Replies to referee 1: Transient Attracting Profiles in the Great Pacific Garbage Patch

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We thank the referee for their careful summary of our research project and for their helpful comments on our paper.

Summary by the referee

The paper identifies TRAPs – objectively defined (frame-independent) analogs of hyperbolic points, in the eastern N. Pacific using a 20-year long record of mesoscale surface currents derived from SSH altimetry and wind-induced Ekman estimates. The authors present statistics of TRAPS – lifetime, propagation speed, strength of attraction, probability of occurrence etc., investigate the relative vorticity patterns around TRAPs, and look for the influence of TRAPs on real drifters passing nearby by constructing composite maps of drifter velocities in the vicinity of TRAPs.

The results suggest that TRAPs are most commonly located in regions between mesoscale eddies, have similar westward propagation speeds to mesoscale eddies, and are associated with the hyperbolic flow geometry in their vicinity. The most typical vorticity patterns around TRAPs correspond to a quadrupole – 2 cyclonic and 2 anticyclonic vortices, with a TRAP at the center between them.

The paper is easy to read and the statistics is carefully estimated and clearly presented.

My main comments are:

1 Mesoscale velocity data

The mesoscale currents used for the analysis are likely only marginally applicable for predicting the small-scale distribution of garbage on a day-to-day basis and thus would only marginally help in any real cleanup efforts, which is the main motivation that the authors give for this work. I am not convinced that TRAPs and their statistics would be unchanged if the submesoscale flow features were resolved. This should be clearly explained, so as not to overstate the usability of TRAPs for real garbage cleanup.

reply

We appreciate the comment and agree that in the manuscript, we should highlight that different statistics may result for TRAPs computed from submesoscale velocities. It is also true that we do not obtain any fine details from the altimetry data used here, but if submesoscale flow feautures would alter the motion of a drifter over a few days, we would see it in our drifter experiment. We could think of it as retaining an aggregate effect of submesoscale motion, which is what is relevant for our purposes and the time scales we are interested in.

We propose to replace the paragraph starting line 450 by this new version:

> Even though our study cannot resolve important submesoscale processes like e.g. filamentation, Langmuir cells or submesoscale vortices, it demonstrates the capability of TRAPs to predict material transport from first-order mesoscale observations. We observed the effect of TRAPs on drifters, both drogued and undrogued, that sample any oceanic structures found along their path, including submesoscales. Thus, our results include the aggregate effect of such flow components on the daily drifter position that we use in the analysis, even though it is not resolved by the satellite altimetry itself. Our algorithms offer a great chance to reapply the TRAPs concept to future high-resolution observations that will be provided by the current SWOT mission (International Altimetry Team, 2021). TRAPs computed from submesoscale velocities will probably show different characteristics than their mesoscale counterparts but are crucial to an application of the concept during offshore cleanups. An interesting approach would be to study the flow around drifter-TRAP pairs with long retention times. These long retention times might be due to drifter trapping within submesoscale vortices and filaments that result from instabilities at mesoscale fronts (van Sebille et al., 2020; Zhang et al., 2019). Mesoscale TRAPs indicate these mesoscale fronts and might provide a window to enhanced material clustering at the submesoscale where we also expect higher numbers of small-scale TRAPs. However, it remains to be investigated whether mesoscale TRAPs from large-scale observations of sea surface height $\mathcal{O}(10-100\mathrm{km})$ can be used as a proxy for material accumulation at operational scales $\mathcal{O}(1-10\mathrm{km})$. Subject to current research is the recast of our TRAPs record (Kunz, 2024b) to periods with available SWOT measurements with resolution about an order of magnitude higher than the data used here. Since the geostrophic assumption is needed to obtain a sea-surface velocity from SWOT measurements, such exploration can be complemented with additional observations in coastal regions from high-frequency radar which

gives the full and not only the geostrophic sea-surface velocity. These surveys can further improve the applicability of TRAPs to offshore cleanups and their integration within a cleanup system.

2 Parameter choices

There are several subjective choices that likely affect the statistical results. First, limiting traps to 1 deg arclength seems both arbitrary and unnecessary. I don't think it is necessary to put any limit on TRAPs lengths. It would be better to identify the full extent of a TRAP line length and analyze its statistics. Second, a 75 km radius was used for the pairing of drifters and TRAPs. Again, this seems like an arbitrary and unnecessary choice. It would be better to define the area of influence for each TRAP around the local minimum, perform statistical analysis of the basin of influence, and use the basin of influence for pairing with drifters.

reply to 1° TRAP length

Higher thresholds for TRAP lengths automatically lead to less distinction between nearby structures. A stop condition for the integration of a TRAP curve like the 30% attraction strength criterion introduced by Serra et al. (2020) is necessary to obtain distinguishable TRAPs instead of infinitely long tangents to a subset of the eigenvector field $\boldsymbol{e}_2(\boldsymbol{x}, t)$. This cutoff criterion makes sense physically because attraction of nearby parcels becomes negligible as distance increases away from the core. We illustrate this in Fig. 1 below where TRAPs are cutoff wherever the attraction strength falls below 30% of the core attraction, in panel (a), and where no such stop condition applies, in panel (b). Considering the profiles in panel (a), we acknowledge that a second length condition like the 1 degree arclength might then be redundant. However, our statistics refer to the position and attraction of the TRAP *core* and the main diagnostics of the paper do not depend on TRAP length. There are only two definitions that are dependent on TRAP length:

1. the radius of the vorticity curve parameterisation: without a maximal arclength of 1 degree, one would have to define an upper limit for the radius to capture the vorticity field sufficiently close to the TRAP core

2. the rotation angle for the composite maps of drifter velocities in the vicinity of TRAPs: without a maximal arclength of 1 degree, one would have to define for every drifter-TRAP pair the part of the TRAP curve that needs to align with the zonal axis, such that the rotation of all drifter trajectories allows to identify patterns in a composite map (or apply another mapping)

We consider the choice of 1 degree arclength acceptable for our purposes since our conclusions are insensitive to this choice. But we also recommend to drop this second condition in future studies.

We now highlight this in the Methods section by replacing line 137 with this new version:

> We truncate TRAP curves wherever the attraction rate along the curve falls below 30% of the attraction at the respective core. This cutoff criterion makes sense physically because the attraction of nearby parcels becomes negligible as distance increases away from the core. Without cutoff, TRAPs can become indefinitely long and merge with nearby structures which makes them hard to distinguish. Their converging ends then put wrong emphasis on regions between TRAP cores where the attraction rate is comparably low, see Fig. S1 for details. In

addition, we limit TRAPs to a maximal arclength of 1° since TRAP lengths are of minor importance to our analysis and the statistics will refer to the position and attraction of the TRAP *core*. This choice does not affect our main diagnostics but is optional and can be neglected in future studies.

We also propose to insert Fig. 1 as new Fig. S1 in the Supplementary Material.

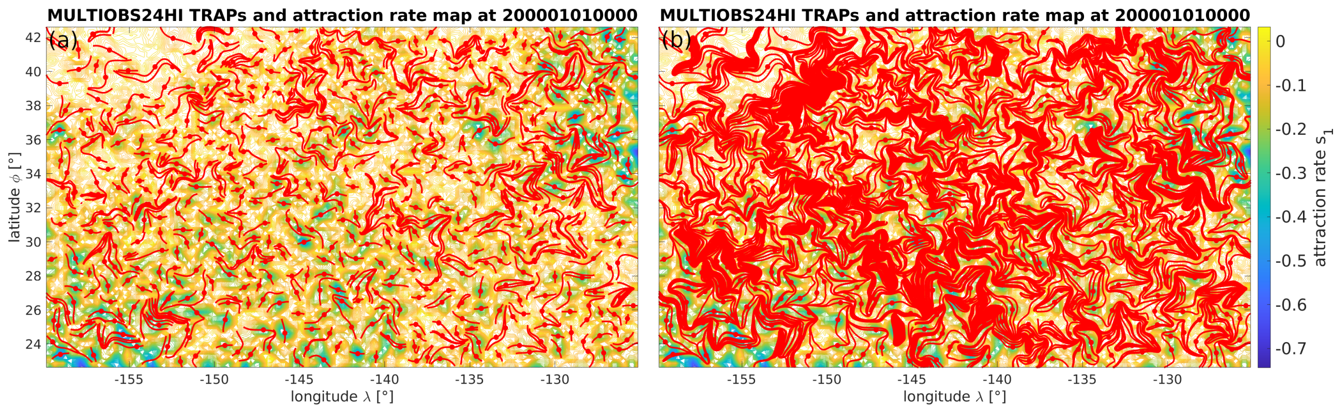

Figure 1. TRAPs with different lengths. (a) TRAPs with a maximal arclength of 100 degrees and cutoff at 30% of core attraction strength. (b) TRAPs with a maximal arclength of 100 degrees and no cutoff.

reply to 75 km search radius

In the readme 'Drifter-TRAP pair detection' within the repository of the pair algorithm we state:

> 75 kilometres is roughly about 1.5 times the average speed radius of mesoscale eddy detections in this region which we consult from The altimetric Mesoscale Eddy Trajectory Atlas (META3.2 DT) provided by AVISO+ et al. (2022).

This seemed a reasonable search radius to us considering that we look for drifter movement in the periphery of eddies. We acknowledge that this choice seems arbitrary and explain our further motivation for it. We have run this algorithm for different values of the search radius r ranging from 50 km to 300 km. 86% of all drifter days occur within 75 km distance to their closest TRAP core. The mean distance and its standard deviation of drogued drifters to their closest TRAP core is $\overline{d} \approx (51 \pm 25)$ km, for undrogued ones it results in $\overline{d} \approx (49 \pm 24)$ km. The mean distance between TRAP cores is around $\overline{d} \approx (78 \pm 29)$ km. Figure 2a shows the respective distributions of distances between drifter positions and their closest TRAP core as well as between TRAP core positions and their closest, neighbouring TRAP core. Panel (b) emphasises that the vast majority of drifter positions is within a radius of 75 km. Beyond this limit, data is insufficient to derive more conclusions than the ones shown in Figure 10 of the manuscript.

For the 14% of drifter days beyond the 75 km limit, we observe a significant increase in the number of one-day pairings. If drifters are really attracted in a far distance, it is likely that they meet other structures in the way which terminates the pairing algorithm. Such a one-day 'retention' becomes arguable considering the temporal resolution of the data as well as the distance to the actual structure. Short-term pairings with distant drifters can also occur when a TRAP attracts a distant drifter but dissipates during the drifter's approach. To address this, we also tested a search radius based on the remaining lifetime of a TRAP which reduced the amount of short-term pairings but did not lead to any remarkable insights. With these aspects and the coarse resolution of our data in mind, it seemed straight-forward and reasonable to us to apply a 75 km threshold from the beginning.

Our pair algorithm searches for the closest TRAP around a drifter and therefore, its detection is insensitive to the individual attraction strength or impact range of surrounding TRAPs. As a consequence, drifters may be located within the impact range of one TRAP but will be assigned to another TRAP, if the latter is closer, even if the drifter is beyond its impact range. This could lead to a short-term pairing with the closer TRAP and an underestimated retention time with the impacting TRAP, towards which the drifter will be eventually attracted. Considering the actual impact range of a TRAP could therefore improve the accuracy of retention times and motion patterns of drifters around TRAPs. The definition of a dynamic impact range would be a valuable contribution to the TRAPs concept and would also benefit its operational application. We are currently not aware of a mathematical definition for an objective 'basin of attraction' that is compatible with the concept. However, basins of attraction are a known concept from dynamical systems theory, e.g. see Strogatz (2014); Heitzig et al. (2016); Menck et al. (2013). We also think that the eigenvalue fields $s_i(\boldsymbol{x}, t)$ and eigenvector fields $\boldsymbol{e}_i(\boldsymbol{x}, t)$ contain more information that can be used for such a definition.

This endeavour opens a variety of theoretical questions which would be better placed in a separate research project. Our observational study can serve here as an example of motivation. The approach we use is sufficient to show the aggregate effect of TRAPs on drifters and to provide a first estimate of the retention times that drifters can spend around a TRAP.

We propose to modify the paragraph starting in line 213 as follows:

> We want to see how drifters behave in the surroundings of a TRAP and therefore detect pairs of drifters and nearby TRAPs. In Kunz (2024a) we provide a comprehensive description of our pair algorithm that works from a drifter's perspective and searches for the closest TRAP within a distance of 75 kilometres. We choose this limit since it represents the average distance $\overline{d}$ plus one standard deviation between a drifter and its closest TRAP core, i.e. $\overline{d} \approx (51 \pm 25)$ km for drogued and $\overline{d} \approx (49 \pm 24)$ km for undrogued drifters. 86% of all drifter days occur within 75 km distance to their closest TRAP core, see Fig. S3 in the Supplementary Material for the respective distributions. For every instance of a drifter-TRAP pair, the algorithm records the drifter's distance to the closest TRAP. It also saves attributes like e.g. the TRAP age τ at first encounter, the TRAP lifetime Λ and its attraction rate s_1. Moreover, we will know the daily vorticity pattern in which a drifter-TRAP pair is embedded, and we measure the pair's duration, i.e. the retention time φ of a drifter around its closest TRAP. A lot of pairings will only last for a day due to ephemeral TRAPs with lifetimes of $\Lambda = 1$ day, due to drifters passing by in the periphery of a TRAP or due to a drifter meeting another structure in the way. We exclude these one-day pairs from our analysis since we cannot infer any motion statistics from them. Especially, we observe a lot of one-day pairings for drifters beyond the 75 km limit. We note that our pair algorithm searches for the closest TRAP around a drifter and therefore, its detection is insensitive to the individual attraction strength or impact range of surrounding TRAPs. The definition of a dynamic impact range would, however, be a valuable contribution to the TRAPs concept that we propose for future research. Our approach here will allow us to show the aggregate effect of TRAPs on drifters and to provide a first estimate of the retention times that drifters can spend around a TRAP.

With this we propose to include Fig. 2 as new Fig. S3 within the Supplementary Material.

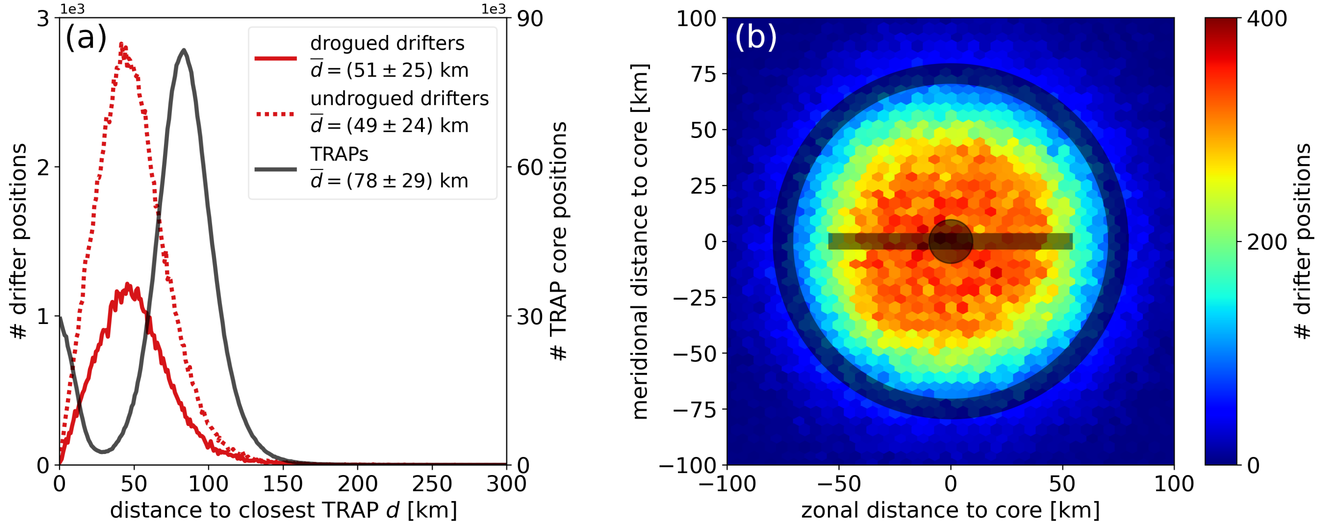

Figure 2. Drifter distances to TRAPs. (a) Distribution of distances between drifter positions and their closest TRAP core (red lines) as well as between TRAP core positions and their closest, neighbouring TRAP core (black line). (b) Spatial histogram of drifter position counts around their closest TRAP. Similar to Fig. 10 within the manuscript, drifter positions are rotated towards the zonal axis and counted within hexagonal bins.

3 Drifter retention

The authors seem to suggest that drifters (and other floating objects like garbage) are more likely to be found near TRAPs than in other regions of the flow. However, I don't think there is any confirmation of this claim in the paper. It would be interesting to compare the statistics for the drifters occurrences and retention times within TRAPs to that within the mesoscale eddies and maybe even for a random subset of regions of comparable size and spatial distribution.

reply

We would like to clarify that we are not looking for encounter probabilities of drifters around TRAPs in comparison to other regions of the flow. Rather, we are looking for regions of confluence and separation where drifters and floating objects will aggregate, even if temporarily, due to the hyperbolic structures that TRAPs identify.

We propose to correct an unfortunate word choice in the paragraph starting line 358:

> We identify 33,878 drifter-TRAP pairs with retention times of $\varphi > 1$ day. These pairs cover 73% of all drifter days and exhibit a mean retention time of $\overline{\varphi} \approx (4.8 \pm 3.7)$ days which reflects the transient impact of TRAPs, i.e. drifters are ~~accumulated~~ attracted and dispersed again within a few days.

We now highlight this in the Conclusions by editing line 406ff as follows:

> Therefore, the life cycle of TRAPs can explain why we observe hyperbolic drifter transport primarily throughout the mature phase of long-living TRAPs. At this stage, the surrounding flow is particularly organised and generates high strain. We find that hyperbolic transport around TRAPs takes on average $\overline{\varphi} \approx (5.3 \pm 3.8)$ days. In general, retention times can be very short and especially strong TRAPs quickly attract and disperse material. But we also detect a few drifters that spend multiple weeks around a TRAP. The highest retention time we measure counts $\varphi = 46$ days.

It would be worthwhile to study the likelihood of drifters to be found near TRAPs. We did investigate drifter times spent around TRAPs and within mesoscale eddies. In line 434 we mention this aspect and point to Fig. S3 in the Supplementary Material (Fig. S5 in the revised Supplementary Material), Fig. 3 below, where we present the time series of drifter days identified around both structures. We acknowledge that this part needs more clarification and propose to replace the description in lines 434 - 438 by this new version:

> We derived a 20-year time series of the number of daily drifter positions spent around TRAPs and within mesoscale eddies detected by AVISO+ et al. (2022) to compare the retention of drifters by both features, see Fig. S5 for details. We find that on average, the share of drifter days around TRAPs or within eddies approximately equals the proportion of surface area covered by these structures. This suggests no preference of drifter positions for any of these features. However, the number of drifters within our domain barely supports the analysis and at times with few drifters, we observe high standard deviations in the respective shares of drifter days. Drifters become more

abundant towards the end of the time series where the share of drifter days around TRAPs tends to surpass the respective proportion of covered surface area, in contrary to eddy detections. More studies are needed to clarify if a preference of drifter positions could be observed in experiments with more drifters, a greater domain, and on what time scale this might occur.

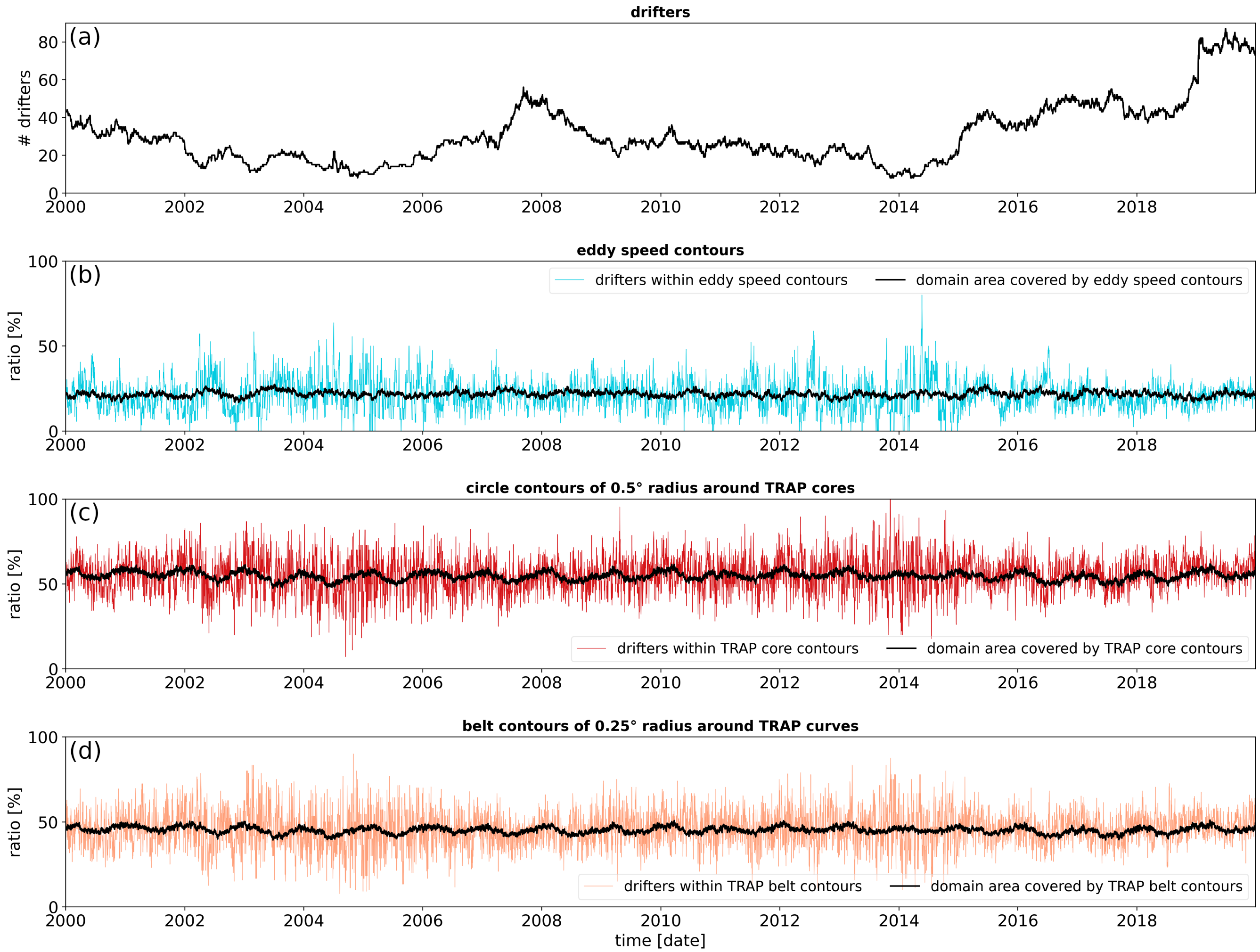

Figure 3. Time series of the surface area enclosed by, and drifter positions detected within TRAP and eddy contours. (a) Time series of the daily number of drifter positions within the study domain. (b) The black line indicates the proportion of domain area covered by daily eddy speed contours. The coloured line represents the ratio of daily drifter positions within these eddy contours. (c) and (d) as (b) but for contours around TRAP cores and TRAP curves, respectively. Mesoscale eddies as detected by AVISO+ et al. (2022).

4 Other revisions to be mentioned for disclosure

We want to correct an unfortunate word choice in line 384:

> The situation appears rather chaotic with no specific motion pattern to detect.

Chaotic here is probably not a good choice because in the literature of trajectories and hyperbolic motion it has a specific meaning, a meaning that happens to be opposite to what we wish to convey. We propose to change this to:

> The situation appears rather disorganised with no specific motion pattern to detect.

We want to correct a typo in line 358 to keep it consistent with other numbers using a comma instead of a dot:

> We identify 33.878 drifter-TRAP pairs ...

We propose to change this to:

> We identify 33,878 drifter-TRAP pairs . . .

We will edit the the short summary in the manuscript as follows:

> TRansient Attracting Profiles (TRAPs) indicate the most attracting regions of the flow and have the potential to facilitate offshore cleanup operations in the Great Pacific Garbage Patch. We study the characteristics of TRAPs and the prospects for predicting debris transport from a mesoscale permitting dataset. Our findings provide an advanced understanding of TRAPs in this particular region and demonstrate the importance of TRAP lifetime estimations to an operational application. Our TRAPs tracking algorithm complements the recently published TRAPs concept and prepares its use with high-resolution observations from the SWOT mission. Our findings may also benefit research in other fields like e.g. optimal drifter deployment, sargassum removal, the identification of foraging hotspots or search and rescue.

And we apply the same corrections for the version on the article page:

> TRansient Attracting Profiles (TRAPs) indicate the most attracting regions of the flow and have the potential to facilitate offshore cleanups in the Great Pacific Garbage Patch. We study the characteristics of TRAPs and the prospects for predicting debris transport from a mesoscale permitting dataset. Our findings show the relevance of TRAP lifetime estimations to an operational application and our TRAPs tracking algorithm may benefit even more challenges that are related to the search at sea.

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