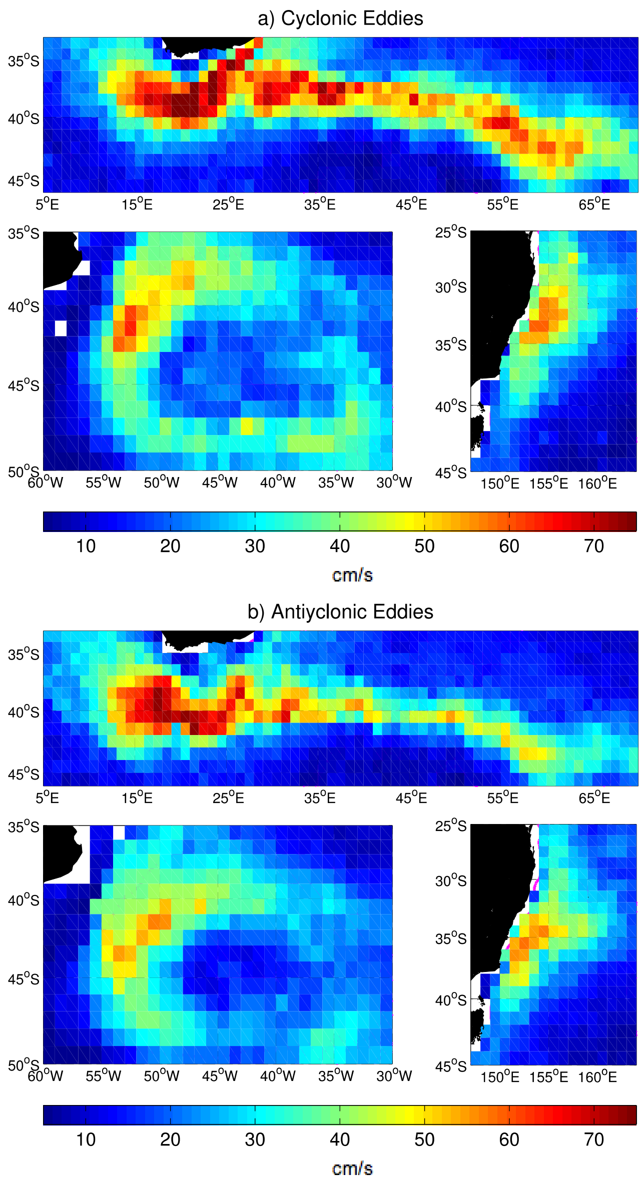

Figure 3: Same as in Figure 2 but for eddy's rotation speed (cm/s).

For clarity, we recalculated the histograms, adding proper labels and changing the binning and also removed the rotation speed histogram due to redundancy, following suggestions of Anonymous Referee #2 (Figure 4). Now, the histograms show eddies' amplitude and spatial distribution more clearly.

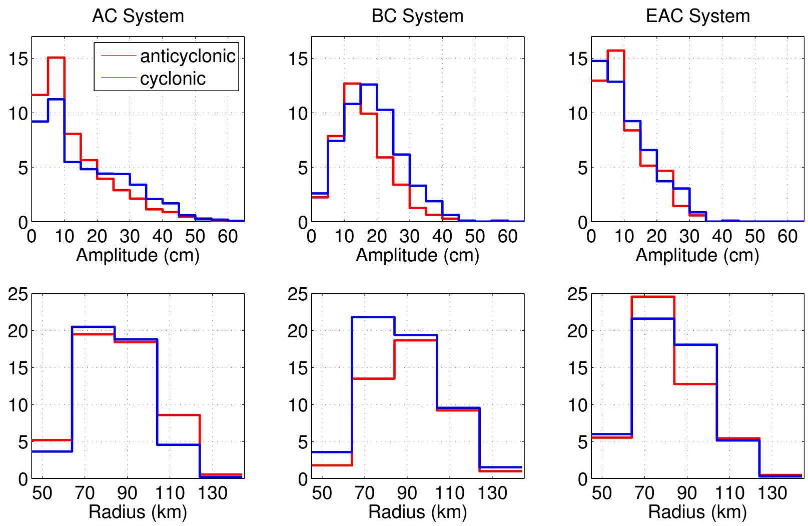

Figure 4: Histograms of amplitude and radius for AC, BC and EAC System eddies.

However, we agree with the reviewers that 2D contour plots are more meaningful than the histograms. Therefore, we chose to omit the histograms and add the amplitude spatial distribution to the manuscript. We thank the reviewers for the relevant insight. The final figure (Figure 5) shows the spatial distribution of radius (a) and amplitude (b), with cyclonic and anticyclonic eddies merged.

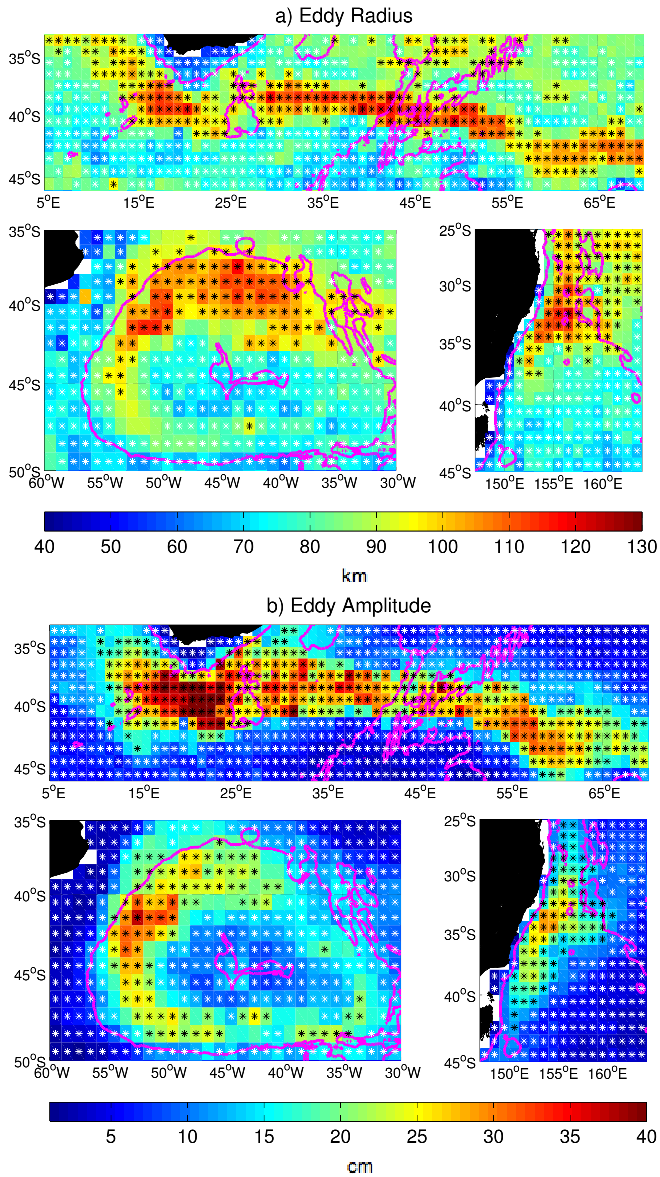

Figure 5: Mean a) radii (km) and b) amplitude (cm) of eddy-like features (lifetime > 4 weeks) in the AC, BC and EAC Systems in a 1^o x 1^o grid. Magenta lines indicate the 4000, 3000 and 2000 m isobaths, respectively. White (black) stars indicate cells with values significantly smaller (higher) than the system mean.

We describe the figure on the results section as follows:

As we can see, there is more to the high values of mean EKE in these three systems than the abundance of eddies. To further understand the spatial distribution of eddies, Figure 3 shows the horizontal length (radius) and amplitude occurring over these regions.

AC System eddies with significantly larger radius and amplitude occur in the Agulhas Retroflection and along the ARC path, while eddies with significantly smaller radius (Figure 3a) and amplitude (Figure 3b) occur to the south of the ARC. The distribution of eddies with large radius and large amplitude agrees with the mean EKE distribution in Figure 2a. Therefore, mean EKE, eddy radius and eddy amplitude distribution all match in this system, meaning that large radius eddies are also the most energetic ones.

BC System eddies' radius (Figure 3a) and amplitude (Figure 3b) spatial distribution do not match. Eddies with significantly larger radius occur in the entire northern domain of the Argentine Basin, while eddies with significantly larger amplitude cluster in the BC retroflection region ($\sim 55^o W, 41^o S$*). Eddies with significantly smaller radius and amplitude coexist in the centre of the Argentine Basin. Here, eddies' amplitude spatial distribution relates better to mean EKE distribution (Figure 2a) than to eddies' radius distribution.*

EAC System eddies with significantly larger radius (Figure 3a) and amplitude (Figure 3b) only overlap near the current's retroflection region ($\sim 31^o S$*), which is also where mean EKE is higher in this system (Figure 2a). Again, high mean EKE values relate better to eddy amplitude distribution than to eddy radius. Eddies with significantly larger radius occur in the Coral Sea, north of the EAC separation region. Eddies with significantly smaller radius occur in the Tasman Sea.*

Moreover, the spatial patterns in Figure 3 are very similar to both cyclonic and anticyclonic eddies (not shown). Therefore, we chose to combine both polarities in the making of the *figures.*

And discuss the results in the Discussion section as follows:

"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. "

4) "p146 line 10: This drift occurs due to interactions between eddies and the vorticity field of surrounding water parcels (Morrow, 2004; Cushman-Roisin and Beckers, 2006), resulting in an equatorward (poleward) drift of anticyclonic (cyclonic) eddies, regardless their hemisphere." This is the only reference to vorticity. Further discussion on the dynamics / processes / context would be interesting.

Following reviewers' suggestions, we added further dynamical discussions in the manuscript's Discussion section. Nevertheless, we did that keeping in mind that the aim of the paper is to perform an eddy census, with their surface properties and propagation in three WBC. The global eddy dataset used in the study was suitable for our objectives, but it refrains us from in depth dynamic processes analysis. The dynamic discussions were incorporated to the manuscript as follows:

1. On eddies meridional drift:

[...] "Eddies' meridional drift is seen in these eddies and, to a smaller extent, in eddies within the Cape Basin. Oceanic eddies have an intrinsic westward movement, mainly due to the planetary β-effect (Nof, 1981a). However, this purely zonal displacement is not always true in the open ocean. Other factors, such as mean flow advection, interaction with other eddies, the topographic β-effect, and a the meridional drift mentioned above can interfere with eddy displacement. This meridional drift occurs due to interactions between eddies and the vorticity field of surrounding water parcels (Morrow, 2004; Cushman-Roisin and Beckers, 2006), resulting in an equatorward (poleward) drift of anticyclonic (cyclonic) eddies, regardless of their hemisphere. "

2. On EAC System eddies clustering along the Australian slope:

   "The cluster of EAC eddies south of the EAC retroflection region may be related to their rotation sense. Shi and Nof (1994) suggested that EAC anticyclonic eddies, when encountering a continental wall, would propagate polewards due to the combination of three effects: a) the "image effect", b) the β-force and c) the "rocket effect". For the case of EAC anticyclonic eddies travelling west and meeting the Australian slope, the image and rocket effects would have a southward component and the β-force would have a northern component. According to the authors, for this case, the resulting component of these acting forces is southward. "

3. On eddies not propagating into continental shelves:

   In all three systems, eddies do not propagate into the continental shelf, being retained at the slope. This behaviour can be explained by a) the shallow depths of shelves compared to eddies depths, b) the presence of WBCs, and c) the propagation of eddies along lines of same potential vorticity. First, as previously shown, the mean eddy *radius considering all the systems is 86.7 km. If we consider this 86.7 km radius eddy to be a lense type we can estimate its depth, as the following (Nof, 1981b):*

$$H = \frac{f_0^2 r_0^2}{8g'} \quad (1)$$

where

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

Considering the eddy is in a 1,5 layers model and having $\rho_1 = 1025 kg/m^3$ *and* $\rho_2 = 1027.4\ kg/m^3$ *(Rykova et al., submitted; considering mean densities for AC, BC and EAC canonical eddies), we have an approximate eddy mean depth of 360.4 m. This means that eddies would not drift to regions shallower than that depth (i.e. continental shelves). Second, westward propagating eddies approaching a western boundary will only reach the continental slope if their Rossby radius is larger than the local WBC's Rossby radius (Azevedo et al., 2012). If not, the eddy might be advected poleward by the current. Third and last, eddies propagate along lines of same potential vorticity, established by local bathymetry. In the EAC System the eddy propagation along the 3000 m isobath, but never crossing to shallow regions, had been previously reported by Mata et al. (2006), but never crossing this isobath to shallow regions.*

5) The maps and most of the figures were generally clear and appropriate, but the cyan and pink line on fig 4 are hard to see.

We thank the reviewers for the suggestion and have changed the colour of eddies' tracks propagating south of Tasmania, which are now black (Figure 6).

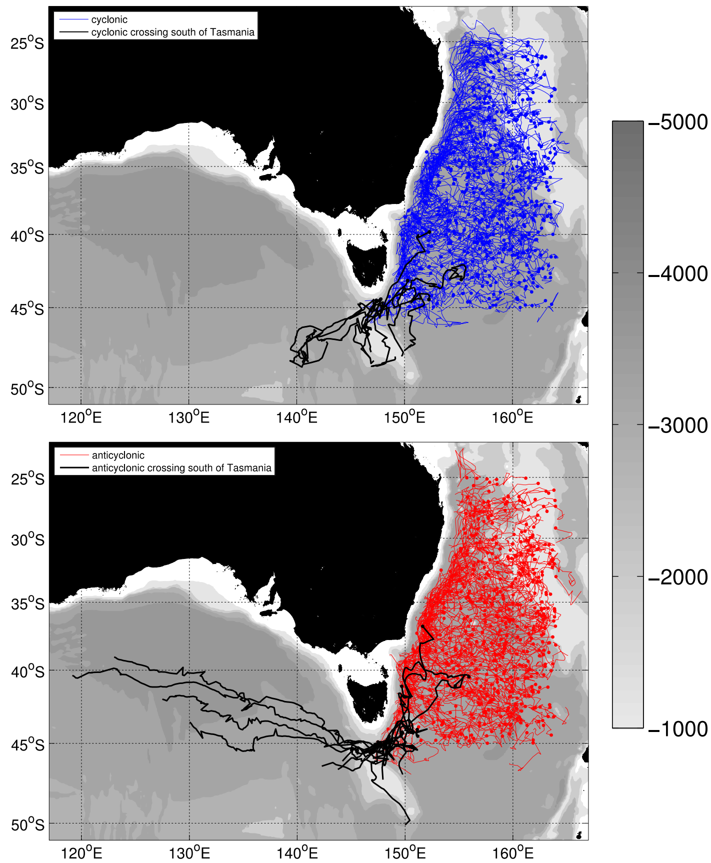

Figure 6: Trajectories of a) cyclonic and b) anticyclonic eddies first identified in the EAC System between Oct/1992 and Apr/2012. Eddies' tracks that cross south of Tasmania are shown in black.

6) Fig 4: Are the quiet patches east of Australia (154^{o}E, 38^{o}S) of interest?

The quiet patches mentioned by the reviewers on Figure 4 on the original manuscript are indeed relevant (also Figure 6 in this reply). We thank the reviewers for such thorough analysis. This quiet patch is now more evident when we look at eddies' density spatial distribution (Figure 2 on the improved manuscript; calculated by request of Anonymous Referee #1). At the same location ($\sim 153^o$E, 37^oS), we have cells with less than 50 eddies, surrounded by cells with more than 150 eddies.

This region is known as a highly energetic region, with many eddy interactions (Mata et al., 2006). When we look at Aviso's Sea Level Anomaly maps we see a lot of eddy activity and merging in that region, as well as in the whole area of the EAC retroflection. There, both cyclonic and anticyclonic eddies interact with each other, with mainly cyclonic eddies repeatedly merging (not shown). Therefore, considering it is indeed a region of high eddy occurrence and activity, we believe that the quiet patch does not indicate an eddy absence, but a challenge to the eddy identification algorithm. Because the eddies are merging, their shape is constantly changing and, in some cases, may not be identified as a closed contour feature by the algorithm (see manuscript's Data and Methods section and also Chelton et al., 2011). We added a short discussion on that in the revised manuscript, as follows:

"EAC eddies' tracks show a region of reduced activity centred at $\sim 153^o E$, $37^o S$ (Figure 7), for both cyclonic and anticyclonic eddies. This region of reduced activity is also clear in the eddy density spatial distribution in Figure 2b. However, this is a region known for enhanced eddy activity (Mata et al., 2006), and high EKE (Figure 2a), making this low eddy density unexpected. When looking at subsequent Aviso's SLA maps we see high eddy activity and repeated merging events in that region (not shown). Merging events might post a challenge to the eddy identification algorithm, as mentioned in Section 2. This challenge is due to the variable shape of eddies during such events. Therefore, we suggest that the reduced activity region at $153^o E$, $37^o S$ in Figures 7 and 2b are due to a challenge posed to the eddy identification method in highly energetic regions. "

7) p141 line 13: "As expected" - Why?

The eddy behaviour referred to is expected due to eddies' intrinsic westward propagation. Also, it is known that some Agulhas Rings (anticyclonic eddies shed by the Agulhas Current Retroflection) do propagate westward across the South Atlantic (e.g. Beal et al., 2011). Nevertheless, we are aware that not all eddies formed at the Agulhas Retroflection region do overcome the Walvis Ridge and reach the South Atlantic Ocean (i.e. de Steur and van Leeuwen, 2009). To avoid any confusion, we have removed the sentence "as expected" from the text. We also added:

"AC System eddies propagate along the "eddy corridor" in the Cape Basin at 4 cm/s, on average, and up to 7 cm/s. Reported mean eddy propagation speed within the Cape Basin range from 6 cm/s (Garzoli et al., 1996) to 11 cm/s (Goni et al., 1997). Therefore, our mean value falls in the smaller end of the reported mean speed range. Still in the Cape Basin, eddies propagate northwestward. This propagation pattern does not match the one shown by Fu (2006) for that region. The author reports a mainly westward propagation. We believe these differences to be attributed to differences in methods and also to the fact that in Fu (2006) "eddies" are defined as all mesoscale current variability (i.e. eddies, fronts, planetary waves, and current meanders). "

8) Further copy-editing for English is required throughout, e.g. "particularities" and the use of "after" on p137.

We thank the reviewers for the comment. We have performed a more thorough review on the manuscript. The term "particularities" was replaced by the more proper term "aspects", and the term "after" was replaced by "using". Anonymous Referees #1 and #2 acknowledged minor typos that were corrected. The revised manuscript was also assessed by a native speaker. We also added extra effort into improving the manuscript's written quality.

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