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Interactive comment on "Ventilation dynamics of the Oxygen Minimum Zone in the Arabian Sea" *by* Henrike Schmidt et al.

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The paper by Schmidt et al. investigates the dynamics of the ventilation of the Arabian Sea and its role in shaping the intensity and variability of the oxygen minimum zone (OMZ) located there. To this end, the study uses Lagrangian trajectories based on a velocity field derived from a reanalysis by the HyCOM model. The authors claim that the eastern part of the OMZ is ventilated mostly from the north by the PGW in winter whereas the western OMZ is ventilated essentially from the southeast during the summer season. The study investigates the ventilation seasonality and timescales as well as the potential role the Arabian marginal seas (the Red Sea and the Persian Gulf) play in this regard.

I) General comment:

The subject of the paper is highly relevant in the general context of understanding the pathways and timescales of the ventilation of the Arabian Sea and how they impact the OMZ. However, I have several major concerns that prevent me from recommending this manuscript for publication. First, the paper is poorly written. The objectives are not stated clearly and key details of the Lagrangian experiments are missing. Moreover, the explanations given by the authors are sometimes vague or difficult to understand. More importantly, the experimental design does not seem to be appropriate to draw conclusions in a quantitative manner. Below, I develop these points with more specific comments.

Reply to reviewer #1 We would like to thank the reviewer for taking the time and for providing constructive and very specific comments, which helped to improve the manuscript considerably. We have carefully addressed his/her comments. Based on the comments we reworked the passage concerning the design of the Lagrangian experiment in section '2.2 Design of the experiment'. The key details are now explained more precisely and presented more clearly. Also, the data are better presented and results are stated more clearly. In the manuscript we modified several figures (Figs. 3, 6, 7, 8) as well as table 1 and skipped figures 10 and 11. In the supplement we added new figures (Fig. S1, S3, S4, S5) and modified one figure (Fig. S6). The point-by-point responses follow below (written in bold).

II) Specific comments:

1) The study is focused on two sites at 19N (one at 62N and the other at 66.6N). It is not clear what motivates this choice or why are they supposed to represent the dynamics of the whole OMZ?

We shifted the motivation of the choice of the release points to section 2.2 'Design of the experiment': "The contrast in extension and seasonal cycle, not only in oxygen but also in biogeochemical activity (Hood et al., 2009; Resplandy et al., 2012; Brewin et al., 2012), of the ASOMZ for the eastern and western basin encourages to analyse the ventilation of each half of the basin individually. Therefore, we define two release locations in the eastern (ER) and western (WR) part of the core of the ASOMZ (Fig. 1). The western part is associated with the area of high primary production and the eastern part is associated with the area of lowest oxygen values. Both release areas represent the core of the OMZ and are defined as circles with a radius of twice the grid spacing, thus 1/6°, around the launching coordinates, which are 19.04° N and 66.64° E for the ER and 19.04° N and 62.00° E for the WR. The Lagrangian particles are spread equally over that area and are all released at the same time (for one run)."

2) Another point related to the design of the experiment and the robustness of the results is the focus on one particular layer (sigma=27). Why restrict the analysis to this layer if the focus is on the entire OMZ? (especially given the fact that the world's thickest OMZ in the Arabian Sea extends vertically over a wide range of densities from 26 to 27.2)?

The careful choice of the isopycnal is based on two reasons that have been described in section '2.2 Trajectory computation', which has been now reworded to section '2.2 Design of the experiment'. In addition we calculated the pathways of the Lagrangian particles on two further isopycnals that are associated with the PGW and RSW. Please see text: "Our experiments are based on the assumption that PGW and RSW are the main local source water masses that are relevant for the ventilation of the ASOMZ and that the oxygen rich waters follow largely their isopycnal layer horizontally. Therefore, advective pathways from Lagrangian particles into the OMZ are calculated on an isopycnal associated with the source regions of the PGW and RSW as well as the OMZ core region. A good representative isopycnal surface of 27 kg/m3 was chosen for most experiments based on two main reasons: The isopycnal lies in the upper core of the ASOMZ (Fig. 3) with low oxygen values of less than 10 μmol/kg nearly throughout the entire year (Fig. 4a). Furthermore, this is the density layer with seasonal changes in oxygen concentration (Fig. 4a). The core densities of PGW (σ = 26.4 kg/m3) and

RSW (σ = 27.4 kg/m3), which appear to be the main source water masses ventilating the ASOMZ, bracket the isopycnal density of σ = 27 kg/m3. For the AS, the supply of oxygen was suggested by Banse et al. (2014) to be on the isopycnal surfaces of 27 kg/m3 at depths between 300-500 m depth." . . . "Several sensitivity runs were conducted many of them with a reduced number of particles to save computational costs. A comparison between full and reduced number of particles gave very similar results (not shown here). In order to estimate the representativeness of the main Lagrangian pathway analysis on the 27 kg/m3 isopycnal surface two further runs on a shallower and deeper isopycnal were done (for PGW σ = 26.4 kg/m3 and RSW σ = 27.4 kg/m3). These experiments also used repeated daily velocity data for the calendar year 2006 for costs savings. " The results based the two further runs are presented in the supplement (Figs. S3-S5).

3) A related issue is the use of two-dimensional trajectories along one isopycnal surface, failing to take into account upwelling and diapycnal mixing, while these processes may contribute strongly to the ventilation of the OMZ. In particular, we know that the winter convection and water mixing in the north is an important source of ventilation in the northern Arabian Sea. Not being able to take this into account, appears to me to be a major weakness of the study.

Right, beneath the advection also diffusion as well as consumption affects the oxygen budget. We changed the design of the experiment of the calculation of Lagrangian particle pathways, which are now based on shorter model runs (8 years) in order to estimate the impact of diffusion on the ventilation. This is stated in the manuscript in section '2.2 Design of the experiment': "To estimate the impact of slower diffusion effects on the ventilation of the ASOMZ we compared the typical 8 year long results (Tab.1) to longer 13 year model runs. Again, both experiment gave very similar results pointing towards a secondary role of the slower processes."

Thus, we also changed Figures 6 & 7, which are now based on the 8 year long runs and not on the 13 year long ones. The former results are not influenced by that change:

“Several sensitivity runs were conducted many of them with a reduced number of particles to save computational costs. A comparison between full and reduced number of particles gave very similar results (not shown here).”

We have also changed the title to “Seasonal variability of the circulation in the Arabian Sea at intermediate depth and its link to the Oxygen Minimum Zone” in order to avoid misunderstanding and to point out that we focus on the advective contribution to the ventilation oxygen minimum zone and its seasonal variability.

4) The details of the particle release experiments are not well described. Are all 50000 particles for each site (ER vs WR) released the same day at the same lat/long point? How is this supposed to capture the spatiotemporal variability around each site?

We addressed the details of the particle release experiments in the new section ‘2.2 Design of the experiment’ and in section ‘2.4 Trajectory validation and statistics’. Section 2.2: “Both release locations represent the core of the OMZ and are defined as circles with a radius of twice the grid spacing, thus 1/6°, around the launching coordinates, which are 19.04° N and 66.64° E for the ER and 19.04° N and 62.00° E for the WR. The Lagrangian particles are spread equally over that area and are all released at the same time (for one run). For the forward trajectories two additional release locations in the Gulf of Aden, simulating the spreading of Red Sea Water (RS, 49.04° E and 13.04° W) and in the Gulf of Oman, simulating the spreading of Persian Gulf Water (PG, 59.04° E and 24.00° N; Fig. 1) were chosen.”

“The Lagrangian particles were advected using the two dimensional velocity fields from HYCOM reanalysis velocity fields followingÂăbasic relations of continuous deformation (see Supplement, Lamb, 1879).ÂăThis approach is consistent with more recent techniques as described in van Sebille et al. (2018). The daily velocity fields were vertically linearly interpolated onto the target isopycnal surface. The number of Lagrangian particles released is 50000 for the runs that were mainly used for statistical purpose (see also Section 2.4) and 10000 for runs 1 to 10 (Tab. 1). The particles were advanced using an Euler forward-in-time integration scheme using a time step of 1/20 day. Both forward and backward trajectories were calculated and particle positions are stored every 4th day. In addition to the model velocity field a random walk of particles is applied to represent subscale diffusion of 20 m2/s. Near the coast a special case of random walk in the offshore direction is used to prevent trajectories leaving the ocean. The choice of magnitude of random walk is connected to the spatial and temporal grid resolution. A sensitivity experiment with different subscale diffusion coefficients of 10, 20 and 25 m2/s does not reveal significant different results (not shown here). Nevertheless, there are some grid boxes along the coastline and especially near islands, where the particles get trapped. These spuriously high probabilities were not considered for further analyses. Moreover, the velocity fields of HYCOM are obviously divergent, in particular in up and downwelling regions near coasts and islands (e.g. the Maledives, Socotra). Several sensitivity runs were conducted many of them with a reduced number of particles to save computational costs. A comparison between full and reduced number of particles gave very similar results (not shown here)."

Section 2.4: "To test the reliability of the calculated Lagrangian trajectories 5 model runs with identical setup were performed (each with 50000 particles, 13 years duration, starting all at the ER in December 2012). The differences between these runs are discussed in Section 3.5. To detect the interannual variability the runs with the duration of 13 years used for the statistics were compared to a climatological run, which was performed with velocity fields with the mean daily velocity of the 13 years at each grid point and day. Furthermore, the 8 year long runs (runs 1- 6; Tab. 1) were started with a temporal offset of 2 years between the individual runs. For the analysis of seasonality and transit time, we used the mean of these runs to smooth out the interannual variability. Seasonal differences in particle movement around the release locations can be predicted by starting the calculations with a lack of 3 month (January, April, July and October). This was done for forward calculated trajectories from the RS/PG release to predict the spreading op RSW/PGW."

5) From Table 1, there seem to be large differences in the ventilation sources depending on the duration of integration and the date of particle release (for instance runs 1-5 vs run 7 or run 17). This suggests that the results are not robust with respect to the time of release, and hence they may not necessarily represent the large-scale picture. I suspect the results to be affected by the mesoscale variability around the two sites, which prevents drawing any solid conclusions regarding the ventilation of the Arabian Sea at large.

Yes, you are right. There are differences in the ventilation source depending on the year of the particle release. This is due to the interannual variability in the AS and we discussed that point in more detail now. Discussion and Conclusions: "The comparison of travel times and particle amounts between different years (Tab. 1) and also with climatological runs shows high discrepancies and standard deviations which let suspect a strong dependency on interannual variability, that is likely driven by the strength of the monsoon forcing. Another point that underlines the connection between the monsoon forcing and strength and variability of watermass advection into the ASOMZ is the comparison between the 3 isopycnal layers (Tab. 1). With increasing depth the transit times become longer, pointing towards weaker currents and circulation."

6) The study focuses on the suboxic core of the OMZ (here defined as O2<10mmol/m3) and uses the World Ocean Atlas (2013) for analysis. Yet, it is known that this dataset strongly overestimates oxygen at low concentrations and hence underestimates the size of the suboxic core of the OMZ and its intensity (see Bianchi et al., 2012 and Banse et al., 2014). Empirical corrections have been proposed to minimize this problem by Bianchi et al (2012) and other studies.

Yes, we are aware of the fact that climatologies strongly overestimate oxygen concentration at values below 10 mol/kg. In this study oxygen values are primarily used for the definition and variability of the ASOMZ to choose the representative points of release for the Lagrangian particles. The choice of the western and eastern release points depend on the seasonal variability of the ASOMZ, therefore we focus on the relative

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changes not on the absolute values of oxygen. Hence, exact values of oxygen are of minor interest. The objective of the experiment is on the advective pathways of Lagrangian particles relevant for the supply of the ASOMZ and their seasonal variability.

7) The questions of the seasonal maintenance of the OMZ and its eastward shift have been explored by several studies in the past and several drivers have been proposed to explain these observations (e.g., Resplandy et al., 2012, McCreary et al., 2013, Acharya and Panigrahi, 2016). It is not clear what this study adds to what has been proposed before.

This study is based on reanalysis data and the focus of our experiments is on the seasonality of the pathways of Lagrangian particles that have an impact on the upper ASOMZ. We raised these points more clearly in the manuscript by changing the title and also in the discussion: " All in all, the seasonal changing advective pathways into the ASOMZ fit quite well with the weak seasonal oxygen cycle and show clear differences between the eastern and western basin. Thus we conclude that the water mass advection plays a crucial part for the eastward shift of the ASOMZ and might also for the maintenance of low oxygen throughout the year."

8) The model resolution, although in the eddy-resolving range, may not be fine enough to resolve the outflow of the RSW and PGW as these depend on the geometry of narrow straits (especially the Strait of Bab el Mandeb) that requires very high-resolution to be properly represented.

In this study the outflow of the PGW and the RSW is defined by the crossing of the particles of the meridional sections at the entrance of the Gulf of Oman (60°E) and the Gulf of Aden (51°E), respectively (see Fig. 7 for the location of the sections), where the model resolution allows to resolve the advection of the Lagrangian particles from the source regions.

9) Authors claim that the results were insensitive to the choice of the diffusion coefficient. Yet, previous works (see for instance Gnanadesikan et al, 2012, 2013) clearly

show that the volume and intensity of OMZs can be very sensitive to the choice of the mixing coefficient. Authors need to explain this.

For the advective pathways, the choice of the mixing coefficient plays a minor role. (Gnanadesikan,2012). However, we claim that our advective pathways of the particles are insensitive to the subscale diffusion coefficient we add to the trajectory pathways. This must not be related to the mixing coefficient, that is already set in the HYCOM model. We cannot influence that.

10) The estimation of ventilation timescales is very confusing. Authors use several sections very close to the sites of particle release (Fig 8) and focus on short timescales (1year backward and forward experiments, Fig 10 and Fig 11). How can this help to understand the dynamics of the large-scale ventilation of the whole OMZ?

The estimation of ventilation timescales or transit time is now explained in more detail in section '2.3 Trajectory visualization': "The point to point transit time describes the time that each individual Lagrangian particle takes to transit between defined regions (van Sebille et al., 2018). The transit time is analysed along identified main advective pathways into the ASOMZ between distinct sections (see Section 2.2). The transit time is not unique, as different Lagrangian particles might travel between two regions on different ways in different length of time (Phelps et al., 2013). The here discussed transit times are thus defined by the times where 50% of the particles crossed the distinct sections (percentages refer to the total number of Lagrangian particles that have crossed the section after the whole time span of the simulation (8 years). Therefore, no particle is counted twice as only the first crossing time of each particle at each section is detected. Additionally, the seasonal cycle of Lagrangian particles crossing these sections can be determined."

The choice of the sections is also explained in more detail in the new section '2.2 Design of the experiment': "After analysing the pathways of Lagrangian particles within the ASOMZ (Section 3.2) we focused on the seasonal variation of the circulation in the

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AS (Section 3.3). To address this question we chose distinct sections along the main advective pathways of the Lagrangian particles (Fig. 1) and calculated the transit times of the particles to get from one region to another for different pathways: two zonal sections are at equal distance south and north of the release locations (17° N, 21° N) to investigate the impact of the northeast and southwest monsoon on the advection of the particles, a meridional section separates the eastern and western half of the basin between the release locations at 64.3° E to determine the interior circulation, two meridional sections are located at the borders to the Gulf of Oman and Gulf of Aden as the source of the main water masses and another zonal section at 10° N serves as a southern boundary of the AS as our research area to get an insight of the inflow from the south and its variation."

We decided to skip Fig. 10 and Fig. 11 as they do not give any additional information in terms of the seasonal variability.

11) Finally, several paragraphs and sections are vague and poorly written. For instance sections 3.2, 3.3 and 4 are not easy to understand.

We carefully rewrote main parts of the sections 2, 3, and 4 and hope that the details of the experiment as well as results and conclusions are now easy to follow and to understand.

III) Additional comments:

Fig 7: The sections are not really located where they should. Not all particles in the Gulf of Aden are originating from the RS nor are all particles in the Gulf of Oman coming from the PG!!!

As stated above we draw inferences about the outflow of the PGW and the RSW by the crossing of Lagrangian particles of the meridional sections at the entrance of the Gulf of Oman (60°E) and the Gulf of Aden (51°E), respectively. We are aware, that not all particles from the Gulfs origin in the RS and PG, but all particles from the RS and

PG have to pass through the Gulfs. With the small overflows, it is very difficult to track particles all the way back. Anyway, this does not change the pathways and seasonality in the AS itself.

Fig 8: What motivated the choice of these sections?

The motivation of the section is now stated in section '2.2 Design of the experiment': "After analysing the pathways of Lagrangian particles within the ASOMZ (Section 3.2) we focused on the seasonal variation of the circulation in the AS (Section 3.3). To address this question we chose distinct sections along the main advective pathways of the Lagrangian particles (Fig. 1) and calculated the transit times of the particles to get from one region to another for different pathways: two zonal sections are at equal distance south and north of the release locations (17° N, 21° N) to investigate the impact of the northeast and southwest monsoon on the advection of the particles, a meridional section separates the eastern and western half of the basin between the release locations at 64.3° E to determine the interior circulation, two meridional sections are located at the borders to the Gulf of Oman and Gulf of Aden as the source of the main water masses and another zonal section at 10° N serves as a southern boundary of the AS as our research area to get an insight of the inflow from the south and its variation."

Fig 9: What is shown in Fig9a and Fig9b? This is not mentioned in the caption.

Thanks, we added the missing information to the figure caption (please, see text): "Figure 9: Mean seasonal cycle of particle percentage travelling between distinct sections along their main pathways and their release points in the western basin (left column) and the eastern basin (right column), respectively. Sections are along 21° N shown as dotted dark blue line and 17° N as solid purple line (a, b), 64.3° E as dashed light blue line (b, c, d), 60° E as solid yellow line, 51° E as dotted red line (c, d), 10° N as dotted light green line (east) and solid green line (west) (e, d). For line colour and type please see also Figure 8."

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Figs 10 and Fig 11: Why restrict the trajectories to 1 year forward/backward?

We decided to skip Figs. 10 and 11 as they do not give any additional information for the main message of the study. (Anyway, the motivation of these runs has been mentioned in section 2.3 and numbers of these calculations are discussed in the text in section 3.4 of the first version of the script.)

Please also note the supplement to this comment:
https://www.biogeosciences-discuss.net/bg-2019-168/bg-2019-168-AC1-supplement.pdf

Interactive comment on Biogeosciences Discuss., https://doi.org/10.5194/bg-2019-168, 2019.

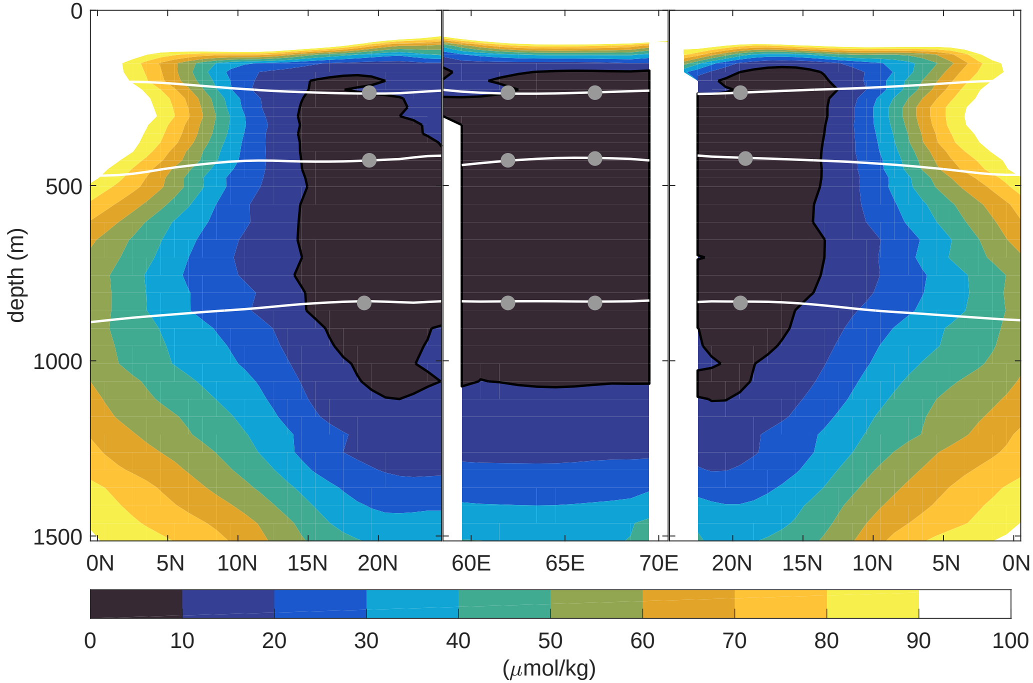

Fig. 1. Figure 3: Annual mean of dissolved oxygen concentration along 62°E (left), 66.5° E (right) and 19° N (middle) from the WOA 13 climatology (see Figure 1). Advective pathways from Lagrangian particles a

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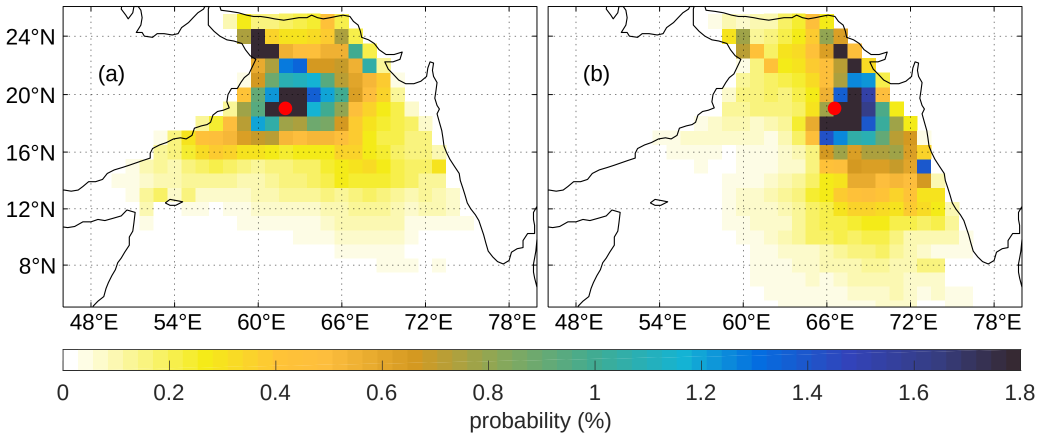

Fig. 2. Figure 6: Probability that a 1°x1° bin is occupied by a Lagrangian particle during the time span of 8 years for backward trajectory calculations from (a) the western (WR) and (b) the eastern (ER) part

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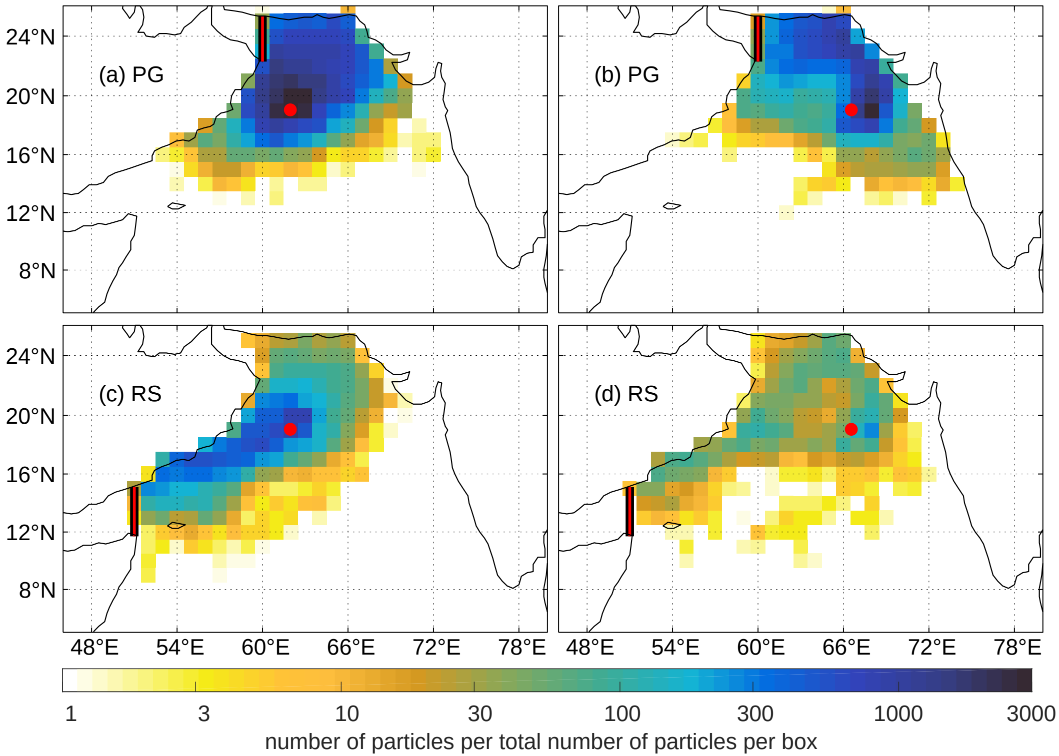

Fig. 3. Figure 7: Lagrangian particle position probability maps show the most pronounced pathways of fluid particles along the isopycnal σ=27 kg/m3 for the backward trajectory analysis, entering the Persian G

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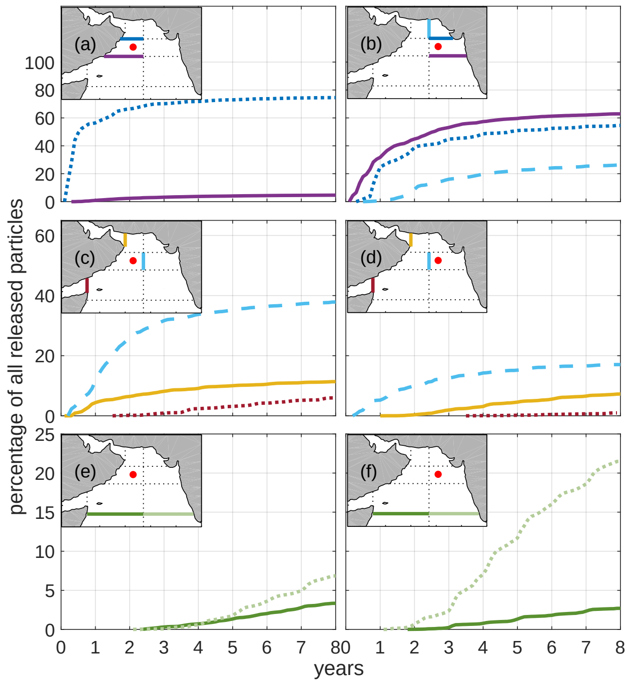

Fig. 4. Figure 8: Cumulative point to point transit times of Lagrangian particles calculated between distinct sections (see maps) along their main pathways and their release points in the western basin (left

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