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The vertical structure of mesoscale eddies in the Azores Current corridor: a combined altimetry-Argo analysis

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Summary: In this manuscript, authors present results of an extensive analysis and census of mesoscale eddies in the Azores Current corridor. Using both satellite measurements of absolute dynamic topography and Argo float measurements of temperature and salinity, authors characterize mean eddy structure in three regions. Altimeter derived eddy tracks are used to find Argo profiles completed within eddies and to construct composite eddy structures. Results reveal east-to-west differences in mean eddy vertical structure linked to distinct locations and water masses of formation. A temperature and salinity heave and spice decomposition reveal much of the eddy signal to be associated with heave. Overall, the manuscript presents a comprehensive and careful analysis. Additional detail and clarification should be added to address how any potential biases could be linked to data sparsity (in space or time). The manuscript is a bit long, and readers may get lost in the details (many sentences quoting temperature/salinity differences from one region to the next). I would recommend focusing on the key results as they relate to larger scale circulation or how this region is unique with respect to mixing of unique water masses in the presence of a mid-ocean ridge.

We greatly appreciate your comments and suggestions, as we believe they have helped improve the quality of the manuscript. We hope that we have addressed all comments as thoroughly as possible.

We also recognise that the level of detail in some sections made the manuscript dense. This issue has been addressed in the revised version, which has been shortened by approximately four pages.

Main Comments:

1. Would recommend revision of “more barotropic/baroclinic” language. As Argo measurements extend only to ~2000 dbar, statements about depth independent structure over the sampled depth range would be more appropriate. Barotropic typically refers to depth independent over the entire water column.

We understand your comment. We agree that the term barotropic is conventionally used to describe a flow that is depth-independent over the entire water column.

In the revised manuscript, we have replaced the terms “more barotropic/baroclinic”: “more uniform” instead of “more barotropic”, and “with a well-defined subsurface maximum”.

2. What additional information or key results are revealed through separate heave and spice calculations of SA and CT? Would it not be simpler to calculate heave and spice change with respect to neutral density surfaces alone?

We understand your question, and indeed, it would be simpler to compute heave and spice solely with respect to neutral density surfaces. However, in our study region the presence of Mediterranean Water (MW) is particularly important east of the MAR. Because MW has a strong and distinct salinity signature, analysing variability only in density space would mask the signal linked to it: inversion of signal around 750-1000 dbar seen only the salinity (Figure 8g of the manuscript) and not in the temperature.

Important differences do appear (Figure 8), but they do not seem to be discussed in detail (e.g. why is the SA heave (Fig. 8g) less spread out in the vertical than CT heave (Fig. 8d)?).

As the revision of the text was made, we also discussed Figure 8 in more detail.

Answering to your direct question: The presence of MW in regions R1 and R2 produces a strong salinity signal, including an inversion in the vertical gradient of its climatological profile. Because heave is calculated as the product of the isopycnal vertical displacement (IVD) and the gradient of the climatology, this inversion generates a visible inversion of the signal around 750–1000 dbar (Figure 8g). As a result, the CT heave appears more vertically spread than the SA heave.

I would also recommend adding more detail to the definition and calculation of ISOD (Eq. 1).

The text was altered to: “In this work, we use the ISOD to characterise the mesoscale structures and infer which process dominates. Following (Bindoff and Mcdougall (1994) and later Han and Yan (2018), the ISOD equation can be written as:

$$\Delta X|_p \cong X_{SPI} + (-X_{HEV}) + residue \cong \Delta X|_n + (-\Delta p|_n \nabla X) + residual \qquad (1)$$

Where $\Delta X|_p$ represent changes at a pressure level, $\Delta X|_n$ the changes along a given isopycnic surface, $\Delta p|_n$ the difference in pressure for each chosen isopycnal surface reflects the isopycnal vertical displacement ($-\Delta p|_n$- IVD), and ∇X is the climatology vertical gradient. A residual (RES) term is added associated with mixing and/or diffusion, which, for a well-stratified water column, should be near zero.

The ISOD of CT and SA was computed using the same methodology for both the Argo and climatological profiles, following these steps: 1) Neutral isopycnal surfaces (NIS) were computed using the software available at http://www.teos-10.org/preteos10_software/neutral_density.html (Jackett and McDougall, 1997) and subsequently interpolated onto a fixed grid. 2) CT, SA, RHO, and pressure were then computed along each NIS. 3) SPI and isopycnal vertical displacement (IVD) were computed as the difference between the Argo and climatological profiles along each NIS. 4) SPI and IVD were interpolated back onto pressure coordinates using the climatological density profiles. 5) HEV was computed as the product of the interpolated IVD and the vertical gradient of the climatological profile. 6) CT and SA anomalies were computed in pressure coordinates. 7) The residual term (RES) was defined as the difference between the total anomaly and the sum of HEV and SPI for each variable. This term can be associated with double diffusion and/or internal mixing in the eddy's boundaries or its interior, or even other processes (like eddy stirring - e.g. McGillicuddy, 2016) that are not explained by the change of the property along the isopycnics (SPI) or due to their deflection (HEV); however, their origin is not the scope of this study and will not be referred to.

In summary, each Argo profile was converted into profiles of CT and SA anomalies, as well as IVD, HEV, and SPI (for both CT and SA). These metrics were then used to construct the eddy composites, which are analysed to assess how mesoscale structures affect the water column in our study region."

Where the detail of the ISOD calculation is underlined.

3. The three regions considered have significantly different surface areas. How does this, and subsequently the number of contributing profiles to composites, impact results.

The regions chosen for this study reflect different dynamics along the AzC before reported in our 2020 study (Silva-Fernandes and Peliz, 2020) apart from the region west of the ridge. The size of region 3 (west of the ridge) was reduced due to its proximity to the northwest corner of our domain, which is already under the influence of the Gulf Stream.

Despite the differences between the regions area, we do not believe that it impacts the composite results for the reasons below:

1) The number of sampled eddies is relatively high in both regions 1 and 2, being only smaller in region 3 due to its reduced size. In all regions this number is above 100 profiles (table 2) which from a statistical perspective this sample cannot be considered biased.
2) The composites are constructed in eddy-centred, normalised coordinates rather than in geographic space. Therefore, differences in regional surface area do not directly influence the composite structure, but only the number of available samples contributing to the statistics. Furthermore, the normalised distance of each profile from the eddy centre is radially well distributed (Figure 2b), which minimises potential bias when computing the radial composites.

Roughly how many unique eddies are being sampled/averaged in each composite?

In the table 2 the number of trajectories sampled refers to the trajectories of unique eddies. The number of eddies is the number of eddies being sampled along track belonging to those trajectories.

For example, in R1, 87 unique anticyclones (corresponding to 87 different tracks) were sampled 244 times in total along their trajectories, with a mean of 2.8 times in each track.

This is partly addressed in Table 2, but I'm left wondering as to the ratio of altimeter tracked eddies vs. Argo profiled eddies.

The total number of tracked eddies (individual trajectories) and the Argo profiled eddies, for the AzC System (the complete study region) and the individual regions is presented in the table 1.

Table 1 - Number of tracked eddies (TE) and Argo profiled eddies (APE)

		TE	APE	APE/TE (%)
AzC System	Anticyclones	5909	450	7.6
	Cyclones	5230	439	8.4
R1	Anticyclones	884	87	9.8
	Cyclones	807	85	10.5
R2	Anticyclones	1405	91	6.5
	Cyclones	1226	89	7.3
R3	Anticyclones	574	55	9.6
	Cyclones	537	40	7.4

Although the percentage of tracked eddies relative to the total number of trajectories is relatively low, the ratio of Argo floats emerging inside eddies (both anticyclones and cyclones) compared to those emerging outside eddies is consistent with values reported in previous studies.

In our study, a total of 2,393 Argo profiles (31%) emerged inside eddies and 7,641 outside eddies within the AzC system. For the AzCCo region specifically, 33% of the profiles emerged inside eddies. For comparison, Keppler et al. (2018) reported that 34% of profiles emerged inside eddies, whereas Lin et al. (2019) found a lower percentage of 16%.

4. A bit more should be said about the horizontal and temporal resolution of the altimeter product used, especially with respect to the first baroclinic deformation radius in this region.

While horizontal resolution of the available product is relatively high, much interpolation is carried out behind the scenes.

We have expanded Section 2.3 to clarify the horizontal and temporal resolution of the altimeter product and its relation to the first baroclinic deformation radius in the region. The CMEMS ADT product has a spatial resolution of ¼° and a daily temporal resolution. Although the grid spacing is relatively fine, the mapped fields are derived from interpolated along-track measurements, with an effective spatial resolution of approximately 200 km at mid-latitudes. In the study region, the first baroclinic deformation radius ranges between ~30 and 50 km, which lies near the lower end of the mesoscale spectrum. Consequently, features at this scale are only partially resolved, whereas larger mesoscale eddies are well captured.

The paragraph in section 2.3 reads as: "Absolute dynamic topography (ADT) maps between 2000 and 2020 from the Copernicus Marine Service (CMEMS; https://data.marine.copernicus.eu/) were used. The gridded product is based on merged observations from multiple satellite missions with ¼° spatial resolution and daily temporal resolution. Although the grid spacing is relatively high, the mapped fields are generated through interpolation of along-track measurements, with an effective spatial resolution of ~200 km at mid-latitudes (Ballarotta et al., 2019; Taburet et al., 2019), being structures with ~50 km radius resolved (Chelton et al., 2011, 2019). In our region, the first baroclinic deformation radius is approximately between the values of 30 and 50 km (Chelton et al., 1998), lying near the lower end of the mesoscale spectrum; features at this scale are therefore only partially resolved by the altimetric product, whereas eddies significantly larger are well captured. ADT fields were high-pass filtered using a first-order Bessel filter with a 700 km wavelength cutoff (Mason et al., 2014) to remove large-scale variability and then interpolated in space and time to the locations of the ARGO profiles. These maps were used to superimpose the atlas eddy trajectories."

Line-by-line:

L6: a bit misleading if you subsequently discard half of these profiles?

We understand your comment. It was corrected to more than 10000.

L26: consider conclusions of Abernathey and Haller 2018 (10.1175/JPO-D-17-0102.1)

The reference was removed.

L31: provide some longitudinal reference as well

The Azores current is located at 34ºN east of MAR.

The text was altered to:

L35: define a "free" eddy

As a "free eddy" we meant a coherent eddy.

The new sentence reads as: "The latitudinal band surrounding the jet, which we will loosely refer to as the Azores Current Corridor (AzCCo) is characterised by coherent eddies, meanders, and filaments, mostly evolving from baroclinic instability of the jet (Klein and Siedler, 1989; Alves and De Verdière, 1999), as well as several other types of structures propagating into the corridor."

L52: "presents more detected cyclones" this is confusing and/or is an incomplete sentence?

We meant more detected cyclones comparatively to anticyclones. The sentence was corrected in the text.

L54: consider adding corridor references to Figure 1 ... as at least two corridor regions are separately identified?

Figure 1 was separated into two figures (see figure R1):

- Figure 1a - bathymetry of the study region and reference to the main topographic features in the region as well as the main corridors of eddies known.
- Figure 1b - mean EKE.

We also added in both figures an approximate representation of the Azores Current main axis following Silva-Fernandes and Peliz, 2020.

L60-61: maybe remove parentheses around citation?

Corrected.

L64: here and elsewhere, reference to regions or features (i.e. Azores plateau) need a visual reference. It is unclear what region is being referred to, especially if plotting of bathymetric contours only to 2500m. I don't see a plateau in Figure 1.

By "plateau," we refer to the region of relatively shallower bathymetry compared to its surroundings, corresponding to the portion of the Mid-Atlantic Ridge where the Azores islands are located. Its location is indicated in Figure R1 (Figure 1a in the revised manuscript).

L71: Figure 1 - consider using a log color scale for the EKE plot, the saturated high EKE region in the NW corner is a bit distracting. Would recommend expanding the lat/lon range of the plot or including an insert to provide greater geographical reference. Would also recommend using a fill color for land regions.

The EKE map was modified to represent a larger region (see Figure R1 bottom). Instead of a log scale, we expanded the top part of the colormap and changed the limit of the maximum EKE to the 1600 $cm^2 s^{-2}$ level. We also added white contours every 50 $cm^2 s^{-2}$ until the 400 $cm^2 s^{-2}$ level and then every 200 $cm^2 s^{-2}$. The colour white was chosen to represent land.

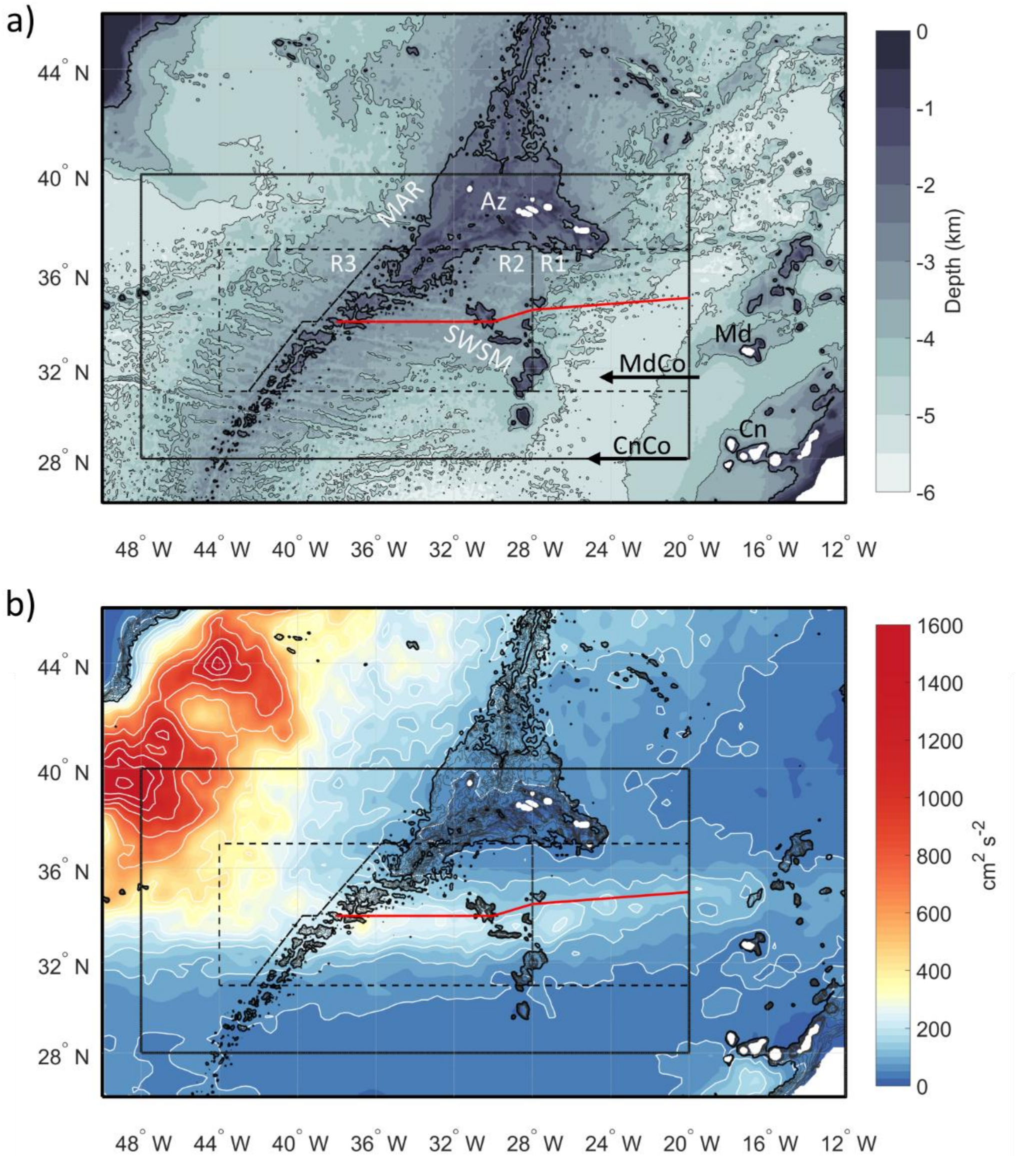

Figure R1 - (Figure 1 in the revised manuscript) (top – Figure 1a in the revised manuscript) Bathymetric map. The thick black contour represents the 2.5 km bathymetric and the black thin ones the 4 and 5 km bathymetric (bottom – Figure 1b in the revised manuscript) Mean EKE for the period 2005-2017. The contours are highlighted in white every 50 cm2/s2 until the 400 cm2/s2 level and then every 200 cm2/s2. The thick black contour represents the 2.5 km bathymetric. On both figures the black box represents the study region and the black dashed boxes the 3 regions of the AzCCo; the dotted line represents approximately the current axis between 20 ^{o}w and 40 ^{o}W following Silva-Fernandes and Peliz, 2020. Land areas are represented in white.

L75: I don't believe Argo needs to be in all capital letters (as it is not an acronym or initialism). Would say "Argo float profiles" and "altimetric measurements of absolute dynamic topography".

Corrected.

L89-105: citations for Argo and WOA should be included, not just links to datasets

These were added.

L98: what MLD definition is used?

We used the MLD definition from the GSW toolbox, following de Boyer Montégut et al., 2004. The mixed layer pressure is computed as 0.03 g/kg greater than the surface density.

L99: a bit more should be said about WOA and contributing observations. What is the spatiotemporal coverage in this region? Does the climatology primarily rely on the same Argo measurements used here?

We used the 2005–2017 monthly 0.25° WOA temperature and salinity fields as the reference climatology. This period corresponds to the Argo era, during which the upper 2000 m of the ocean is primarily sampled by Argo floats. Because our goal was to compute mesoscale anomalies from Argo profiles, using this climatology provides a consistent background state and minimizes biases associated with earlier, unevenly sampled periods.

L111: I believe it is possible for spice anomalies to arise without "eddy trapping". Trapping refers to a specific case of isolated cores of coherent vortices?

We understand and agree with your comment, as spice anomalies can arise from processes such as lateral advection of different water masses or mixing, without requiring eddy trapping.

In the context of our study, however, "eddy trapping" refers specifically to coherent eddies. The ability of an eddy to trap water is related to the ratio U/c, where $U$is the swirl velocity and $c$the propagation speed. When $U/c \gg 1$, the eddy is nonlinear and capable of retaining water during its formation, releasing it later as the eddy weakens (Chelton et al., 2011; McGillicuddy et al., 2016). The eddies tracked in this work exhibit high U/c values (not shown), and are therefore considered nonlinear, with the capacity to trap water along their trajectories. Accordingly, in this work, eddy trapping was quantified using spice anomalies within the cores of these coherent eddies.

L116: "+ residual"? The | notation is a bit confusing. Should the values to the right of the | be subscripted? Meaning deltaX on a surface of constant pressure?

Residue was corrected to residual. p and n are meant to be subscripted, indicating changes along an isobaric surface - p - and along an isopycnic surface - n. This was also corrected in the equation 1.

L137: this is a bit confusing. the following paragraph clears this up, but at this point it is unclear if smoothed ADT fields were interpolated to Argo profiles or ADT eddy tracks were interpolated.

We interpolated the ADT filtered field to the location/time of the Argo floats, not the centroid of the detected eddy.

L173: “all Argo”?

By all Argo we mean the Argo profiles that sampled anticyclones and cyclones inside the AzCCo.

The text was altered to: “Its x (east–west) and y (north–south) components were also computed, and the locations of the Argo profiles sampling the eddies in the regions along the AzCCo are shown in Figure 2b.”

L175: missing period, “symmetry”?

We meant symmetry. Corrected.

L187: “Argo profiles”

Corrected

L193: Figure 3 - what distinction is to be made in panels b,d,f of All vs. AzCCo statistics?

All refer to all eddies sampled in our study region and AzCCo to those sampled inside the AzC corridor. This description was added to the caption of the Figure 3.

L241: missing region name for panel b?

Corrected.

L257: Figure 6 - do these plots derive from WOA or the contributing Argo profiles?

They derived from the WOA climatology.

L258: Figure number missing?

We meant from Figure 6. It was corrected in the text.

L275: consider making all panels the same size and including subplot labels for each of the four panels. It is a bit confusing as is.

Corrected.

L320: Very nice figure

We appreciated your comment, thank you.

L447-448: this sentence doesn’t really provide new information?

The sentence was removed.

L463-470: This discussion (along with the conclusion section) seems a central result of this analysis.

Extensive characterization of eddy structure differences across the three regions considered makes the manuscript a bit cumbersome. Greater synthesis and focus on key takeaways would make it all more digestible.

We appreciate this comment. In response, we revised the Results, Discussion, and Conclusions sections to reduce redundant descriptions and improve synthesis, with greater emphasis on the key findings. These revisions aim to make the manuscript more concise and easier to follow.

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