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 3

We thank reviewer 3 for their thoughtful comments and raised questions to improve 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.

Oelerich et al. examine a longstanding problem, attempting to estimate a subgrid eddy tracer diffusivity tensor using Lagrangian data, both from observations and an eddy-rich model experiment. They explore Lagrangian particle statistics and their relation to tensor anisotropy in the presence of a background mean flow, including the presence of flow structures and implied links between flow kinematics, transport and mixing. Overall, this endeavour is worth pursuing and the basic message - to carefully consider the form of the eddy tracer diffusivity tensor in regions of significant mean flow - is worth continued communication to the modelling community. However, I have some concerns over the clarity and substantive novelty of this message. I wonder whether the manuscript could be revised to address my major concerns, as I would like to see these results published, if possible.

Major comments:

1. Novelty: I would like to see the aspects which are novel, compared to, e.g. Klocker and Abernathey (2014; https://doi.org/10.1175/JPO-D-13-0159.1), emphasized more in this study.
We agree with the reviewer to emphasize the new results of our study more. We would like to highlight that key differences between our study and Klocker and Abernathy (2014) do exist. First, Klocker and Abernathy (2014) focus on the quantification of the meridional diffusivity and mixing suppression by zonal flow, whereas we estimate the full tensor (L108-109) and discuss the effect of the mean flow on all tensor components. As far as we know, our study is the first to quantify these diffusivities for the Benguela upwelling region. Additionally, our study compares the effect of the mean flow on both single and pair particle diffusivities for the first time simultaneously. Furthermore, we specifically quantify the contribution not resolved by the altimeter product to the diffusivity, whereas Klocker and Abernathy (2014) only used altimetry-derived velocity fields. We discussed the relation to Klocker and Abernathy (2014) in the discussion and also added a citation in the introduction with regards to mixing suppression by mean flows. We have added the following lines in our manuscript to emphasize novel aspects:

L109-111:Additionally, our study compares the effect of the mean flow on both single and pair particle diffusivities for the first time simultaneously. Furthermore, we specifically quantify the contribution not resolved by the altimeter product to the diffusivity.

In addition, we added two new tables (Table 2 and 3) that summarize the results for the different flow components in terms of mixing length theory, the first one for the major-minor axis decomposition and the second one for all the tensor components.

We discussed the relation to Klocker and Abernathy (2014) in the discussion and conclusion section. Based on the results highlighted by Table 2 and 3. The following lines have been added:

L559-581: The diffusivity can be written as the product of kinetic energy, i.e. the velocity autocorrelation at zero time lag, and the integral time scale and we summarize the results for all flow components in Table 3. The results show that after mean flow subtraction, the kinetic energies for the zonal and meridional directions become more similar to each other with ratios of 1.1-1.2 for the observations, the POP simulation and the OSCAR product. However, the zonal integral time scales are 3.6 (observations), 2.6 (POP) and 1.5 (OSCAR) times larger than the meridional ones. The reduction in time scale for the meridional direction can be related to mixing suppression by a zonal mean flow as discussed in (Klocker 2012b, Klocker and Abernathy 2014 and Griesel et al. 2015).

The degree of mixing suppression can be based on mixing-length theory but taking eddy propagation relative to the mean flow into account. In the presence of a zonal background flow, the meridional diffusivity can then be written as:

$$\kappa_{yy} = R(0)\frac{\gamma}{\gamma^{2} + k^{2}(\bar{U}-c)^{2}}$$

where γ is a typical Lagrangian decorrelation time scale and is equal to the growth rate of unstable waves in linear instability theory (Griesel,2015), k is related to a typical eddy size and can be regarded as the wavenumber of maximum growth in linear instability theory (although both might differ in the presence of an inverse energy cascade), U is the zonal background mean flow, c is a typical translational speed of the eddies and α=0.35 as diagnosed by Klocker and Abernathey (2014).. It is the difference of U and c that leads to the mixing suppression effect, otherwise the diffusivity is equal to the velocity autocorrelation at zero lag times the Lagrangian decay scale γ. For the POP simulation we use the eddy sizes and translational speeds as diagnosed from an eddy tracking algorithm (Griesel, 2015), which amount to 90 km for the average eddy radius and -0.033 m/s for the zonal translational speed. With γ as the decay scale (time to first zero crossing) for the meridional direction of about 1/(12 days) and using our mean flow values averaged over the drifter trajectories, the time scale is about 3 days, which is close to the Lagrangian integral time scale obtained for POP for yy (Table 3). On the other hand, if we apply equation 21 to the suppression by the mean meridional flow, using the region-averaged meridional translational eddy speeds of 0.003 m/s and γ =1/(182 days), we arrive at a time scale of 14 days, which is indeed close to Tyy from Table 2. These time scales are also consistent with the ones obtained by Klocker and Abnernathey (204) and Ruehs et al. (2018).

To emphasize the new aspects provided by the Tables 2 and 3 we have edited and added the following lines to the manuscript:

L499-509:The diffusivities can be written as the product of major and minor axis kinetic energies and integral times scales, as in equation (7) (Table 2). It is found that after mean flow subtraction, the ratio of major to minor axis kinetic energies is 1.24 and 1.25 for the observations and the POP simulation, respectively. It is mainly the integral times scales that explain the large anisotropy in diffusivities. After mean flow subtraction, the major axis time scales are about 14 days for the observations and 12 days for the POP simulation, while the minor axis time scales are -0.21 and 3 days for the observations and POP simulation respectively. It should be noted that while the small anisotropy in the kinetic energy components is similar in the POP simulation and the observations and the major integral time scales are the same similar, the kinetic energies are larger in the observations (Table 2) explaining the larger major axis diffusivities compared to the POP simulation. The $R(0)$ are significantly larger in the observations than in the POP simulation, even after subtraction of the OSCAR velocities (third row in Table 2). This implies that the kinetic energy associated with inertial oscillations might contribute to the diffusivities in section 5.2, even though the integral time scales for u'' are small.

L583-592:We find that the diffusivities in the observed drifter data set are larger than the ones inferred from the POP trajectories, particularly after mean flow subtraction. After mean flow subtraction, the integral times scales are slightly larger in the POP simulation compared with the observations, but overall similar (second and fifth row of Table 3). However, the velocity autocorrelation at zero lag after mean flow subtraction, is 2-3 times larger in the observations than in the POP simulation and is thus explaining the larger eddy diffusivities in the observations. This is partly due to the fact that the background flow in the POP simulation is larger and more highly resolved in the POP simulation than in the OSCAR surface currents product, hence leaving a smaller EKE residual, and illustrates the importance of using high resolution background flow components. However, also the total kinetic energy ($R(0)$ for u_{OBS} in Table 3) is larger in the observations than in the POP simulation, while the $R(0)$ when considering the contribution from the OSCAR velocities alone (last two rows in Table 3) are more comparable to the POP simulation.

L595-602: We found that these motions contribute 8% to the xx component and 42% to the yy component of diffusivities after mean flow subtraction. These small scale motions include inertial oscillations, which are hypothesized to not contribute much to the net diffusion, since they may only lead to oscillations in the velocity autocorrelation, which average out in the integral over time lag. Indeed, as Table 3 shows, the integral times scales for u''_{OBS} are only about 1 day for the xx and yy components. However, the velocity autocorrelation at zero lag is significant and is largely due to the kinetic energy in the inertial motions. Further studies with more trajectories are needed to clarify the role of inertial motions for mixing.

2. Clarification of the similarities and differences between Eulerian and Lagrangian representations of the eddy tracer diffusivity(*) tensor. Typically, climate models use an Eulerian or quasi-Lagrangian (e.g. if moving vertical coordinate) form, but much of the manuscript refers to either a Lagrangian tensor or is not clear whether Eulerian or Lagrangian is referred to. Similar goes for references to diffusivity, diffusion and similar in the Introduction, e.g. lines 70-95.
We use the time mean of Eulerian data together with the Lagrangian trajectories that provide space-time information. The theoretical underpinning to estimate Lagrangian diffusivities in a spatially inhomogeneous mean flow and the connection to the Reynolds-averaged tracer transport Eq. (1) was developed by Davis (1987, 1990). We have already pointed this out in the introduction (L95-99).

L96-200: Davis (1987) and Davis (1991) devised the underlying theory how to compute the diffusivity tensor in principle in the presence of an inhomogeneous background mean flow where, instead of diagnosing the statistics from the absolute Lagrangian velocities and displacements, diffusivities are computed from residual velocities and displacements after the Eulerian mean has been subtracted.

For further clarification we have added the following lines in the methods section:
L200-201: In that sense, the diffusivity introduced by Davis (1987) is a mixed Eulerian-Lagrangian quantity that can directly be related to the eddy tracer fluxes in a diffusive parameterization, as derived in Davis (1987).

We further discussed the different kinds of diffusivity estimation methods in the introduction.
L61-65: Diffusivities can be quantified using both Eulerian and Lagrangian methods (Griesel et al. 2014, Abernathey et al., Griesel et al. 2019). The Lagrangian approach is based on the spreading of floats or tracers as they follow the flow (Taylor 1921,1953; Nakamura 1996), whereas Eulerian diffusivities can be quantified e.g. from Eulerian eddy tracer fluxes (e.g. Eden 2006, Griesel 2014).

3. As has been stated in the other reviews, I am also concerned about the definition of the "mean" flow and associated implications. This needs further exploration and justification. Also, the time analysis window mismatch needs addressing, as suggested in the other review, for example.
We agree with the reviewer that the definition of average should be clarified in this study. To define the background mean flow we use a time mean, where the time interval is one year, which is larger than the typical eddy timescales in the study region. A certain amount of spatial coarse-graining is also implied since in the observations the time mean is based on 1/3° resolution (OSCAR product) and in the simulation the time mean is based on 1/10° resolution (POP simulation).

We have added a more specific description to the definition of the background mean flow in L50-51 in the introduction and also added further clarifications on the background mean flow in the methods sections (L207-211). A table (Table 1) summarizing the description of the different flow components used in this study was added.

With respect to the time analysis window mismatch we would like to clarify that for the OSCAR product the resolution is 5-daily and for the POP simulation the resolution is daily. We have clarified this information by adding a table (Table 1) that states the spatial and temporal resolution of products used.

L50-51: ... where the overline denotes an average over intervals in time and space that are larger than typical eddy scales, and ' the deviation from that average, while Q describes the sources and sinks of the tracer T.

L210-214: In the observational drifter data set $\overline{U}$ is the time mean velocity of the 1/3° OSCAR surface currents interpolated to the drifter locations, while in the POP simulation $\overline{U}$ is the time mean of the 1/10° Eulerian currents interpolated to the numerical drifter locations (Table 1). Note the current altimeter-derived products, such as the OSCAR product, have effective resolutions in space and time in this region of about 100 km and 30 days (Ballarotta et al. 2019) and thereby also imply a spatial coarse-graining.

4. In several places, e.g. line 199, "submesoscale" motions are mentioned. These usually have a relatively strong vertical velocity component, compared to mesoscale eddies. Although a 3x3 tensor is mentioned early in the manuscript, only a 2x2 tensor appears to be diagnosed. How should this be reconciled? Also, are there any implications for using 2-particle pair statistics with a 3x3 tensor, e.g. that there might be insufficient statistical information to capture flow deformation gradients in 3D or even in 2D? Surely 2-particle stats only sample deformation rate gradient in one direction, don't they?

We agree that it would be useful to also estimate the diffusivities involving the vertical velocities. However, unfortunately we do not have advection by the 3D velocity field available in the observations since the drifters stay on a fixed depth of 15 m. Hence, we are restricted to observing only the horizontal mixing. In the POP simulation, the floats are advected by the 3D model fields but they mostly stay within the 10 - 20 m depth range since vertical velocities in the POP simulation are very small (submesoscale higher Rossby number processes are not resolved). With both single and pair particle statistics we consider the dispersion in different directions. In principle, this would also be possible in 3D, except that one might need more particles than in 2D. Unless we misunderstand the question, we believe that 2-particle statistics can in principle sample the deformation rate gradient in different directions, however it depends on the number of particles.

I would be happy to review a revised version of this manuscript.
I broadly agree with the comments already made by the other two reviewers.