Overall comment:

Note that Fig. 10 and some values in sections 5 and 6 have slightly changed due to using an older version of a data file. Now all time scales, diffusivities and R(0) are consistent throughout the paper. Note also that for better readability we have divided Section 3 (Theory and Methods) into subsections. For further clarity we have also reorganized Section 5 (The effects of the mean flow on eddy diffusivities) with respect to subsections.

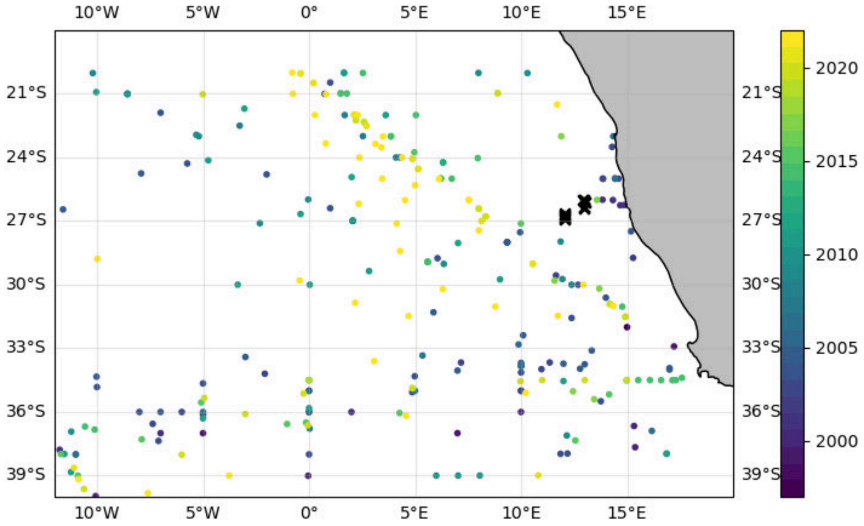
Reviewer 1

We thank reviewer 1 for their very helpful comments and suggestions to increase the overall clarity and readability of our manuscript. Please find our point-by-point responses to your comments below. Reviewer comments are shown in black and our responses are shown in blue. Edited text in the manuscript is shown in purple. Unchanged text that has been copied in for completeness is shown in gray.

This is my first review of a manuscript by Oelerich et al. titled "An estimate of the eddy diffusivity tensor from observed and simulated Lagrangian trajectories in the Benguela Upwelling System". The authors use observed and simulated Lagrangian particle trajectories to estimate the diffusion tensor in the Benguela upwelling region. The authors find that the background mean flow significantly impacts the trajectories and reliable diffusion tensor can only be estimated once the mean flow impact is removed. Likewise, the authors find that motions below 0.3 deg (unresolved by the OSCAR product) contribute significantly to the estimated diffusivities. Although some questions remain as the results are based on relatively short timeseries, I think the manuscript is well written, methods are well established, and the results support the conclusions drawn by the authors. Therefore, I only have a few editorial comments and consider this to be a minor revision.

General

The authors use a drifter dataset that they have contributed in collecting. However, these drifters were all deployed around the same time, and I wonder if the Global Drifter Program has data in the region from other years? I think the manuscript is okay even without additional data, but I would imagine that downloading a few additional GDP trajectories and repeating the computation would be quite straightforward and would make the manuscript more robust and likely more influential.
We appreciate the reviewer's suggestion to expand our analysis to cover additional years. While we would have gladly included more years in our study, the available drifter data in or near the Benguela Upwelling System is unfortunately very limited. The GDP dataset contains 300 to 350 drifters released between 1995 and 2022 (see figure below) in the Benguela Region. However, only a small fraction of these drifters were deployed near our specific study location or in the vicinity of the upwelling region. Moreover, the number of drifters for each deployment is limited and the number is not enough to provide statistically significant results for our analysis.



*Map of deployment locations of all drifters in the GDP data set colour coded by year of deployment. Black crosses indicate the location of the drifter used in the manuscrip*t.

Also, the POP simulation is for a different year than the trajectories/OSCAR data. It is likely that there is a fair bit of interannual variability (see e.g. https://www.science.org/doi/10.1126/sciadv.aav5014), and, therefore, it doesn't make sense to make any direct comparison between the model results and the observational results. It would increase the robustness of the results, if the authors would, for example, show timeseries of (E)KE or some other meaningful parameter/index in the region, such that the reader gets an idea how 'normal' the years 1996/2016 might have been (altimetry derived eddy trajectories might be a source for interesting data – see also the comment below). The OSCAR product is available for both 1996 and 2016, so one could, for example, show the (E)KE in the upwelling region throughout the OSCAR timeseries.
We agree with the reviewer regarding the interannual variability present in this region, which is largely driven by the influence of Agulhas rings. Consequently, there are discrepancies between the POP simulation and the altimetry product, primarily due to differences in spatial and temporal resolution. Moreover, it is important to note that the altimetry era only began in 1993, which poses additional challenges when attempting to reproduce conditions for 1996 and 1997. Specifically, as we go further back in time, the spatial resolution of the altimetry data decreases, making direct comparisons increasingly difficult and less robust. However, we would like to point out that the kinetic energy (KE), both in terms of the temporal mean and snapshot values from the POP simulations for 1996/1997, shows strong similarity to the observations from the altimetry product in 2016 (Fig. 2). These similarities provide a reasonable justification for making this comparison, as it suggests that the key dynamic features of the region are being captured consistently across these datasets, despite the temporal gap.

In addition, as suggested by the reviewer we have included a new Fig. 3, which compares the KE in the OSCAR product and the POP simulation. For further clarification we added the following text to the manuscript:

L286-297: The POP simulation with numerical trajectories is only available for 1996/97, while the observational dataset was obtained in 2016/17. Regardless, as Fig.2 illustrates, the horizontal distributions of kinetic energies are similar. There is visible interannual variability for the region (Fig.

3a) that is largely driven by the variability of the Agulhas rings. While there are discrepancies between OSCAR and POP particularly around 2004, the area-averaged energy levels in 1996 in POP (red solid and dashed lines in Fig. 3a) and in 2016 for the OSCAR product (black solid and dashed lines in Fig. 3a) are similar, and so are the total kinetic energies of POP and OSCAR averaged along the drifter locations (red and cyan diamonds in Fig. 3a respectively). However, the total kinetic energy of the surface drifter dataset at hourly resolution averaged over the surface drifter locations in the observations is substantially higher (black diamond in Fig. 3a). This is largely due to inertial oscillations, visible as semidiurnal oscillations in the time series of the observational drifter velocities (black lines in Fig. 3b,c) as compared to the velocities obtained from POP and OSCAR that are similar in magnitude (red and cyan lines in Fig. 3b,c) but do not capture motions on these time scales.

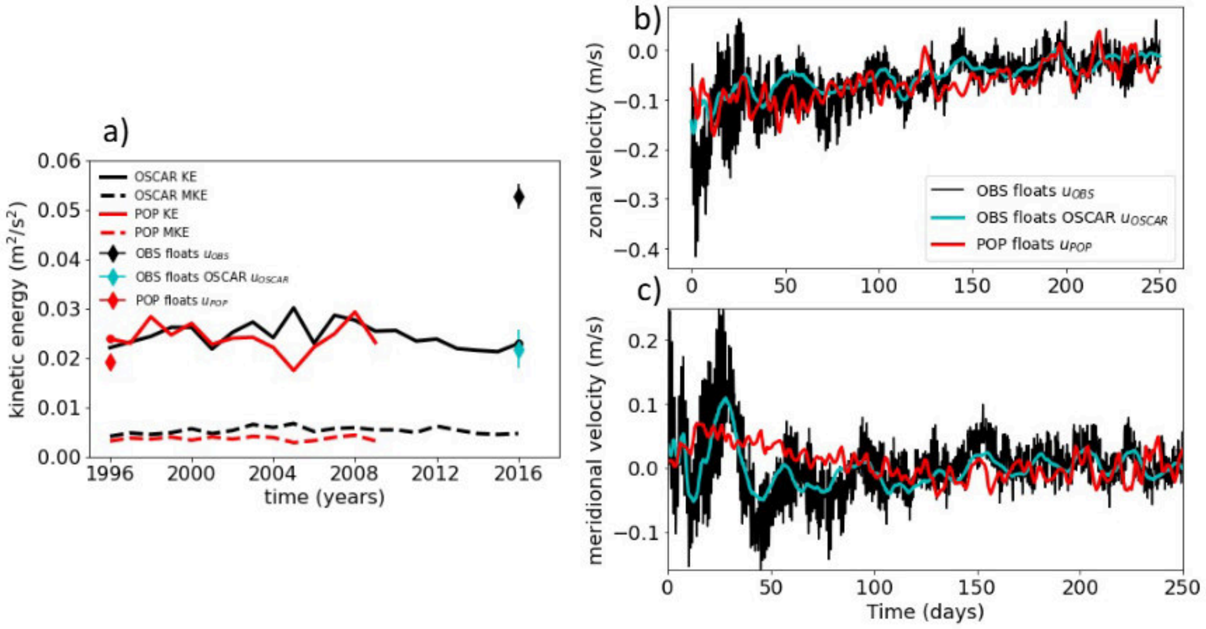


Fig. 3: The time series of annual mean kinetic energies for POP (red) compared with the OSCAR product (black) averaged over the Benguela upwelling region (as shown in Fig.1) are shown in panel a), where the total kinetic energies (solid lines) and the annual mean background flows (dashed lines) are displayed. Additionally, the total kinetic energies averaged over all float locations for POP, the observations and the OSCAR velocities interpolated to drifter locations (red, black and cyan diamonds) are shown. The time series of zonal and meridional velocities averaged over all drifters are displayed in panels b) and c) for POP (red), the observations (black) and OSCAR velocities interpolated to drifter locations (cyan).

The authors maybe interested to read a recent paper by Zhang and Wolfe https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2023MS004004 in terms of timescales. In the future, it could also be interesting to estimate diffusivity from eddy tracks in the Benguela upwelling region.

We thank the reviewer for this reference, which is indeed interesting. We are now citing this study in the discussion and conclusions section.

L608-610: A promising approach was recently suggested by Zhang and Wolfe (2024) who have shown that eddy diffusivity can be inferred from the eddy tracks without the need for drifter deployments or altimetry-derived geostrophic velocity measurements.

L225 This might be a naive question, but is K really symmetric by construction? I have worked before only with diffusivity tensor inversion, and then one needs to still separate the symmetric and antisymmetric part of the tensor. So, I am wondering that if the authors actually rotate K by the angle alpha (equation 20), are the off-diagonal components 0? It is not obvious to me that the equation 18 would automatically produce a symmetric tensor.

It is true that diffusivity tensors usually used in the parameterization of eddy effects in ocean models can be divided in symmetric (eddy-driven diffusion) and antisymmetric (eddy-driven advection) parts as outlined in in the introduction (L51-60). Our diffusivity tensor here is indeed symmetric and parameterizes only the horizontal diffusion. We have added the following line to improve clarity.

L253: The diffusivity tensor κ , which is symmetric by construction, can be diagonalized…

L475 The last two sentences of this paragraph are a bit puzzling. I would probably rather use ‘entrain’ than ‘pull’ (I guess it is still the wind driven upwelling that brings the cold water to the surface, and these waters are then entrained into westward propagating eddies). It is also somewhat well known that the eddies organize into bands (see e.g. citations below) and I wonder if these results also reflect this fact. i.e. there are mixing barriers (fronts) linked to preferred eddy paths.

We agree with the reviewer and have replaced all ‘pull’ with ‘entrain’ as suggested (L305,527,644). It is true that the filaments in the Benguela Upwelling region are mainly zonally oriented due to the action of often counter-rotating eddies that entrain the cold water, and associated with the filaments are also zonally oriented jets at the eddy rims. As far as the so-called striations (alternating zonal jets) are concerned, they are features that usually appear after time-averaging (and additional low-pass filtering). When we average the velocities in time we arrive at Fig. 2a,b). One could argue that there are zonal bands of jets that might be associated with preferred eddy paths (Anticyclonic Agulhas eddies on the one hand and cyclonic eddies that originate from the upwelling region on the other). However, these jets are not alternating in sign and it is unclear whether they would be called striations. We feel that the discussion of striations goes beyond the scope of this paper.

https://agupubs.onlinelibrary.wiley.com/doi/10.1002/2016JC012348 (recent paper in upwelling region of Chile)
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/2005GL022728 (original paper)
https://agupubs.onlinelibrary.wiley.com/doi/full/10.1002/2014JC010088 (bands in SST)

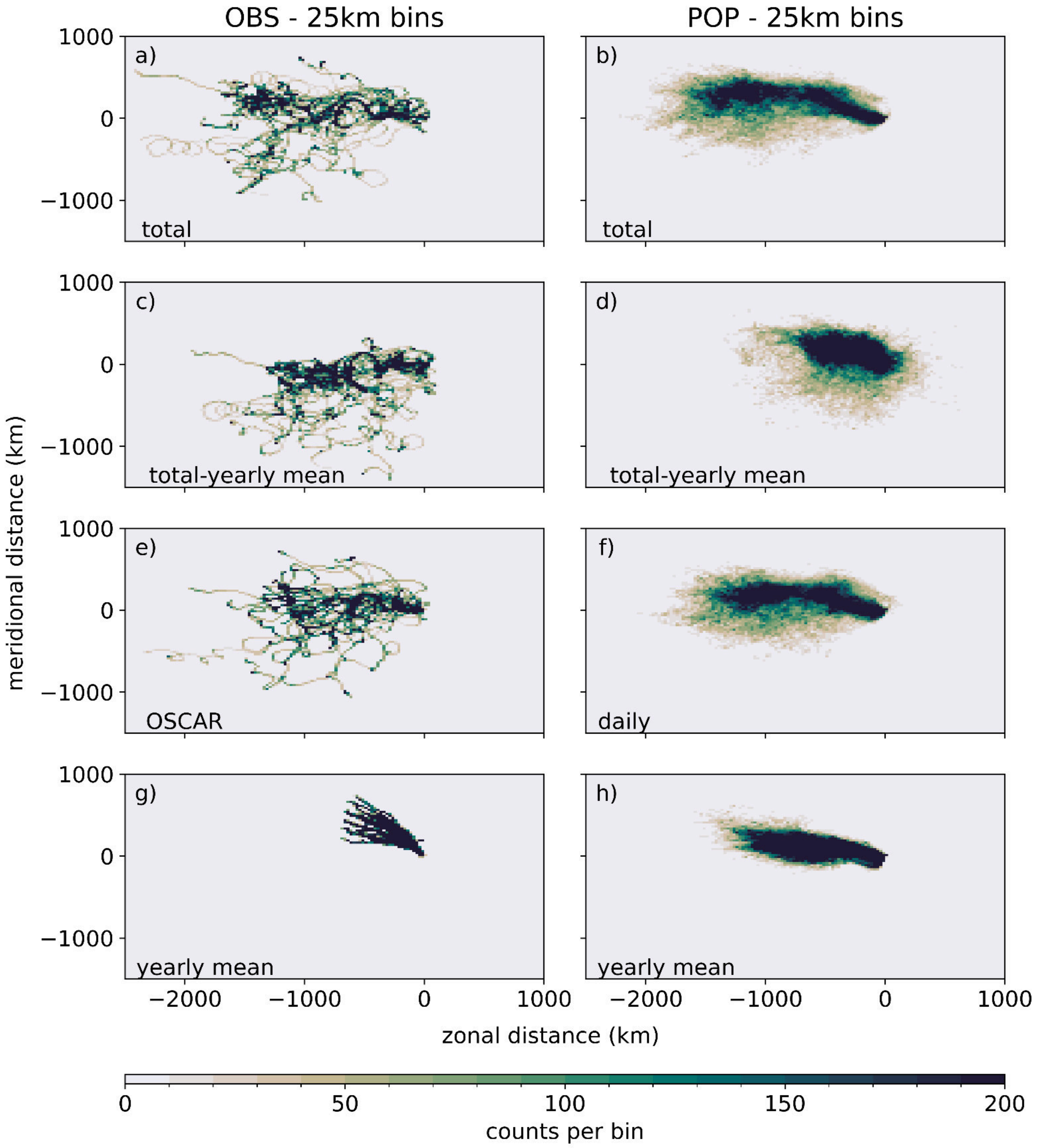
Figures:

Figs. 4-5.: The labels are confusing, I would suggest ‘U included’ and ‘U subtracted’

We agree with the reviewer and have changed the labels to a concise and consistent format. We have included a new Table 1 that clarifies the different flow components used in this study and have consistently labeled all figures throughout.

I wonder if instead of using the individual trajectories in Fig. 3, it would be more informative to show heat maps/contours of trajectory concentration (bin the count of the trajectories). Especially for POP, there are so many trajectories that it is hard to say if there is an underlying pattern in the saturated parts of the figure.

We see the difficulty in visibility of underlying patterns the reviewer addressed. According to the reviewers suggestion we produced a figure showing the trajectory concentration in 25 km bins.



Number of trajectories in each bin over all timesteps and trajectories with a used bin size of 25 km for observations (left column) and 10km for POP (right column) for each type of trajectory: full (a,b), total-yearly mean (c,d), OSCAR (e), POP daily (f) and yearly mean (g,h).

However, we have decided to produce a new version of Fig. 3 (now Fig. 4) showing a subset of the drifter trajectories from the POP Simulation (every 5th trajectory) to improve visibility on underlying trajectory patterns. Note that the coloring of trajectories was chosen such that every trajectory has a slightly different color in the range of blue or red so that patterns of individual trajectories can be shown more clearly. We also produced a new version of Fig. 7 (now Fig. 8) showing the pseudo-trajectories from the integration with the residual velocity u’’ to improve the visibility of underlying patterns.

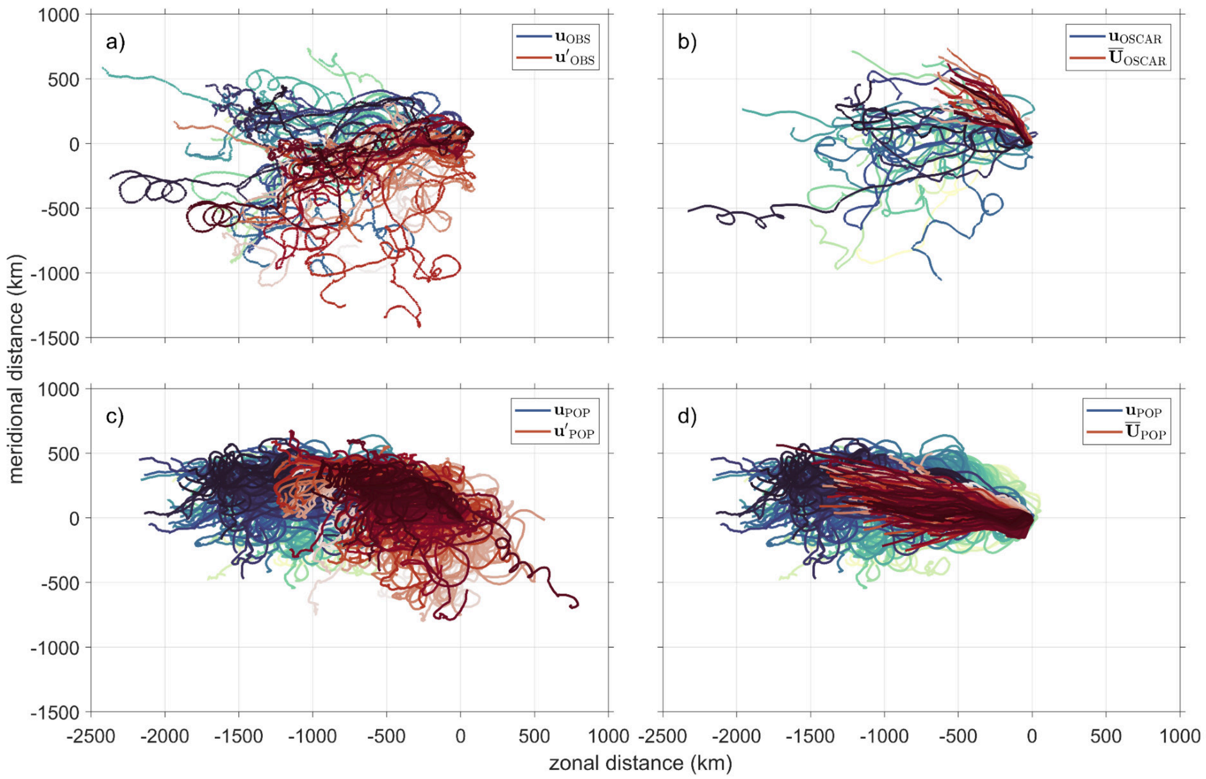
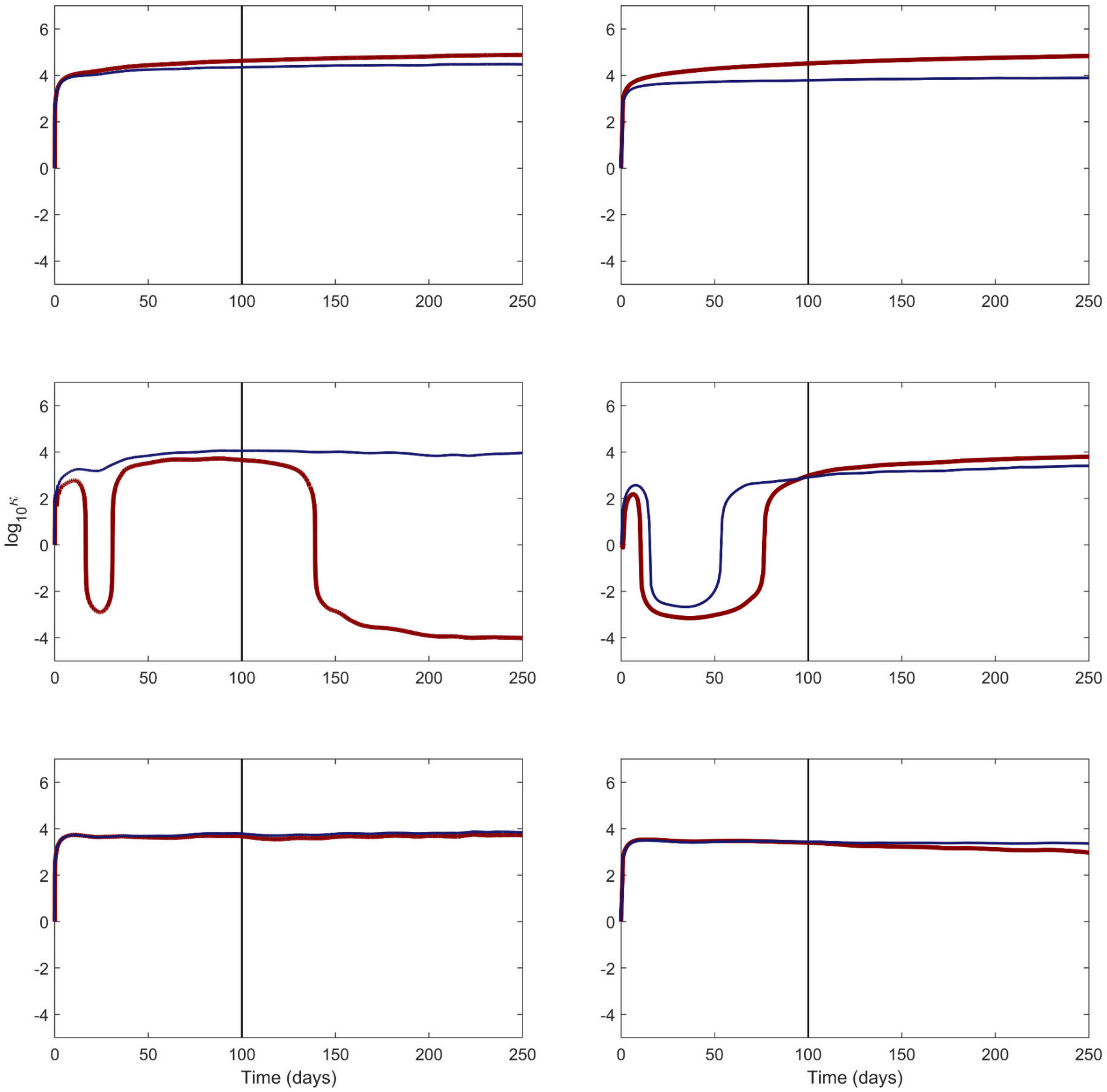


Fig. 4: The pseudo-trajectories (compare Equation 13) for the observations (a,b) and the POP simulation (c,d). Note that all trajectory components are shown in the cartesian coordinate system. For the POP every 5th trajectory is shown to improve visibility of underlying patterns. The original trajectories are marked in shades of blue (a,c) and the pseudo-trajectories from the integration with u' *(Equation 12) are marked in shades of red (a,c). The pseudo-trajectories from the integration with the OSCAR surface currents* u_{OSCAR} *and the POP simulation daily mean velocities* u_{POP} *are highlighted in shades of blue (b,d) and the ones with the annual mean velocities interpolated to the drifter locations* $\overline{U}|r(t)$ *are shown in shades of red (b,d). All pseudo-trajectories have been constructed such that (0,0) is the origin. Note that the coloring of trajectories was chosen such that every trajectory has a slightly different color in the range of blue or red so that patterns of individual trajectories are highlighted.*

I would suggest log scaling for all the plots with diffusivity tensor terms (in python one can use symlog to have log scaling for both positive and negative values).

Thank you for suggesting the use of log-scaling to represent the eddy diffusivities. We tested the representation of eddy diffusivities using a log scale, as recommended. However, we found that the log-scaling did not improve the visibility or interpretability of the eddy diffusivity behavior. In fact, due to the nature and distribution of our data, the log-scale representation either compressed critical features or amplified minor variations, making it more difficult to extract meaningful insights. Therefore, we have opted to retain the original linear scaling, as it provides a clearer and more accurate depiction of the eddy diffusivity patterns and their uncertainties.



Example of single-particle eddy diffusivities with log-scaling.

Style:

There are a few occasions with citations in brackets within brackets, like L107. I would suggest removing the inner brackets around the citations in these cases. We agree with the reviewer, inner brackets of citations appearing in brackets have been removed.

L505 This is a rather long sentence. I would suggest breaking it into two. We agree with the reviewer. Due to a comment from another reviewer this sentence has now changed and is also shorter. Please see lines below:

L593-595: This relates to the research question, which addresses the role of smaller scale motions that are detected by drifters but not by current altimeter products in influencing diffusivities and anisotropy. The study highlights the significant contribution of these unresolved motions.