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Analysis of potential MH370 debris trajectories using ocean observations and numerical model results

--Manuscript Draft--

Full Title:	Analysis of potential MH370 debris trajectories using ocean observations and numerical model results
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Abstract:	Flight MH370 disappeared in March 2014. Potential location sites of the plane entering the water are being considered within a vast region of the Indian Ocean, west of Australia, where extensive search efforts are coordinated by the Joint Agency Coordination Centre of Australia. We present methodology that uses the historical data set of drifters and the specific trajectories of several drifters that ran ashore on Reunion and whose trajectories were in the search region at an earlier time. The methodology is enhanced with the use of synthetic surface trajectories derived from the Surface Currents from Diagnostic (SCUD) Model, allowing us to generate maps of particle density probability to assess potential sources with trajectories that could have ended up in the vicinity of Reunion Island. It also provides an estimate of the most likely windage affecting the floating debris on its way to Reunion. The recent discovery of new debris linked to MH370 in Mozambique, South Africa, Mauritius and Tanzania is consistent with results presented here and confirms the general westward drift and travel time of the debris from the search area.
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Response to Reviewers:	Dear Editor, I am pleased to resubmit the revised version of TJOO-2016-0007 “Analysis of potential MH370 debris trajectories using ocean observations and numerical model results”. I appreciate the valuable feedback provided by the reviewers, who helped to improve the quality of the manuscript. We have carefully addressed each comment as outlined below and modified the manuscript accordingly. Response to Reviewer #1 1.Comment: Page 4-L44. Remove or clarify definition. We agree with the reviewer and the definition has been omitted. 2.Comment: Page 12-L24. How the mean windage was obtained? We ran the model with a source along the arc and many values of windage. Then we determined the windage whose density around Reunion was the largest at a time of flaperon landing. The "winner" was 0.8% and our interpretation is that this windage had the highest probability to be in "a right place in a right time", while higher windage traveled faster and passed by the island sooner and lower windage did not reach it yet. We agree with the reviewer that more information should be included to describe this process. We added text to further clarify our methods. In response to the reviewer comment the following sentence has been added (page 11

line 24): “This value corresponds to the windage whose density around Reunion Island is the largest at the time of the flaperon landing”.

Response to Reviewer #3
1.Comment:
Mention and identify the atmospheric forcing field. Consider wind speed and direction uncertainties and their effect on trajectories.

Coefficients of SCUD model are derived using QuikSCAT winds for years 1999-2009. In later years, the model is forced by ASCAT winds that were calibrated to match QuikSCAT during nearly two years of the overlap. Satellite data provide full coverage on a time scale of three days. Technically, daily winds are calculated as a three day running mean.
SCUD model does not resolve high-frequency motions. This is due to the absence of high-frequency (periods shorter than 3 days) wind forcing and absence of high-frequency (periods shorter than inertial period) dynamics. As a result, model solution may be inaccurate in first days after the particle release. However, high-frequency motions do not transport the flotsam far. For example, looping patterns are very common in trajectories of drifting buoys (Lumpkin, 2015). However, this looping (due to inertial oscillations or eddies) are mostly disturbances superposed on the large-scale path set by (sometimes weaker but persistent) low-frequency large-scale currents. Uncertainties and errors of the model, originating from imperfect satellite data (including here wind direction and speed) and simplified dynamics, may have effect on the accuracy of individual trajectories. However, due to their randomness, these errors should not create any significant bias in the motion of a center of mass of a sizable cloud of particles. Unlike other ocean models, the SCUD model warrants that despite various potential errors, its statistics corresponds to the statistics of real drifters. The bias, associated with different geometry of debris is estimated through a range of windage parameters, implemented in the model.

We have included in the new version of the manuscript information about the atmospheric forcing used by SCUD. We also emphasize the robustness of SCUD statistics to potential sources of error, addressing how they correspond to the statistics of real drifters (page 5, line 17).

2.Comment:
Improve Figure Captions for Figures 4,5,8 and 9.

We agree that the captions of those figures need to be improved. Steps have been taken to improve the captions to better explain the individual panels in the affected figures. As a result, all captions have been edited and Figure 4 has been also updated to include the purple box mentioned in the corresponding caption.

3.Comment:
3 minor typographical errors.

We thank you the reviewer for pointing out these typos. We corrected all of them in the revised version of the manuscript.

Finally, we have included an additional table (Table 1) in the manuscript to account for all the pieces of debris currently linked to MH370. We also have made some minor editions. We think that these changes can contribute to improve the manuscript.

Analysis of potential MH370 debris trajectories using ocean observations and numerical model results

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Analysis of potential MH370 debris trajectories using ocean observations and numerical model results

Flight MH370 disappeared in March 2014. Potential location sites of the plane entering the water are being considered within a vast region of the Indian Ocean, west of Australia, where extensive search efforts are coordinated by the Joint Agency Coordination Centre of Australia. The main data set used in this work to address this question corresponds to the historical data set of surface drifters that were deployed and/or traveled in the Indian Ocean. These data allow us to assess historical trajectories and to identify those drifters that have run aground at the same time airplane debris was found on the coast of Reunion Island in July 2015. We present here a methodology that uses the historical data set of drifters and the specific trajectories of several drifters that ran ashore on Reunion and whose trajectories were in the search region at an earlier time. Since this analysis is compromised by the limited number of surface drifters and their biased spatial and temporal sampling, we enhanced the methodology with the use of synthetic surface trajectories derived from the Surface Currents from Diagnostic (SCUD) Model. Since, depending on its buoyancy, marine debris is more or less exposed to the wind and debris degradation and biofouling may change with time the rate of the exposure, tests for a suite of different scenarios were carried out. The methodology used here allowed us to generate maps of particle density probability to assess potential sources with trajectories that could have ended up in the vicinity of Reunion Island. Conversely, if we assume the plane entered the sea in the present search area, it also provides an estimate of the most likely windage affecting the floating debris on its way to Reunion. Results obtained in this work indicate that areas within the Indian Ocean subtropical gyre, including the search area, could be a source of the debris found on Reunion Island. We can also identify those zones that can be excluded as potential crash sites, and provide the estimated travel time and probable ashore positions of the plane debris as given by the analysis of the historical dataset. The recent discovery of new debris linked to MH370 in Mozambique, South Africa, Mauritius and Tanzania is consistent with results presented here and confirms the general westward drift and travel time of the debris from the search area.

Keywords: drifters, ocean currents, debris, Indian Ocean, MH370

Introduction

On 8 March 2014, flight MH370 disappeared after departing from Kuala Lumpur for Beijing with 239 people on board. Based on the last transmitted signal from the plane to the Inmarsat satellite network, the potential location site of the plane entering the water could have been an area west of Australia, where extensive search efforts coordinated by the Joint Agency Coordination Centre (jacc.gov.au) have been concentrated to date (red arc in Figure 1). At the time of the publication of this manuscript, no debris from the missing airplane has been found in the search area. However, on 29 July 2015, a plane flaperon was found washing up on the shores of Reunion Island, located in the western side of the South Indian Ocean (SIO). More recently, there were other discoveries linked to the missing plane, in Mozambique, South Africa, Rodrigues Island (Mauritius) and Tanzania (Table 1). The two panels found in Mozambique in December 2015 and February 2016 have been found consistent with parts of the missing aircraft and are almost certainly from MH370. Similarly, the other pieces found in South Africa and Rodrigues Island are almost certainly from that same aircraft. The wing flap found in Tanzania has been confirmed as originating from MH370.

Large Scale Ocean Dynamics in the Indian Ocean

The search efforts following the debris discovery led to the analysis of the complex Lagrangian ocean circulation, which is capable of connecting distant locations within the SIO and other ocean basins. The surface ocean circulation in the SIO is sustained by a system of major ocean currents that exhibit high seasonal and year-to-year variability in all length scales, which at large spatial scales form the anticyclonic Indian Ocean subtropical gyre (Schott et al. 2009). The main currents of this gyre are the West Australian Current on the east, and the westward-flowing South Equatorial

Current (SEC) on the north, the northern limb of the gyre. The SEC bifurcates off Madagascar, forming the northern and southern branch of the East Madagascar Current (EMC). The gyre is completed by the shallow eastward flowing South Indian Counter-Current, which broadens toward the east allowing a connection from south of Madagascar to off the northwest coast of Australia. A highly complex field of eddies, vortices that have smaller spatial scales than the currents described above and that can travel long distances before dissipating, is superimposed upon this complex system of currents.

In situ and remote ocean observations, in particular those that are part of the sustained ocean observing system, together with wind field observations, are key to monitor and assess ocean currents and their associated eddy field, which together with their spatial and temporal variability control the transport of particles. Examples of how ocean observations are used for particle transport and trajectory applications include studies related to transport of contaminants, such as during the Deepwater Horizon and other oil spill incidents (Goni et al. 2015), the Fukushima cooling water release to the ocean (Rypina et al. 2013), the motion of surface drifters (Olascoaga et al. 2013), the monitoring of marine debris trajectories (Moore et al. 2001; Duhec et al. 2015), and the transport of fish larvae (Cowen et al. 2000).

Hydrographic and Numerical Model Data

We present here results from a study that provides a methodology to backtrack ocean debris based on the location where they were found, and presents new and key information on the potential crash site of flight MH370 in the SIO. This study uses two main data sets that are commonly used to investigate the location and variability of global ocean currents.

The first data set corresponds to trajectories of surface drifters (Niiler 2001), which are buoys that have a subsurface drogue (sea anchor) attached to the buoy that is centered at 15 m depth. They are tracked by satellites and have an average lifetime of approximately 1 year, although some individual drifters' lives can even extend beyond 24 months. Annually, nearly 1100 surface drifters are deployed globally in a rather inhomogeneous fashion in time and space. At any time there are about 400 drifters in the Indian Ocean. Once deployed, a drifter can lose its drogue and turns into a so-called "undrogued" drifter. This event greatly affects the drifter tendency for wind slip relative to the water parcel through a combination of the wind drag on the buoy, wind-driven shear currents, and Stokes drift due to surface gravity waves. The average drifter loses its drogue after 6 months at sea. This study relies on in situ data from undrogued drifters, as the debris are probably at or very close to the surface and this dataset better describes the surface dynamics.

The second data set used in this work corresponds to synthetic (hypothetical) drifter trajectories derived from surface ocean velocity fields obtained from the Surface Currents from Diagnostic (SCUD) Model (Maximenko and Hafner 2010), that incorporates hydrographic, satellite altimetry, and wind data. Coefficients of SCUD model are derived using QuikSCAT winds for years 1999-2009. In later years, the model is forced by ASCAT winds that were calibrated to match QuikSCAT during nearly two years of the overlap. The SCUD model warrants that despite various potential errors, its statistics corresponds to the statistics of real drifters. The spatial resolution of these velocity fields is one quarter of a degree in latitude and longitude, and ocean current fields are provided on a daily basis. The trajectories of surface and synthetic drifters are used in this study to simulate the displacement at the surface in the SIO of debris that could have potentially belonged to flight MH370.

Methodology and Results

In this work, we first trace the surface and synthetic drifters that were at one time located in a rectangular region enclosing the search region, an area of the eastern Indian Ocean off Australia (green box in Figure 1). Of especial interest here are the trajectories of drifters that were in the green box during the period March-April 2014. Secondly, we determine the positions of the drifters prior to reaching an area in the western Indian Ocean close to Reunion Island, indicated by the purple box in every figure, where airplane debris was found. Of particular interest here are the trajectories of the drifters that ultimately arrived in this area during July-August 2015.

Of the 3083 observed surface drifters that have historically travelled in the Indian Ocean from October 1985 to August 2015, 509 (16.5 %) of them travelled (or were deployed) inside the green box (black and red trajectories in Figure 1). From those, 368 drifters were undrogued. Depending on their location in this large area, their trajectories tend to follow the general circulation of the South Indian Ocean subtropical gyre. Of this drifter trajectory subset, 31% reached 75°E between 15°S and 30°S, mostly carried by the South Equatorial Current, even reaching longitudes west of Madagascar, with the rest remaining in the gyre or travelling east towards Australia or south of Australia. Trajectories from the historical drifter data set show that 23% of the drifters coming from the green box eventually reached the purple box (red trajectories in Figure 1). During the period March-April 2014, there were 17 drifters that travelled or were deployed in the green box, of which three (or 18%, a number close to the historical average) reached the purple box, around Reunion Island. Two of them (thick black trajectories in Figure 1) reached the purple box in July and November of 2014. Remarkably, one of them (thick red trajectory in Figure 1) reached the purple box in

July 2015, precisely in the same month that the MH370 debris were found washing up on the shores of Reunion Island.

The trajectories of the 368 undrogued drifters that travelled within the green box and beyond indicate that there are several areas in the SIO with high probability that debris linked to the missing flight could have passed through them. Using the data from the undrogued drifters passing through the search area (indicated by the red segment between 35°S and 40°S in Figure 2), we estimated the probabilities of finding any of those drifters in other regions as well as the mean time taken to reach those locations. These direct trajectories follow a general pattern that includes part of the West Australian Current, and the westward flow on the South Equatorial Current. This is only a small subset of the total number of trajectories that could be used to infer the transport of debris from the search area. The coverage greatly increases using indirect one-step trajectories, which at some point crossed with the direct trajectories and increment the number of drifters used in our analysis. We consequently consider that, at the intersection point of two drifter trajectories, a drifter could take any of the two trajectories, to which we refer here as direct and indirect trajectories, with equal probability.

The use of indirect trajectories, besides contributing to improvement of the coverage, also allows us to expand the temporal coverage over periods larger than the lifespan of an average drifter. On the other hand, indirect trajectories assume that surface ocean conditions were the same for the cross over location, which may introduce errors in the estimates. The total probability encompasses both the direct (percentage of drifters leaving the search area found within each 1x1 degree cell) and indirect (same definition but referring to indirect trajectories) probabilities. Results show (Figure 2 bottom) high probability values in the neighbourhood of the search area, almost reaching the west coast of Australia, and an evident westward pattern between 10°S-30°S, that bifurcates near Madagascar following the 2 branches of the EMC. The northern branch of this current can reach the east coast of the African Continent, to then form the East African Coastal Current and the Mozambique Current. Drifters in the southern branch of the EMC can turn east although many others propagate southwestward, reaching the Agulhas Retroflection system and possibly even entering the Atlantic Ocean. We will make use here of the mean travel time, which is defined as the average time needed to reach a region from the search area. The analysis of the mean travel times shows that the range of time to reach the major coastal areas in the Indian Ocean from the search area is between 0.5 to 1 years for West Australia and 1.5 to 2 years for East Africa, with increasing values for the southern parts of the continent. It is interesting to note that there is a noticeable meridional gradient in the travel time values in a wide region along the east coast of Madagascar. Drifters from the search area could arrive within 1 year to the north of the region, while it could take up to 2.5 years to reach the south of the island. These results are consistent with the finding of the plane debris off Reunion Island, almost 17 months after the plane disappeared and with the recent confirmed findings in Mozambique, almost 2 years later (~21 and ~23 months).

The probability and travel time maps (Figure 2) may help define rational initial ad-hoc spatio-temporal constraints. These areas correspond to the northern limb of the subtropical gyre, vast regions that include Madagascar and extend farther east, and the waters west and south of Australia. The westward trajectories that leave the search area take one main pathway associated with the South Equatorial Current. Trajectories located south of Australia mostly correspond to drifters that first travelled through the southern part of the search region.

Since some of the airplane debris was found on Reunion Island, backtracking the positions of the 375 surface drifters that travelled within the purple box during the last 25 years may help also identify the possible initial location of the debris. Of those 375 drifters that were identified to have reached the purple box in 1980-2015, 274 were undrogued. The trajectories of these 274 drifters (Figure 3-upper panel) indicate that their source location could have been vast areas of the South Indian Ocean. Remarkably, there were four drifters that arrived in the red box during June-July 2015 (Figure 3, thick trajectories). Of the total of 274 undrogued surface drifters that travelled within the purple box, 97 (35 %) were in the green box before arriving in the purple box (Figure 3, red trajectories). The number of drifters with trajectories in boxes of 1-degree side indicates that potential airplane debris may have travelled from areas that belong to the green box, areas of the center of the South Indian Ocean subtropical gyre, and areas north of 15°S. The area within the green box with the highest probability (orange and red colors in Figure 3-lower panel) of being the source of plane debris are mostly in the western section, reaching locations reasonably close to the search area (just a few hundreds kilometers to the north). On the other hand, the southeast and northeast areas of the green box are less likely to have been the source of plane debris (light blue and white colors in Figure 3-lower panel). These hypotheses rely on the uncertain assumption that the average windage affecting both the undrogued drifters and the debris match. Another important constraint is determined by the drifter lifetime once the drogue is lost, which can affect the overall estimates as this factor can significantly change the probability of a drifter getting near Reunion Island. The use of indirect trajectories (see above) allows us to overcome this limitation.

A similar analysis as above was carried out using synthetic drifters that were advected using the SCUD current fields during the period March 2014 to August 2015.

A synthetic drifter is a test passive particle that is moved by the surface flow and that allows us to infer the pathways of transport based on a current model output. The analysis presented here uses different windage coefficients, which account for the correction in trajectories due to the friction between the floating object and the wind. High windage values generally correspond to situations where most of the object is above the sea surface. This factor is included because the movement of particles does not fully depend on ocean currents, but also on winds, which pushes them in the downwind direction. In the case of the plane debris, the windage coefficient can be variable as the buoyancy decreases over time, and approaches zero as the object projection over the surface decreases. Thousands of these synthetic drifters were deployed in a region that encompasses the search area on March 8, 2014. Results presented here focus on the synthetic 246 drifters, which were deployed within a distance of 100 km from the arc representing the search area and cover the temporal period from release to Jul 29, 2015, when the debris was found on Reunion Island. The trajectories of these synthetic drifters (Figure 4) closely match the trajectories of the real drifters shown in Figures 1 and 2. Many of these trajectories move along the South Equatorial Current of the Indian Ocean subtropical gyre. A variable percentage of these drifters reach the purple box (approximately 0%, 11%, 16% and 23% for each windage coefficient). The spatial distribution of the synthetic drifters greatly depends on the values of the windage chosen for each realization. This is especially relevant when wind friction with the debris is not taken into account (i.e. windage=0%). In this case, there are no synthetic drifters in the vicinity of Reunion Island at the end of the simulation. This scenario could characterize the case of underwater low-floating debris that, in the case of the MH370, could represent a significant percentage, especially after the temporal decay of the buoyancy. The 0% windage context is not applicable to debris floating in a narrow layer near the surface and whose trajectories are affected by Stokes drift and other effects. In the other situations where windage is used, most of the synthetic drifters would travel far away from the search area in the eastern side of the Indian Ocean, with a larger number of drifters reaching Reunion Island as the windage increases. Therefore, this may be indicative of the large impact of the wind, in addition to that of the surface currents, to the transport of marine debris.

We also used tracer experiments with the SCUD model to simulate evolution of a multi-windage cloud of debris. In these experiments, equal amounts of tracer with 41 windage values ranging between 0 and 4% were released at the potential crash site on the 7th arc. Wind quickly stratified the solutions by pushing the high-windage tracer (red in Figure 5) towards the west-northwest. The low-windage tracer (blue) was not just drifting slower after reaching Madagascar during summer 2015, but also started recirculating within the subtropical gyre towards the south and then towards the coastlines of Mozambique and South Africa. This analysis relies on the assumption that the starting point falls within the search area. Results can differ in case the crash site was located elsewhere. Another important aspect to consider is that dispersion is likely underestimated, significantly in regions where there is an energetic submesoscale field.

Figure 6 illustrates how, even without knowing the exact spectrum of windages of debris, the model helps to estimate the likely windage value of the flaperon, found on Reunion Island, obtained as:

$$\langle Windage(x,y) \rangle = (Windage * C(x,y,Windage))/(C(x,y,Windage)), \quad (1)$$

where C(x,y,Windage) is the tracer concentration at location (x,y) for a given windage. The “probable” windage of the flaperon $\langle Windage(x,y) \rangle$ was estimated close to 0.8%. This value corresponds to the windage whose density around Reunion Island is the largest at the time of the flaperon landing. This calculation, in which tracer concentration was interpreted as a probability density function for a particle movement, demonstrates that by July 2015 the majority of high-windage debris has already been pushed by the wind away from the Indian Ocean subtropics. As shown in Figure 5, this flow of the low-windage tracer is also consistent with reports on more recent findings of MH370 fragments in Mozambique, South Africa and Rodrigues Island.

Results obtained from this numerical experiment show that debris may wash up in various regions. In the eastern Indian Ocean, some locations along the coast of Australia are particularly good candidates, especially north and south of Perth and the Gascoyne coast. On the western side of the Indian Ocean, Madagascar is a recognizable option, as well as some of the islands along the pathway, such as Reunion and Rodrigues islands. Longer simulations may expand the list of coastal areas in countries where debris could have potentially washed aground to include those located along the east coast of the African continent. These results are confirmed by the analysis of the historical dataset (Figure 7). The distribution of the landings by country is shown in Table 2. All of them correspond to direct and indirect trajectories of drifters passing through the search area. The criterion to decide if a drifter runs aground is the distance to shore when the last transmission from the drifter was received. If it is within 50 km from the shore, it is considered a landing. Australia shows a large number of indirect hits (mostly in the south) as a result of iterations between the direct trajectories and drifters entering the Great Australian Bight. Madagascar, Mozambique and Somalia are countries also having high probability values of having been reached by debris.

As in the analysis done with the surface drifters, thousands of synthetic drifters that were located in the purple box at the end of July 2015 were backtracked to their position in March of 2014 (Figure 8). This technique allowed us to identify potential sources of debris. Results indicate that the sources may be found in several regions of the SIO, including areas west of Australia, and larger regions outside the search area. However, and for windage values consistent with our previous analysis (i.e. 0.8%), results also show that the search area lies within the region with higher probability of being the source of the drifters entering the purple box at the time the flaperon was found. Confining this same analysis to a smaller square of 1.5ºx1.5º centered on Reunion Island (Figure 9), the possible sources of debris arriving to this island in July 2015 can be better delineated. Similarly to the results presented in Figure 4, there are no drifters connecting the search area with Reunion Island when windage is not considered. In the rest of the cases, there are synthetic drifters (represented in red in Figure 9) that can be tracked back to the search area. The probability maps show that several regions in the Indian Ocean may account for the bulk of synthetic drifters that were washed up on Reunion Island. However, the intersection of these maps with the Inmarsat arc clearly defines the search area as a region with high probability of being the source of the debris.

Discussion and Conclusions

We present here a methodology based on the use of surface drifters and synthetic drifters whose trajectories are obtained from the output of the SCUD model to describe the ocean surface circulation, in order to assess the potential location of the crash of the MH370 flight in March 2014. The debris trajectories are mainly affected by a combination of a complex ocean circulation at different length scales and the exposure of the debris to the direct wind forcing, the latter being able to change due to (e.g.) debris degradation and biofouling. The methodology included two main aspects: 1) analysis of the trajectories of potential airplane debris that travelled through the search area, and 2) assessment of the potential origin of airplane debris from trajectories that travelled in the vicinity of Reunion Island.

Since the surface drifter data set has inhomogeneous spatial and temporal coverage, the output of the SCUD model that provides trajectories for thousands of synthetic drifters is also used. Here, different data sets were obtained accounting for the wide range of exposure to wind that the debris may have had, referred to as windage. The synthetic debris trajectories show that for debris exposed more to the wind (higher windage factor), the probability of having airplane debris that originated in the search area and that reached Reunion Island notably increased. This is consistent with the estimate of the most likely windage (0.8%) affecting the flaperon. Similarly to the analysis performed with the surface drifters, the backtracked trajectories of synthetic drifters indicate that particles that reached Reunion Island could have travelled earlier through the search area.

Our methodology, which supports both research and operational activities, includes the following stages:

(1) Analysis of drifter trajectories forward in time to identify potential pathways originating from the search area. It also provides information about potential washing up locations, and direct and indirect travel times obtained from using the 2-iteration approach method.

(2) Analysis of backtracked historical and near real time drifter trajectories to establish the sources of marine debris arriving in the region of interest. The procedure can include confirmed locations of debris as well as prospective ones. The drifter data used in this and the previous stages come from the historical drifter archive as well as from the Global Telecommunication System. The characteristics of the floating debris will determine if drogued and/or undrogued drifter data are used as the source of in situ data.

(3) Analysis of synthetic drifter trajectories computed forward in time using ad-hoc spatial and temporal constraints, which also affect the density and release interval of particles. The underlying surface velocity current fields used in this study were from the SCUD model. The synthetic drifter approach contributes to improving the coverage and reducing the bias caused by in situ drifter data, with deployments and observations inhomogeneous in space and time.

(4) Analysis of backtracked drifter trajectories to assess the potential source areas and to study the time evolution and density of trajectories arriving to the region of interest. Windage is a very important factor to take into account during these last 2 stages, as it could greatly affect the trajectories of the particles and, consequently, the outcome of this analysis.

Historical surface drifter trajectories indicate that debris that originated in the search region could have travelled to vast areas of the Indian Ocean to even reach the coasts of Africa and Madagascar. Notably, two drifters travelled from the search region to the area of Reunion Island during the period between the airplane crash and the finding of the airplane flaperon. Further statistical analysis of the historical surface drifter data set, including a method that uses crossover and dispersion of trajectories, supports the above finding of a clear westward pathway to longitudes 60 and beyond. Moreover, an examination of the location where surface drifters run ashore shows a substantial number of drifters near the eastern coasts of Africa, Madagascar, and Reunion Island. An analysis of the historical trajectories of surface drifters that arrived close to Reunion Island show that a large percentage of these drifters have travelled through the search region at an earlier time.

Our results reflect the large number of parameters and uncertainties that need to be assessed to appropriately track debris in the ocean. Future studies and experiments will help to enhance our understanding of debris dynamics in a broad range of debris size and buoyancy, and assess the value of the windage coefficient that may possibly change by weathering and bio fouling (Ryan 2015) that in turn may influence the debris trajectories (Beron-Vera et al. 2015). Results presented here emphasize the importance of real-time monitoring of surface currents using observational and modeling approaches. Additional studies will also improve our knowledge of the dynamics in equatorial and coastal regions, where complex circulation cannot be explained with simple models. Our study leaves some questions open, such as why no MH370 debris has been found during the Summer-Fall 2014 in the west coast of Australia or later from the east coast of Madagascar.

We expect that future investigation will help to evaluate performances of our methodology and the current state of the marine debris observing system. The desirable outcome would be a reliable surface current field that includes all spatial scales found in ocean dynamics that can be used to monitor the movement of debris under different windage coefficients, time-varying buoyancy conditions, and within an operational framework. This analysis would benefit if the Stokes drift and the wind-driven current shear are also included. In our case, these effects are included in the SCUD coefficients, calibrated using real drifter trajectories. The errors of these coefficients will be reduced when quality controlled drifter data are reprocessed and improved, including the inclusion of seasonality of the Lagrangian biases in some regions. Finally, this study also highlights the importance of sustained ocean observations to monitor ocean conditions that may serve a suite of applications and studies. Local experiments in areas of strong/weak currents and winds would help to add more realism to the existing drift models. Methodologies such as the one used herein, in which a suite of approaches are taken, could potentially improve future search strategies and general debris tracking assessments.

Acknowledgments: Trajectories of surface drifters were obtained from the Global Drifter Program Data Acquisition Center and the Global Telecommunication System. J. Trinanes was funded by NOAA/OceanWatch and NOAA/AOML. G. Goni was funded by NOAA/AOML. Partial support for M. J. Olascoaga was provided by the Gulf of Mexico Research Initiative through the Consortium for Advanced Research on Transport of Hydrocarbon in the Environment (CARTHE) at the University of Miami Rosenstiel School of Marine and Atmospheric Science. N. Maximenko and J. Hafner were partly supported by the NASA grant NNX13AK35G through the Ocean Surface Topography Science Team. IPRC/SOEST Publication XXX/XXXX.

References

Beron-Vera FJ, Olascoaga MJ, Haller G, Farazmand M, Trinanes J, Wang Y. 2015. Dissipative inertial transport patterns near coherent Lagrangian eddies in the ocean. Chaos, 25: 087412.

Bonjean F, Lagerloef G.S.E. 2002. Diagnostic model and analysis of the surface currents in the tropical Pacific Ocean, J Phys Oceanogr. 32:2938-2954.

Cowen R, Lwuiza K, Sponaugle S, Paris C, Olson D. 2000. Connectivity of marine populations: open or closed. Science 287:857-859.

Duhec AV, Jeanne RF, Maximenko N, Hafner J. 2015. Composition and potential origin of marine debris stranded in the Western Indian Ocean on remote Alphonse Island, Seychelles. Mar Pollut Bull. 96:76-86.

Goni, G, Trinanes JA, MacFadyen A, Streett D, Olascoaga MJ, Imhoff ML, Muller-Karger F, Roffer MA. 2015.Variability of the Deepwater Horizon surface oil spill extent and its relationship to varying ocean currents and extreme weather conditions. In: Ehrhardt M, editor. Mathematical Modelling and Numerical Simulation of Oil Pollution Problems New York: Springer-Verlag; pp 1-22.

Maximenko, N.A., and J. Hafner, 2010: SCUD: Surface Currents from Diagnostic model, IPRC Tech. Note 5, 17pp.

Moore C, Moore S, Leecaster M, Weisberg S. 2001. A comparison of plastic and plankton in the north Pacific central gyre. Mar Pollut Bull. 42:1297–1300.

Niiler P. 2001. The world ocean surface circulation. In: Siedler G, Church J, Gould J, editors. Ocean circulation and climate, Volume 77 of International Geophysics Series. London: Academic Press; pp. 193–204.

Olascoaga, ML, Beron-Vera FJ, Haller G, Trinanes JA, Iskandarani M, Coelho F, Haus B, Huntley HS, Jacobs G, Kirwan AD, Lipphardt BL, Ozgokmen T, Reniers AJHM, Valle-Levinson H. 2013. Drifter motion in the Gulf of Mexico constrained by altimetric lagrangian coherent structures. Geophys. Res. Lett., 40:6171-6175.

Ryan PG. 2015. Does size and buoyancy affect the long-distance transport of floating debris? Environ Res Lett. 10:084019. doi:10.1088/1748-9326/10/8/084019.

Rypina II, Jayne SR, Yoshida S, Macdonald AM, Douglas E, Buesseler K . 2013. Dispersal of Fukushima-derived radionuclides off Japan: modeling efforts and model data intercomparison. Biogeosciences 10:4973–4990.

Schott FA, Xie SP, McCreary JP. 2009. Indian Ocean circulation and climate variability. Rev Geophys 47:RG1002. doi:10.1029/2007RG000245.

Figure 1. Trajectories of 368 undrogued surface drifters that were deployed or travelled in a large region (green box) encompassing the search area during 1980-2015 (black and red trajectories) and a subset of 97 drifters from that group (red trajectories) that eventually reached the purple box, which surrounds Reunion Island. Three of these

drifters (thick trajectories in black and red) travelled within the green box during March-April 2014 and eventually reached the purple box. The red thick trajectory corresponds to the drifter that reached the red box on July 2015. The red arc shows the area corresponding to the possible position of the plane when its last signal to the Inmarsat satellite network was transmitted.

Figure 2. Probability fields (left) and travel time maps (right) estimated using the 2-iteration approach (Rypina et al. 2013). The 3 rows refer to the direct (top), one-stop (middle) and total trajectories (bottom).

Figure 3. (top panel) Trajectories (black and red) of the 274 undrogued surface drifters that reached the purple box during 1980-2015. From these 274 trajectories, 97 (black) correspond to drifters that first travelled in the green box before arriving in the purple box. Four trajectories (shown in thick black and red) entered inside the purple box between June-July 2015. Of these four trajectories, one corresponds to one drifter that was present in the green box in March 2014, in a region close to the Inmarsat arc (shown in in Figure 1) but farther north from the current search area. (middle panel) Geographical distribution of the number of drifters in square boxes of 1-degree side that later travelled within the purple box. (bottom panel) Percentage of drifters that reach the purple box for each 1-degree box. There are many regions in the Indian Ocean where at least half of the drifters passing through arrive at the purple box.

Figure 4. Trajectories of synthetic drifters that were deployed in the search area during March 2014 obtained using SCUD analysis for four different windage coefficients (from top to bottom and from left to right: 0%, 0.6%, 0.8% and 1%) . The trajectories of the synthetic drifters that arrived in the purple box are highlighted in red and black (otherwise they are colored in blue). The trajectories in red correspond to drifters with locations within a radius of 150 km centered in Reunion Island. The background colors in the lower panels indicate the percentage of synthetic drifters initially deployed within the search area that travelled in each square box of 1 degree side.

Figure 5. Bi-monthly maps of the SCUD model solution for a mixture of tracers with windage parameters ranging from 0% to 4%. Equal amount of tracer for each windage value has been released in the model on March 8, 2014 at the location marked with a pink line. Different colors represent different windages; high-windage (red) tracer moves faster under the additional force of the wind while low-windage (blue) tracer is lagging behind and follows ocean currents.

Figure 6. Map of mean windage, calculated using Equation (1) in a multi-windage model solution, shown in Fig. 5. The black contour denotes the 0.8% windage isoline.

Figure 7. Trajectories of undrogued surface drifters from the historical dataset. The blue trajectories correspond to drifters washing ashore (otherwise the gray color is used). The small red dots represent the locations of their latest transmission. The larger circles refer to drifters reaching land: in red, for the drifters that at some time travelled through the search area; in blue, the same but for the indirect trajectories. The thicker trajectories represent those drifters arriving to Reunion Island. The one in green represents a trajectory that at some point passed through the search area.

Figure 8. Backtracked trajectories of synthetic drifters that reached the region around Reunion Island (purple box), at the end of July 2014. These figures were constructed using SCUD analysis for four different windage coefficients (from top to bottom and from left to right: 0%, 0.6%, 0.8% and 1%). The red trajectories correspond to the synthetic drifters that at some point approached within 100 km of the arc that defines the search area. The background colors in the lower panels represent the percentage of those synthetic drifters at the time that MH370 disappeared.

Figure 9. Backtracked trajectories of synthetic drifters that reached a small region surrounding Reunion Island at the end of July 2014 obtained from SCUD analysis for four different windage coefficients (from top to bottom and from left to right: 0%, 0.6%, 0.8% and 1%).. The red trajectories correspond to the synthetic drifters that at the time of the disappearance of MH370 were within 100 km to the arc that defines the search area. The background colors in the lower panels represent the percentage of the synthetic drifters at that time in each 1ºx1º cell.

Location	Status	Date	Part Identification	Picture
St. Denis, Reunion	Confirmed	Jul 29, 2015	Flaperon **Image Source: Bureau d'Enquetes et d'Analyses (BEA)**	
Xai Xai, South Mozambique	Almost certainly	Dec 27, 2015	Flap track fairing segment **Image Source: Australian Transport Safety Bureau**	
Vilankulo, Mozambique	Almost certainly	Feb 27, 2016	Horizontal stabilizer **Image Source: Australian Transport Safety Bureau/Boeing**	
Mossel Bay, South Africa	Almost certainly	Mar 22, 2016	Engine cowling segment **Image Source: Australian Transport Safety Bureau/Malaysian MOT**	
Rodrigues Island, Mauritius	Almost certainly	Mar 30, 2016	Panel segment from main cabin **Image Source: Australian Transport Safety Bureau/Malaysian MOT**	
Pemba Island, Tanzania	Confirmed	Jun 20, 2016	Wing flap **Image Source: Australian Transport Safety Bureau/Malaysian MOT**	

Table 1. This table summarizes the different items of debris that have been found to date and that have been confirmed (or almost certainly) from MH370.

Country	Direct Trajectories	Indirect Trajectories
Madagascar	8	59
Tanzania	4	27
Kenya	4	11
Australia	4	92
Mozambique	3	54
Somalia	2	43
Comoros	2	22
Reunion	1	5
Mauritius	1	13
India	1	4
Indonesia	1	12
Other		47

Table 2. Number of surface drifters washed up per country in the Indian Ocean. Only drifters travelling through the search area (red arc) and corresponding one-stop trajectories are reflected in these figures.

Figure1

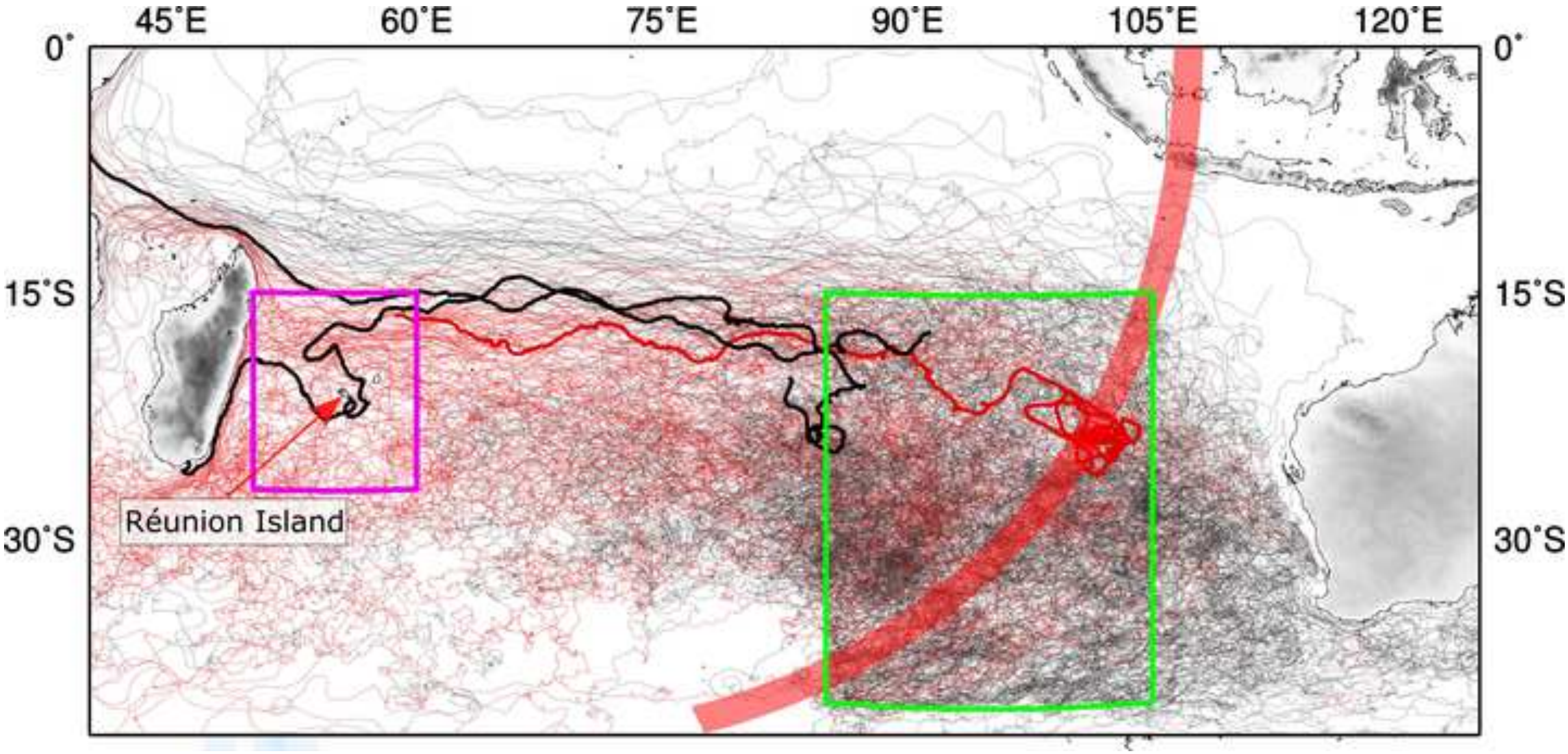
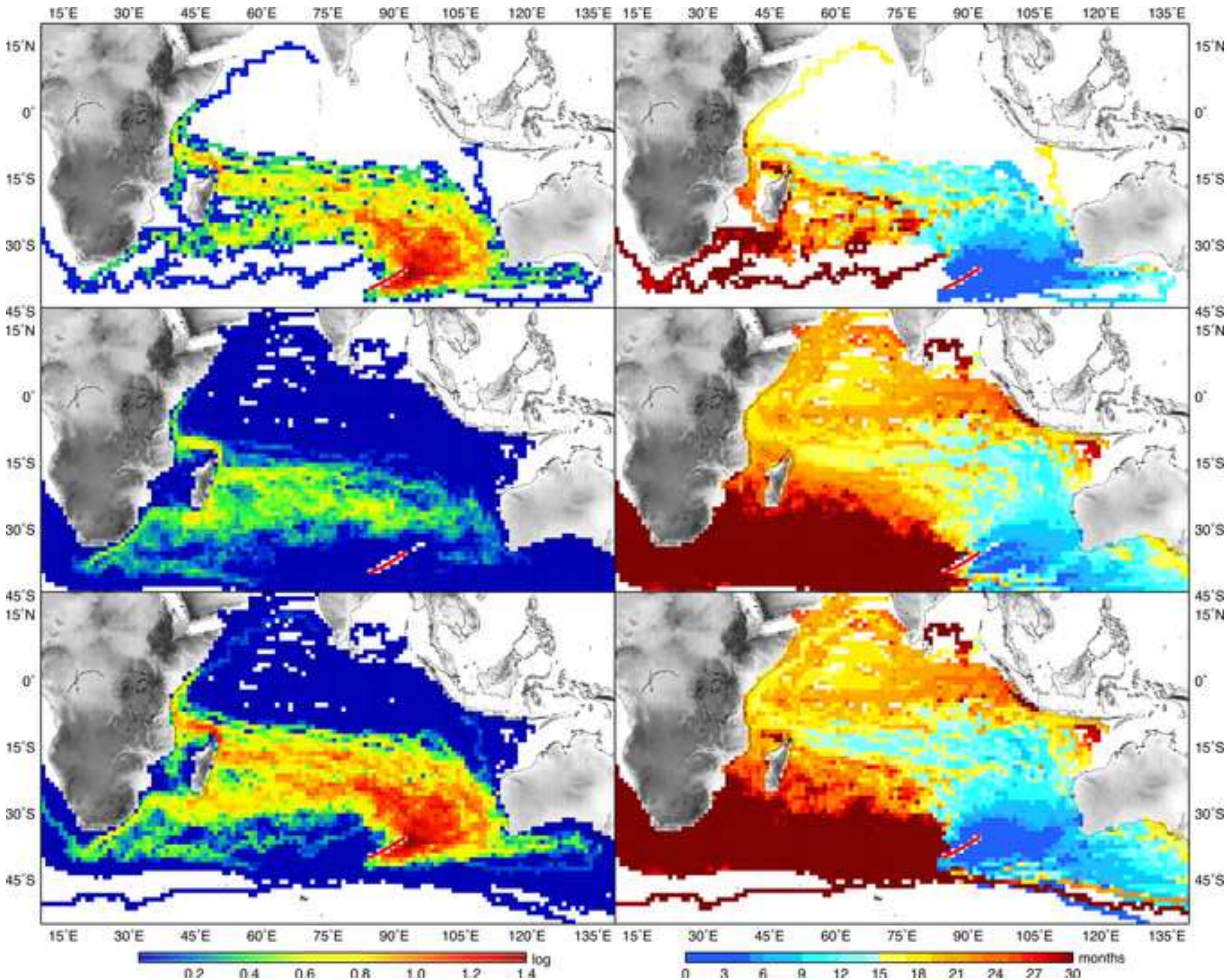
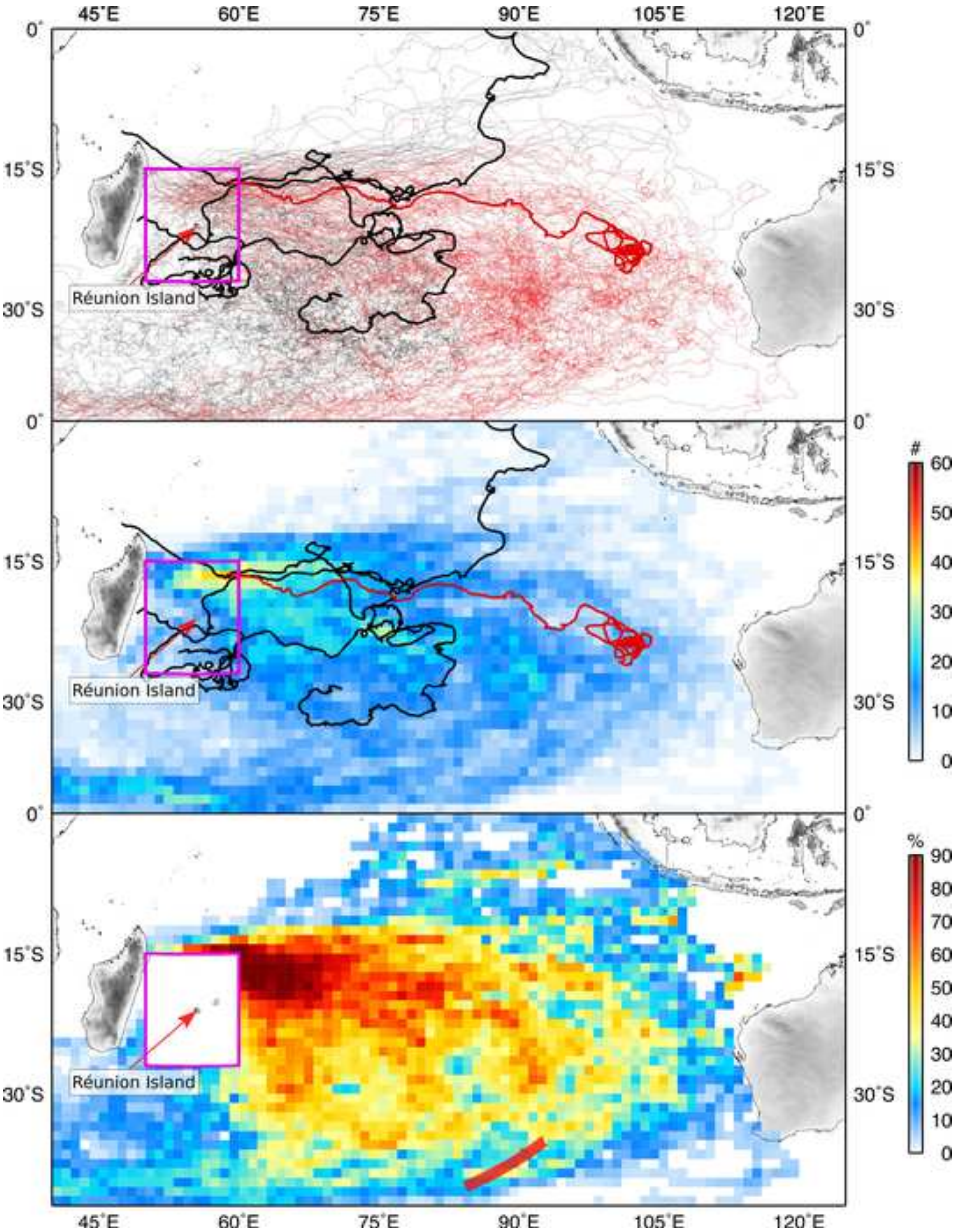


Figure2



15°E
30°E
45°E
60°E
75°E
90°E
105°E
120°E
135°E
15°N
0°
15°S
30°S
45°S
log
0.2
0.4
0.6
0.8
1.0
1.2
1.4
months
0
3
6
9
12
15
18
21
24
27
30

Figure3



45°E
60°E
75°E
90°E
105°E
120°E
0°
15°S
30°S
Réunion Island
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60
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70
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Figure4

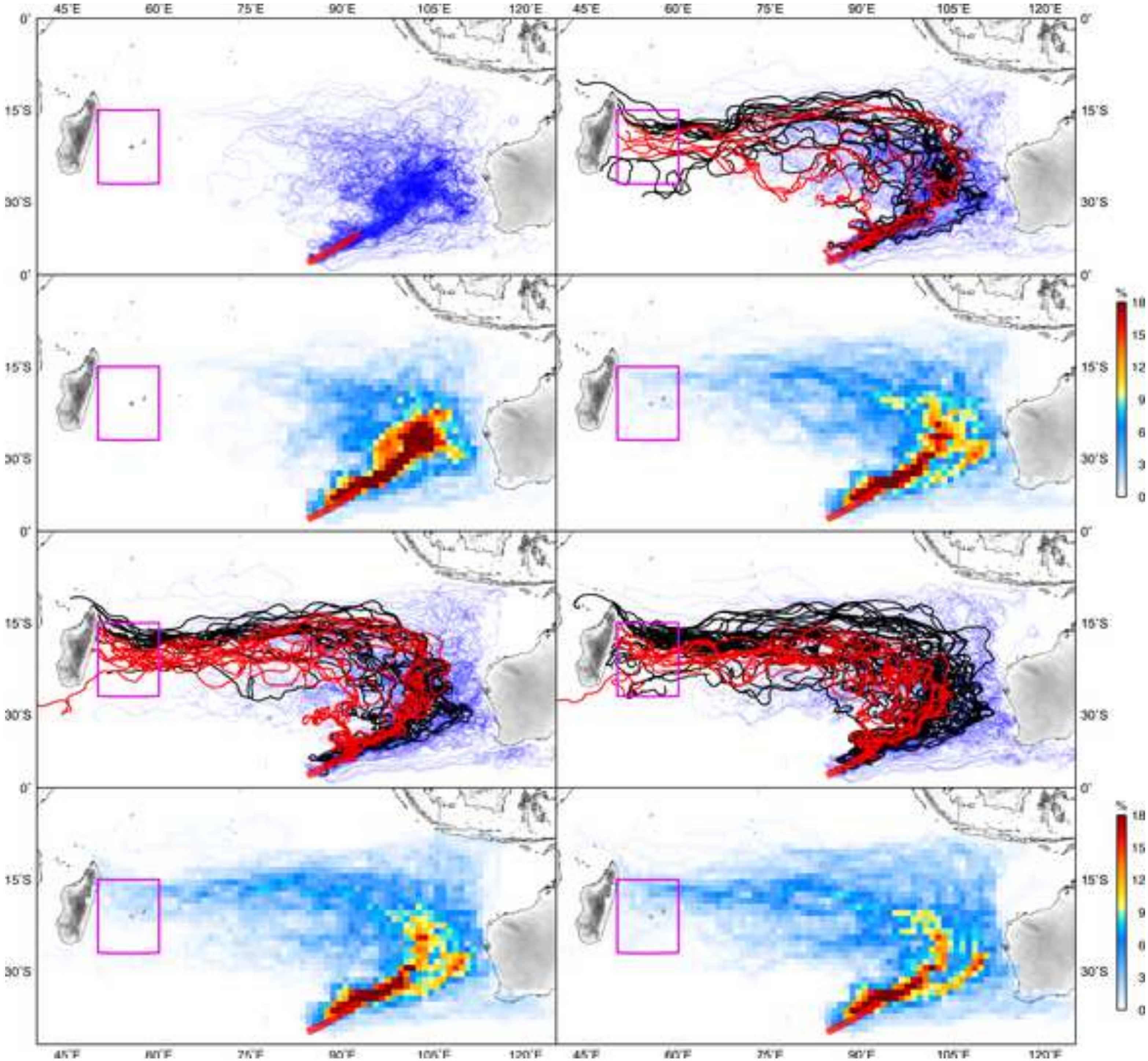
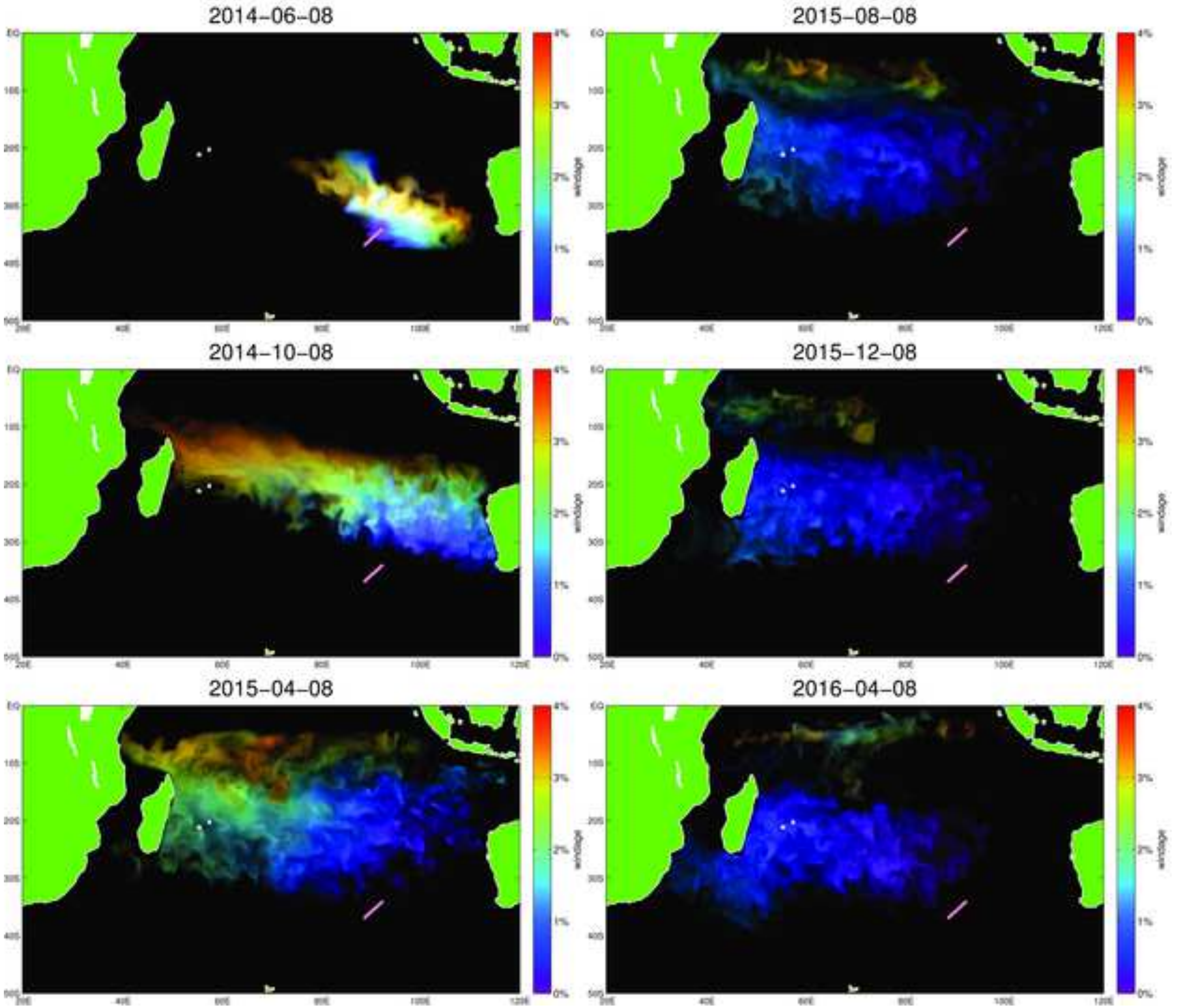


Figure5



2014-06-08
2015-08-08
2014-10-08
2015-12-08
2015-04-08
2016-04-08
windage

Figure6

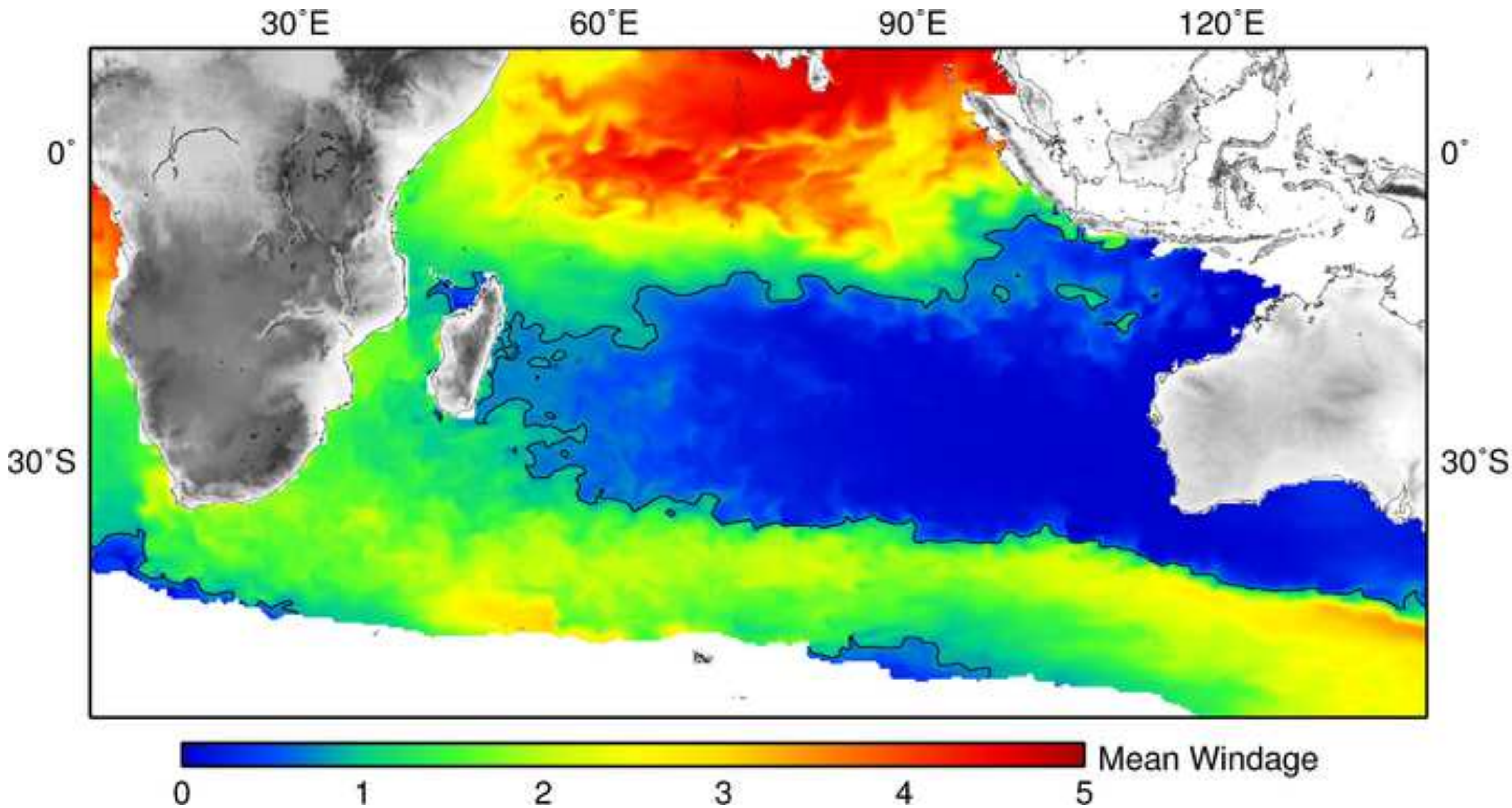
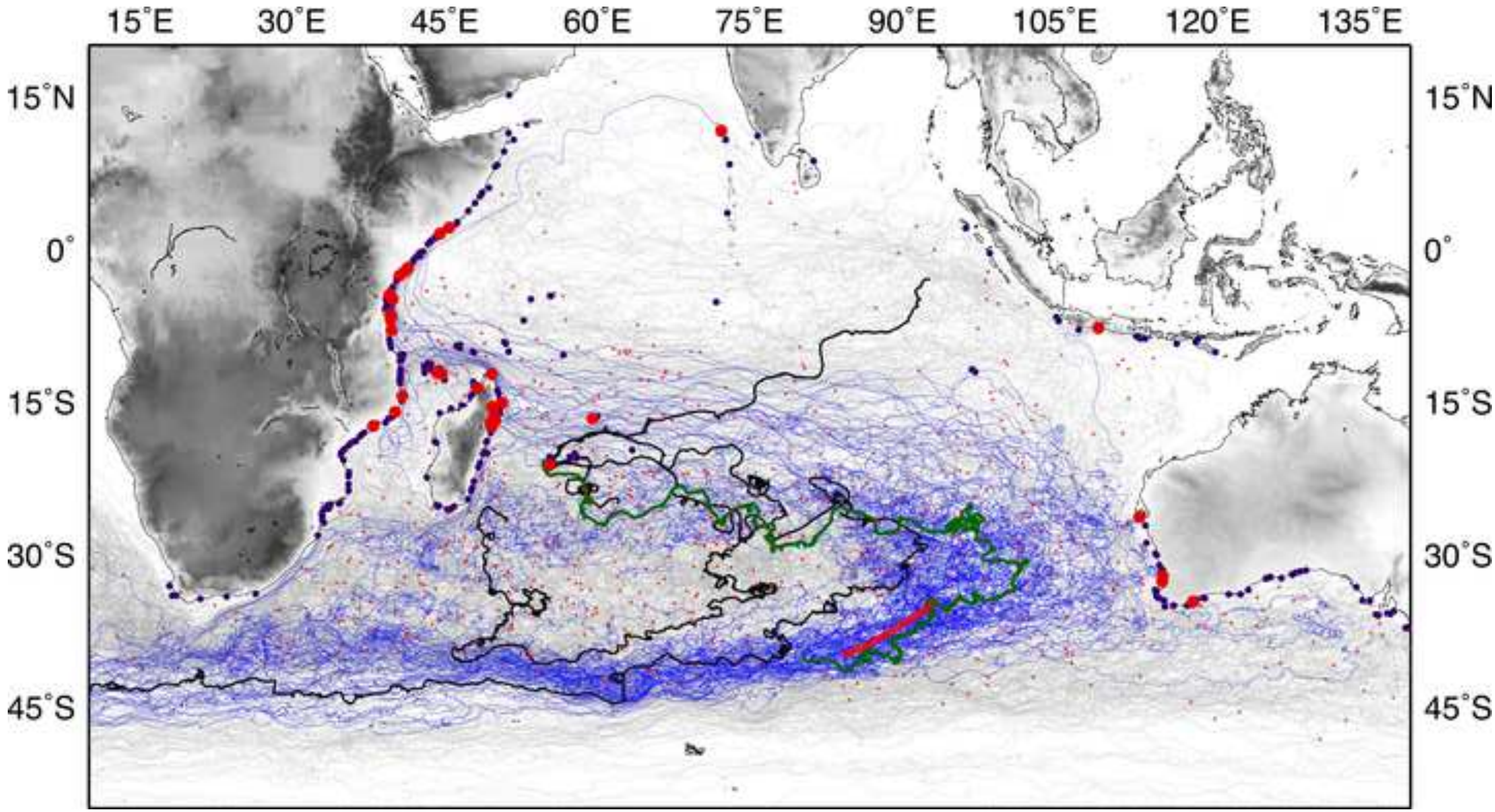


Figure7


15˚E
30˚E
45˚E
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75˚E
90˚E
105˚E
120˚E
135˚E
15˚N
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30˚S
45˚S

Figure8

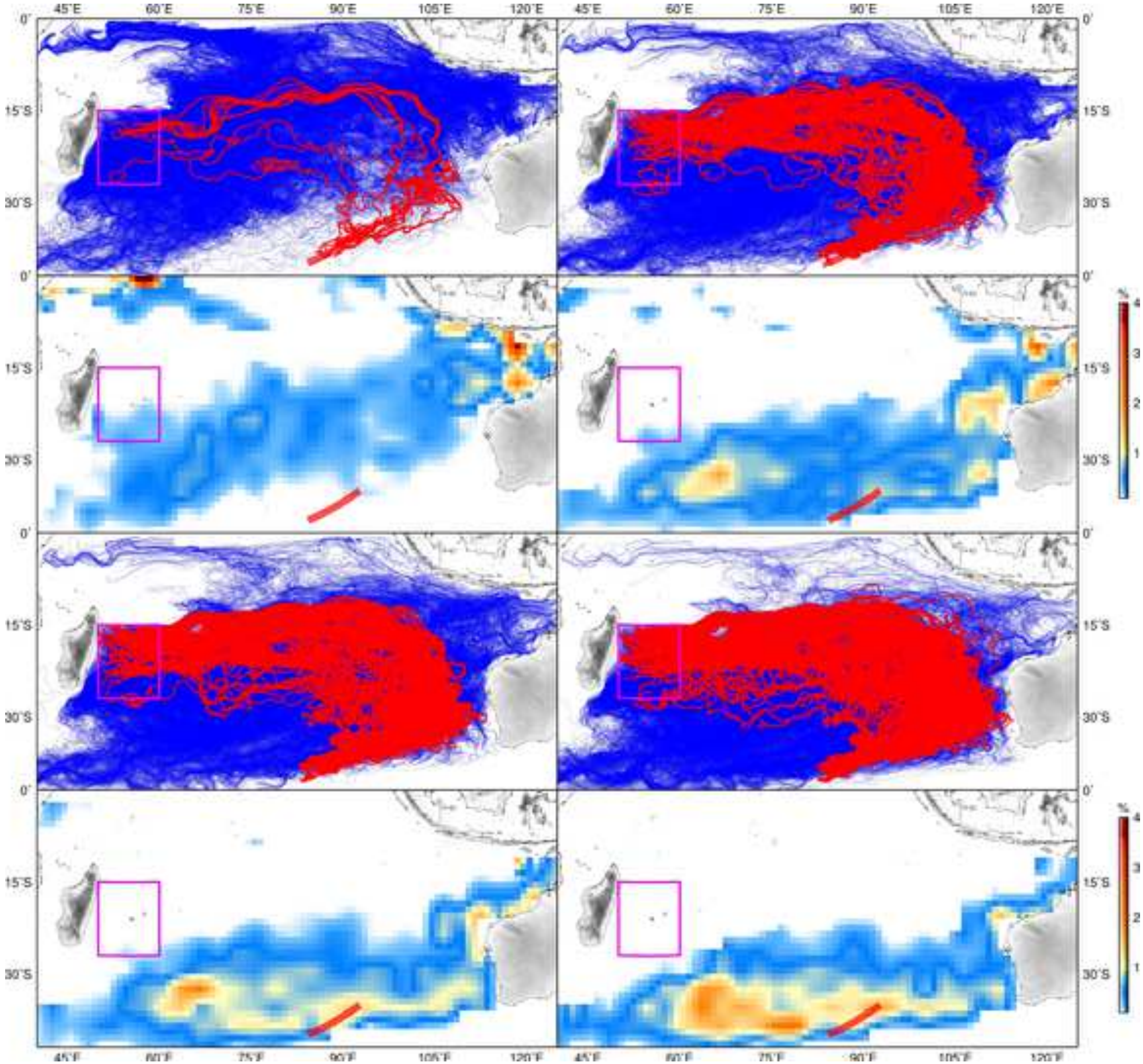

Figure9