Analysis of Flight MH370 Potential Debris Trajectories using Ocean Observations and Numerical Model Results

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Abstract. Flight MH370 disappeared in March 2014. Potential sites of where the plane entered the water are 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 is 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. A methodology is presented that uses this historical dataset of surface drifters, as well as the specific trajectories of several drifters that ran ashore on Reunion Island, that 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 synthetic surface trajectories derived from the Surface Currents from Diagnostic (SCUD) model. Marine debris, depending on its buoyancy, is exposed to varying amounts of wind and, because debris degradation and biofouling may change the rate of the wind exposure over time, we conducted tests for a suite of different scenarios. The methodology enabled us to generate maps of particle density probability to assess the potential sources of trajectories that could have ended up in the vicinity of Reunion Island. We provide an estimate of the most likely windage affecting floating debris on its way to Reunion by assuming the plane entered the sea in the present search area. Our results 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 also identify zones that can be excluded as potential crash sites and provide estimated travel times and probable ashore positions of plane debris through an analysis of the historical dataset. The recent discovery of new debris linked to flight MH370 in Mozambique, South Africa, Mauritius, and Tanzania is consistent with the results presented here and confirms the general westward drift and travel time of debris from the search area.

Key words: drifters, ocean currents, debris, Indian Ocean, flight MH370

Introduction

On 8 March 2014, flight MH370 disappeared after departing from Kuala Lumpur, Malaysia for Beijing, China with 239 people on board. Based on the last transmitted signal from the plane to the Inmarsat satellite network, the potential location of where the plane entered the water could be in 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 this manuscript's publication, no debris from the missing airplane has been found in the search area. However, on 29 July 2015, a plane flaperon washed ashore on Reunion Island, located on the western side of the South Indian Ocean (SIO). More recently, other discoveries of debris in Mozambique, South Africa, Rodrigues Island (Mauritius), and Tanzania have been linked to the missing plane (Table 1). Two panels found in Mozambique in December 2015 and February 2016 are almost certainly from flight MH370. Similarly, other pieces of debris found in South Africa and Rodrigues Island are also certainly from the same aircraft. The wing flap found in Tanzania has been confirmed as originating from MH370.

Large Scale Ocean Dynamics in the Indian Ocean

Search efforts following the discovery of debris on Reunion Island led us to analyze the complex Lagrangian ocean circulation in the Indian Ocean, which is capable of connecting distant locations within the SIO and other ocean basins. The surface circulation in the SIO is sustained by a system of major ocean currents that exhibit high seasonal and year-to-year variability at 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 branches 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 and 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, particularly those that are part of the sustained ocean observing system, along with wind field observations, are key to monitoring and assessing ocean currents and their associated eddy field which, together with their spatial and temporal variability, control the transport of particles. Examples of ocean observations used for particle transport and trajectory applications include studies related to the transport of contaminants such as during the Deepwater Horizon oil spill and other oil spill incidents (Goni et al. 2015), the Fukushima cooling water release into the Pacific 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 a methodology to backtrack ocean debris based on the location of where it was found that provides new information on the potential crash site of flight MH370 in the SIO. The methodology employs two datasets that are commonly used to investigate the location and variability of global ocean currents.

The first dataset corresponds to the trajectories of surface drifters (Niiler 2001), which are buoys that have an attached subsurface drogue (sea anchor) centered at 15 m depth. Surface drifters are tracked by satellite and have an average life span of approximately

1 year, although individual drifters sometimes function for more than 2 years. Nearly 1100 surface drifters are deployed annually around the globe, with about 400 drifters in the Indian Ocean at any given time. Once deployed, a drifter can lose its drogue, becoming an "undrogued" drifter. This event greatly affects the drifter's tendency for wind slip relative to the water parcel through a combination of 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. Our methodology relies on in situ data from undrogued drifters, as debris from flight MH370 is probably at or near the ocean surface, and this dataset better describes surface dynamics.

The second dataset corresponds with 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 the SCUD model were derived using QuikSCAT wind data for the years 1999-2009. For later years, the model was forced by Advanced Scatterometer (ASCAT) wind data calibrated to match QuikSCAT data during nearly two years of the overlap. The SCUD model warrants that, despite various potential errors, its statistics correspond with 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. We used surface and synthetic drifter trajectories to simulate the displacement of debris at the ocean surface in the SIO that could have potentially belonged to flight MH370.

Methodology and Results

We first traced the trajectories of 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 special interest were the trajectories of drifters in the green box during March-April 2014. We then determined the position 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 were the trajectories of drifters that ultimately arrived in this area during July-August 2015.

Of the 3083 observed surface drifters that historically travelled in the Indian Ocean from October 1985 to August 2015, 509 of them (16.5%) travelled or were deployed inside the green box (black and red trajectories in Figure 1). Of these drifters, 368 were undrogued. Depending on their location in this large area, their trajectories tended to follow the general circulation of the SIO subtropical gyre. Of this drifter trajectory subset, 31% reached 75°E between 15°S-30°S, mostly carried by the SEC, and even reached longitudes west of Madagascar. The rest of the drifters remained in the gyre or travelled east towards Australia or south of Australia. Trajectories from the historical drifter dataset showed that 23% of the drifters coming from the green box eventually reached the purple box (red trajectories in Figure 1). During March-April 2014, 17 drifters 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, the same month that debris from flight MH370 washed ashore on Reunion Island.

The trajectories of the 368 undrogued drifters that travelled within the green box and beyond indicate there are several areas in the SIO with a high probability for where debris from the missing flight could have passed. Using data from the undrogued drifters passing through the search area (indicated by the red segment between 35°S-40°S in Figure 2), we estimated the probabilities for finding these drifters in other regions, as well as the mean time needed to reach these locations. The direct trajectories followed a general pattern that included part of the West Australian Current and the westward flow of the SEC. 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. Spatial coverage greatly increased by using indirect one-step trajectories, which at some point crossed the direct trajectories, thus augmenting the number of drifters used in our analysis. We consequently considered that, at the intersection of two drifter trajectories, a drifter could take either of the trajectories, which we refer to as direct and indirect trajectories, with equal probability.

The use of indirect trajectories, besides increasing spatial coverage, also allowed us to expand the temporal coverage over longer periods than the average life span of a drifter. On the other hand, indirect trajectories assume that surface ocean conditions are the same at the cross over location, which may introduce errors into the estimates. The total probability encompasses both the direct (percentage of drifters leaving the search area found within each 1° x 1° cell) and indirect (same definition but referring to indirect trajectories) probabilities. Our results showed (Figure 2, bottom) high probability values in the vicinity of the search area that almost reached the west coast of Australia, as well as an evident westward pattern between 10°S-30°S that bifurcated near Madagascar and followed the two branches of the EMC. The northern branch of this current reaches the east coast of the African continent where it forms the East African Coastal Current and the Mozambique Current. Drifters in the southern branch of the EMC turn east, although many propagate to the southwest, reaching the Agulhas Retroflection system and, possibly, entering the Atlantic Ocean.

We used the mean travel time, defined as the average time needed to reach a region from the search area, to analyze the range of time needed to reach major coastal areas in the Indian Ocean from the search area. Our analysis showed it took 0.5-1 year to reach western

Australia and 1.5-2 years to reach eastern Africa, with increasing values for the southern portions of the continent. It is interesting to note there is a noticeable meridional gradient in the travel time values for a wide region along the east coast of Madagascar. Drifters from the search area could arrive within 1 year to the northern portion of the region, while it could take up to 2.5 years to reach the southern portion of the island. These results are consistent with aircraft debris being found off Reunion Island, almost 17 months after the plane disappeared, and with recent confirmed findings in Mozambique, almost 2 years later ($\sim$21 and $\sim$23 months).

Probability and travel time maps (Figure 2) may help define rational initial ad-hoc spatio-temporal constraints. These areas correspond with 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 SEC. Trajectories located south of Australia mostly correspond with 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 also help identify the possible initial location of the debris. Of those 375 drifters that were identified to have reached the purple box in 1985-2015, 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 SIO. Remarkably, four drifters arrived in the red box during June-July 2015 (Figure 3, thick trajectories). Of the 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 1° size boxes indicates that potential airplane debris may have travelled from areas that belong to the green box, areas in the center of the SIO subtropical gyre and 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 airplane debris is mostly in the western section, reaching locations reasonably close to the search area (just a few hundred kilometers to the north). The southeast and northeast areas of the green box are less likely to have been the source of airplane 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 life span once the drogue is lost, which can affect the overall estimates. This factor can significantly change the probability of a drifter coming close to Reunion Island. The use of indirect trajectories allowed us to overcome this limitation.

We conducted a similar analysis with synthetic drifters that were advected using the SCUD current fields during March 2014 to August 2015. A synthetic drifter is a test passive particle moved by surface flow that allows us to infer pathways of transport based on current model output. Our analysis used different windage coefficients, which accounted for the corrections to the trajectories due to friction between a 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; wind also propels them in a downwind direction. In the case of airplane debris, the windage coefficient can vary, as buoyancy decreases over time and approaches zero as an object's projection above the surface decreases. Thousands of these synthetic drifters were deployed in a region that encompassed the search area on March 8, 2014. Our results focused on the 246 synthetic drifters deployed within a distance of 100 km from the arc representing the search area and covering the temporal period from their release to 29 July 2015 when 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 SEC of the Indian Ocean subtropical gyre. A variable percentage of them 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 value of the windage chosen for each realization. This is especially relevant when the effect of wind friction on debris is not taken into account (i.e. windage = 0%). In this case, there were 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 other situations where windage was used, most of the synthetic drifters travelled far away from the search area in the eastern side of the Indian Ocean, with a larger number of them reaching Reunion Island as the windage increased. Therefore, this may be indicative of the large impact of the wind, in addition to that of surface currents, in transporting marine debris.

We also conducted tracer experiments with the SCUD model to simulate the evolution of a multi-windage cloud of debris. In these experiments, an equal number of tracers with 41 windage values ranging between 0-4% 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) not only drifted more slowly after reaching Madagascar during summer of 2015, but also started recirculating within the subtropical gyre towards the south and then towards the coastlines of Mozambique and South Africa. This analysis relied on the assumption that the starting point fell within the search area, and results can differ in case the crash site was located elsewhere. Another important aspect to consider is that dispersion is likely underestimated, especially in regions where there is an energetic submesoscale field.

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

$$\langle \mathrm{Windage}(x,y) \rangle = (\mathrm{Windage}*C(x,y,\mathrm{Windage}))/(C(x,y,\mathrm{Windage})), \qquad (1)$$

where C(x,y,Windage) is the tracer concentration at location (x,y) for a given windage. The “probable” windage of the flaperon $\langle \mathrm{Windage}(x,y) \rangle$ was estimated close to 0.8%. This value corresponds with the windage whose density around Reunion Island was the largest at the time of the flaperon landing. This calculation, in which the tracer concentration was interpreted as a probability density function for a particle movement, demonstrates that by July 2015 the majority of high-windage debris had 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 of more recent findings of flight MH370 fragments in Mozambique, South Africa, and Rodrigues Island.

Results obtained from this numerical experiment show that debris may wash ashore 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 an analysis of the historical dataset (Figure 7). The distribution of landings by country is shown in Table 2. All of the landings correspond to direct and indirect trajectories of drifters passing through the search area. The criterion to determine if a drifter ran 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 the drifters entering the Great Australian Bight. Madagascar, Mozambique, and Somalia are also countries with high probability values of having been reached by debris.

As in the analysis performed with the surface drifters, thousands of synthetic drifters located in the purple box at the end of July 2015 were backtracked to their position in March 2014 (Figure 8). This technique allowed us to identify potential sources of the 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. For windage values consistent with our previous analysis (i.e. 0.8%), however, results also show that the search area lies within the region with a 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 1.5º x 1.5º centered on Reunion Island (Figure 9), the possible sources of debris arriving to this island in July 2015 can be better delineated. Similar 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 showed that several regions in the Indian Ocean may account for the bulk of synthetic drifters that washed ashore on Reunion Island. However, the intersection of these maps with the Inmarsat arc clearly defines the search area as the region with a high probability of being the source of the debris.

Discussion and Conclusions

We present a methodology based on the use of surface drifters and synthetic drifters whose trajectories were obtained from the output of the SCUD model to describe the ocean's surface circulation and to assess the potential crash location of flight MH370 in March 2014. The debris trajectories are mainly affected by a combination of complex ocean circulation at different length scales and exposure of the debris to direct wind forcing, the latter being able to change due to, for example, 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 dataset has inhomogeneous spatial and temporal coverage, the output from the SCUD model that provided trajectories for thousands of synthetic drifters was also used. Different datasets accounted for the wide range of exposure to wind that the debris may have experienced, referred to as windage. The synthetic debris trajectories showed that for debris exposed more to the wind (i.e. higher windage factor), the probability notably increased for airplane debris that originated in the search area and that reached Reunion Island. This is consistent with the estimate of the most likely windage (0.8%) affecting the flaperon. Similar to the analysis performed on the surface drifters, the backtracked trajectories of synthetic drifters indicated 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. This analysis also provides information on potential

washing ashore locations and direct and indirect travel times obtained from using the two-iteration approach method.

(2) Analysis of backtracked historical and near-real-time drifter trajectories to establish the source of marine debris arriving in the region of interest. This procedure can include confirmed locations of debris, as well as prospective locations. The drifter data used in this and the previous stage are from the historical drifter archive and the Global Telecommunication System. The characteristics of the floating debris will determine whether drogued and/or undrogued drifter data are used as the source of the 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 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 that are inhomogeneous in space and time.

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

Historical surface drifter trajectories indicate debris that originated in the search region could have travelled to vast areas of the Indian Ocean, even reaching 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 crash of flight MH370 and when the airplane flaperon was found. Further statistical analysis of the historical surface drifter dataset, including a method that uses the crossover and dispersion of trajectories, supports the above finding of a clear westward pathway to longitudes of 60° E and beyond. Moreover, an examination of the locations where surface drifters ran 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 shows that a large percentage of these drifters 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 enhance our understanding of debris dynamics across a broad range of debris size and buoyancy, as well as enable us to assess the value of windage coefficients that may possibly change due to weathering and biofouling (Ryan 2015) that, in turn, may influence debris trajectories (Beron-Vera et al. 2015). Results presented emphasize the importance of real-time monitoring of surface currents that use 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 debris from flight MH370 was found during the summer and fall of 2014 along the west coast of Australia or later along the east coast of Madagascar.

We expect that future investigations will help to evaluate the performance of our methodology and the current state of the marine debris observing system. A 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 from the inclusion of both Stokes drift and wind-driven current shear. In our case, these effects were included in the SCUD coefficients, calibrated using real drifter trajectories. The errors in these coefficients will be reduced when quality controlled drifter data are reprocessed and improved, including the seasonality of the Lagrangian biases in some regions. Finally, this study also highlights the importance of sustained 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 existing drift models. Methodologies such as the one used herein, in which a suite of approaches was taken, could potentially improve future search strategies and general debris tracking assessments.

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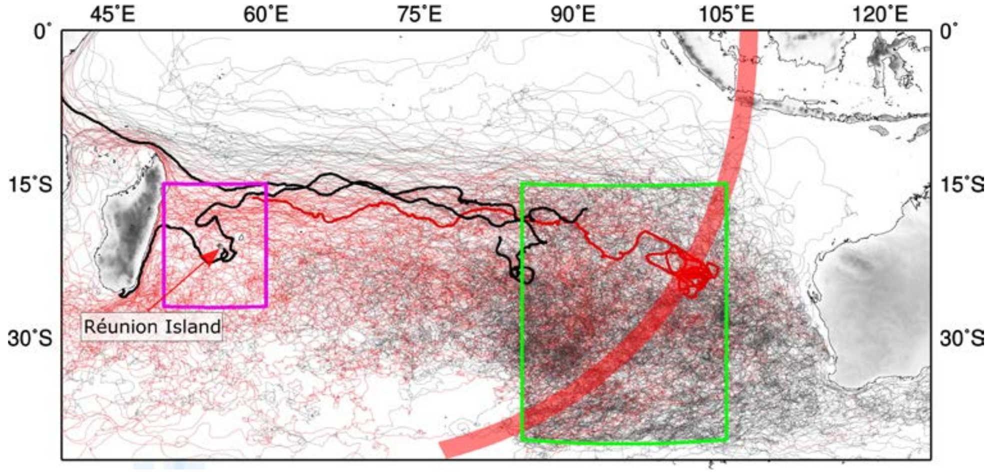

Figure 1. Trajectories of 368 undrogued surface drifters that were deployed or travelled in a large region (green box) encompassing the search area during 1985-2015 (black and red trajectories) and a subset of 97 drifters from that group (red trajectories) that eventually reached the purple box, which 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 in July 2015. The red arc shows the area corresponding with the possible location of the plane when its last signal to the Inmarsat satellite network was transmitted.

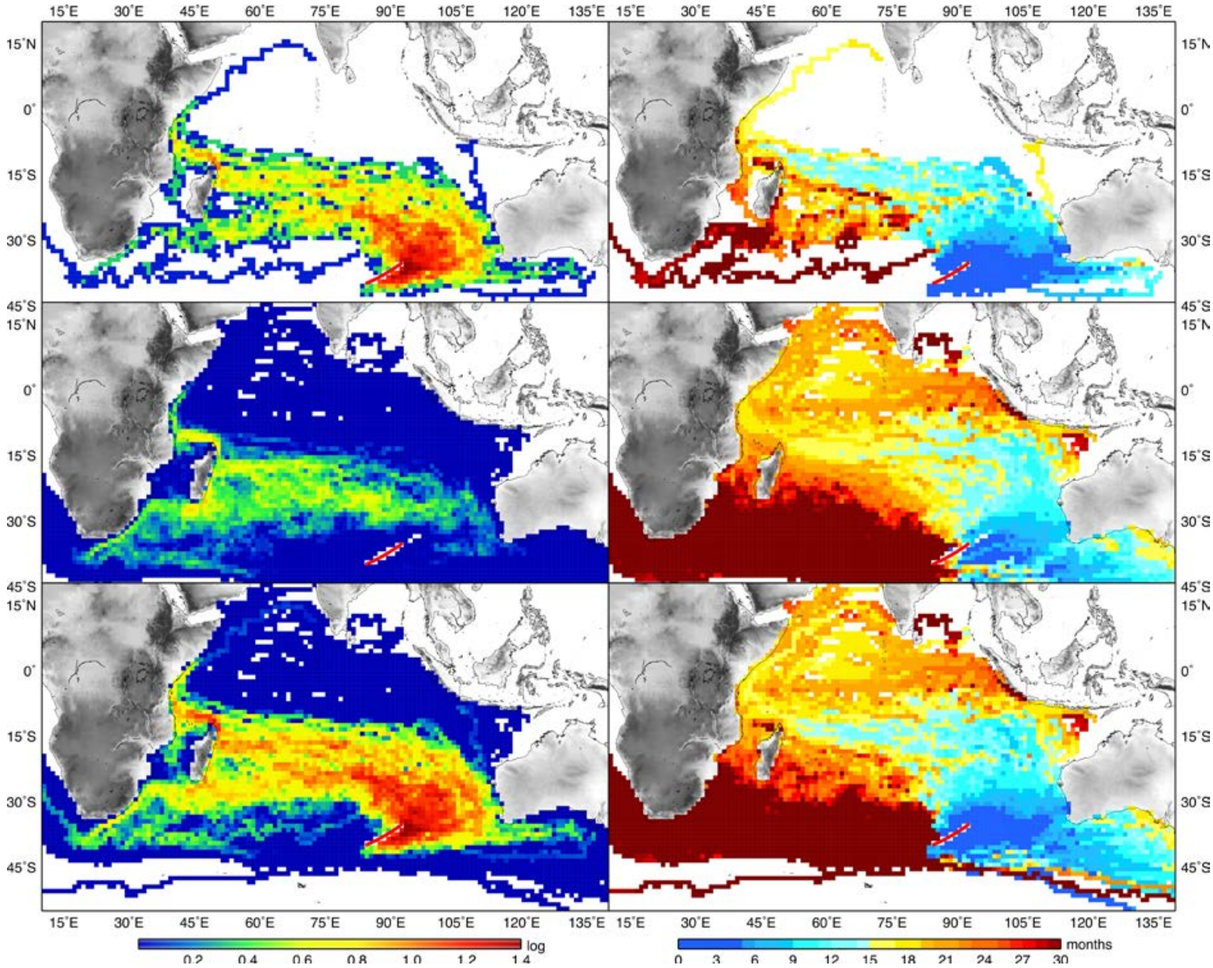

Figure 2. Probability fields (left) and travel time maps (right) estimated using the two-iteration approach (Rypina et al. 2013). The three rows refer to the direct (top), one-stop (middle), and total trajectories (bottom).

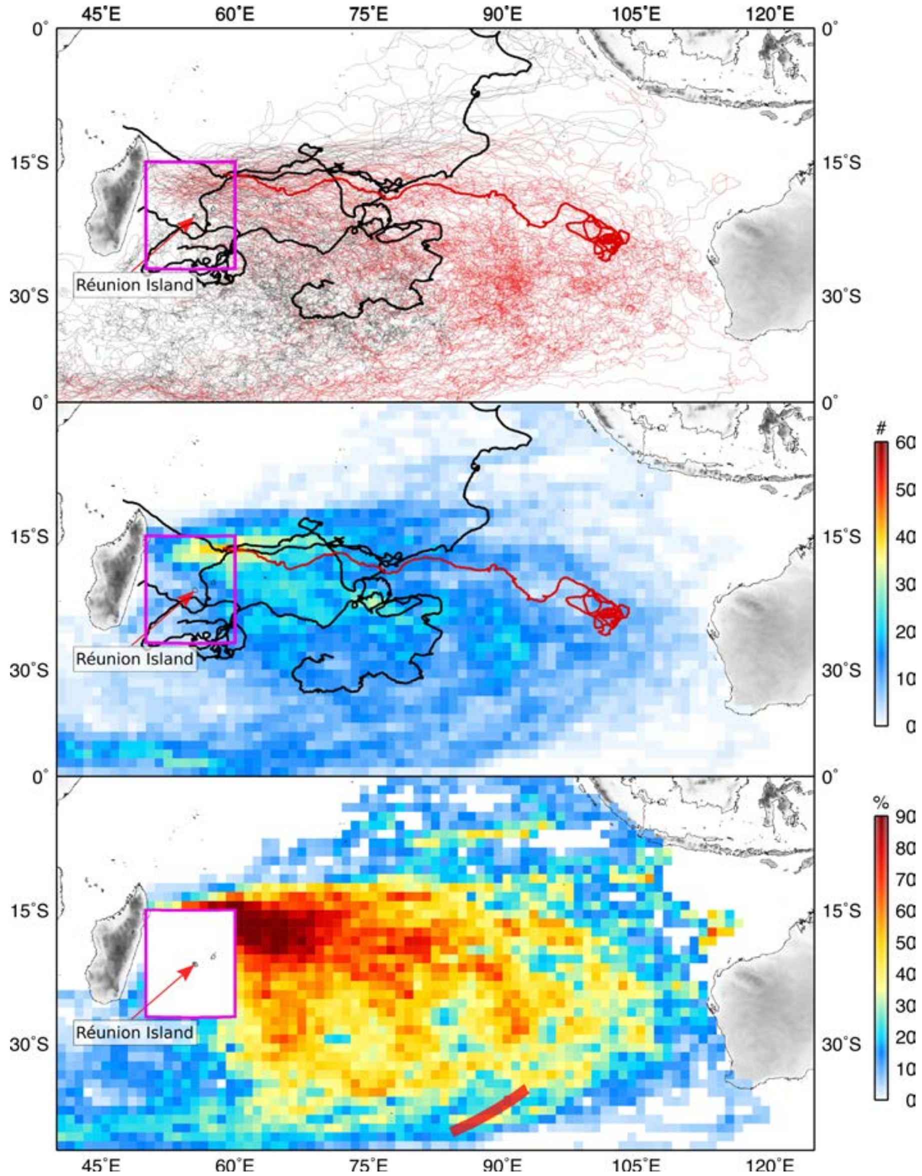

Figure 3. (top panel) Trajectories (black and red) of the 274 undrogued surface drifters that reached the purple box during 1985-2015. Of these 274 trajectories, 97 (black) correspond to drifters that first travelled in the green box before arriving in the purple box. Four trajectories (shown in thick black and red) entered inside the purple box between June-July 2015. Of these four trajectories, one corresponds to a 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° size that later travelled within the purple box. (bottom panel) Percentage of drifters that reached the purple box for each 1° box. There are many regions in the Indian Ocean where at least half of the drifters passing through arrived in the purple box.

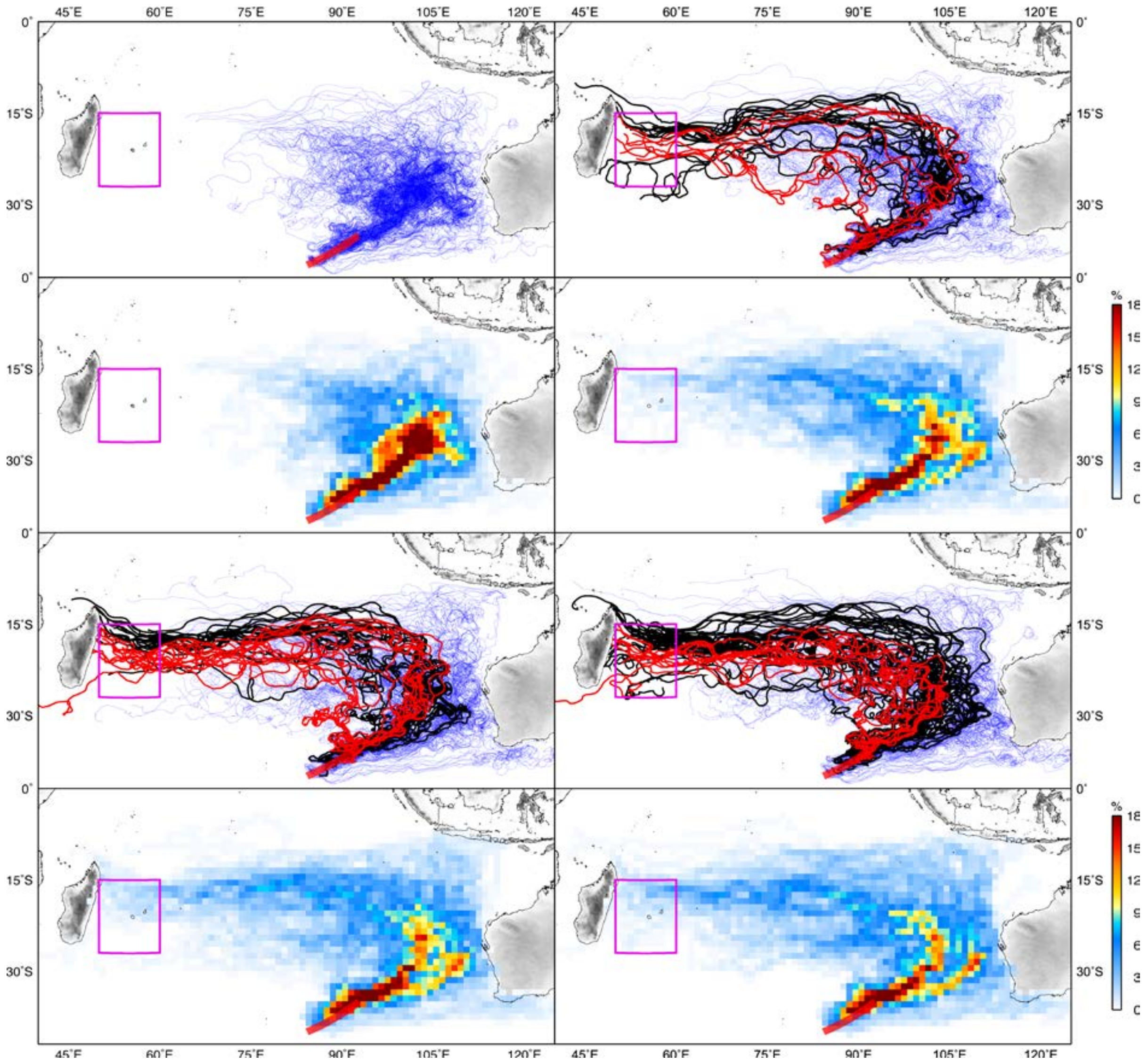

Figure 4. Trajectories of synthetic drifters deployed in the search area during March 2014 obtained using SCUD analysis for four different windage coefficients (from top to bottom and from left to right: 0%, 0.6%, 0.8%, and 1%) . The trajectories of the synthetic drifters that arrived in the purple box 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 at 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 1º x 1º cell.

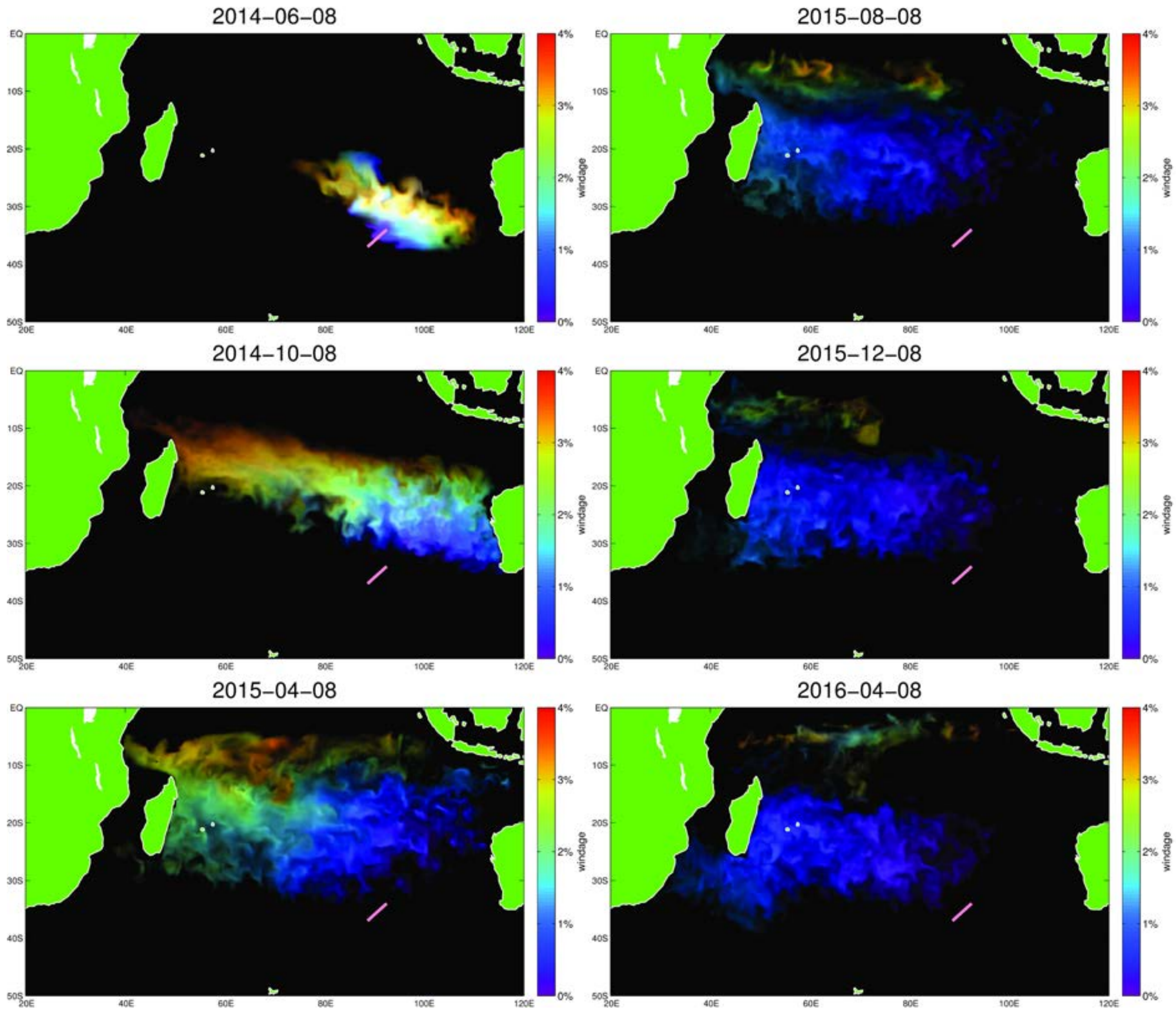

Figure 5. Bi-monthly maps of the SCUD model solution for a mixture of tracers with windage parameters ranging from 0-4%. An equal number of tracers for each windage value was released in the model on 8 March 2014 at the location marked with a pink line. Different colors represent different windages: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

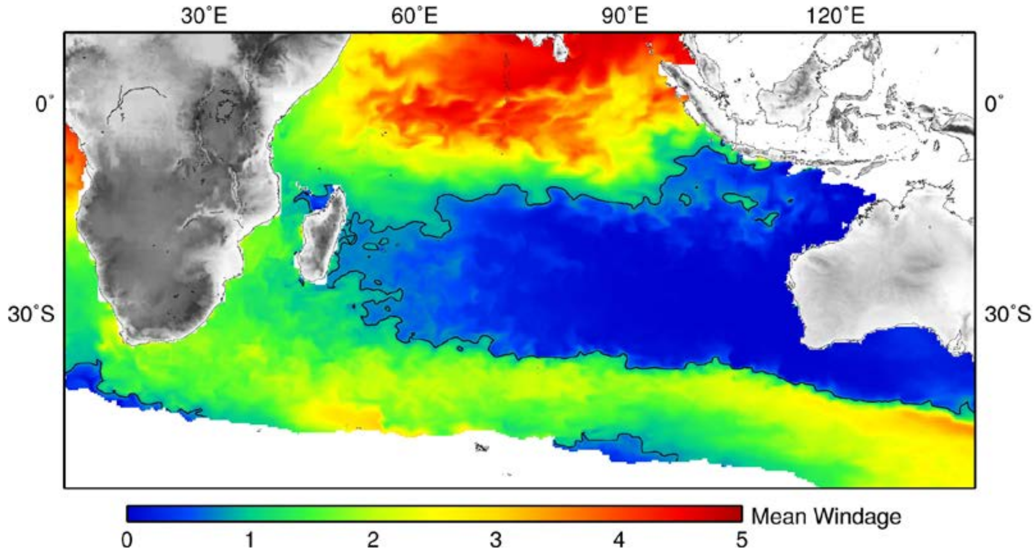

Figure 6. Map of the mean windage, calculated using Equation (1) in a multi-windage model solution, shown in Fig. 5. The black contour denotes the 0.8% windage isoline.

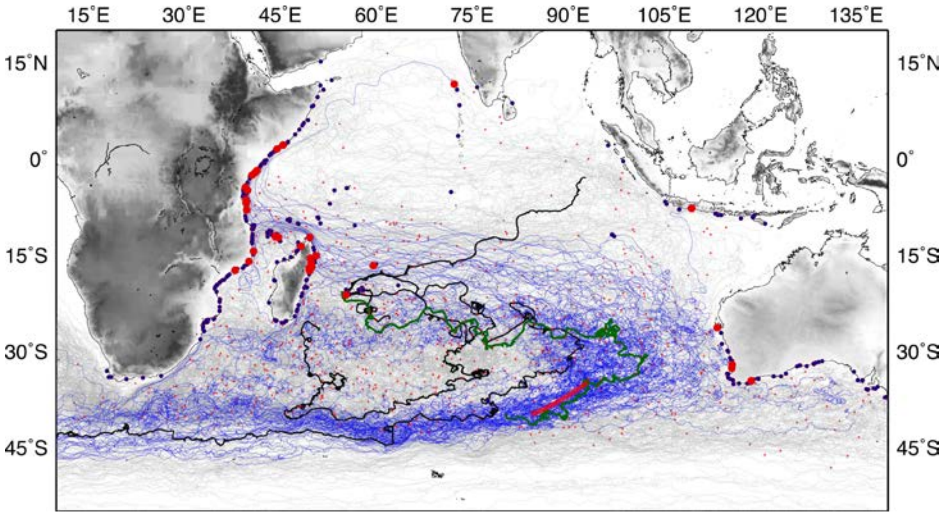

Figure 7. Trajectories of undrogued surface drifters from the historical dataset. The blue trajectories correspond to drifters washing ashore (otherwise the gray color is used). The small red dots represent the location of their latest transmission. The larger circles refer to drifters reaching land: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

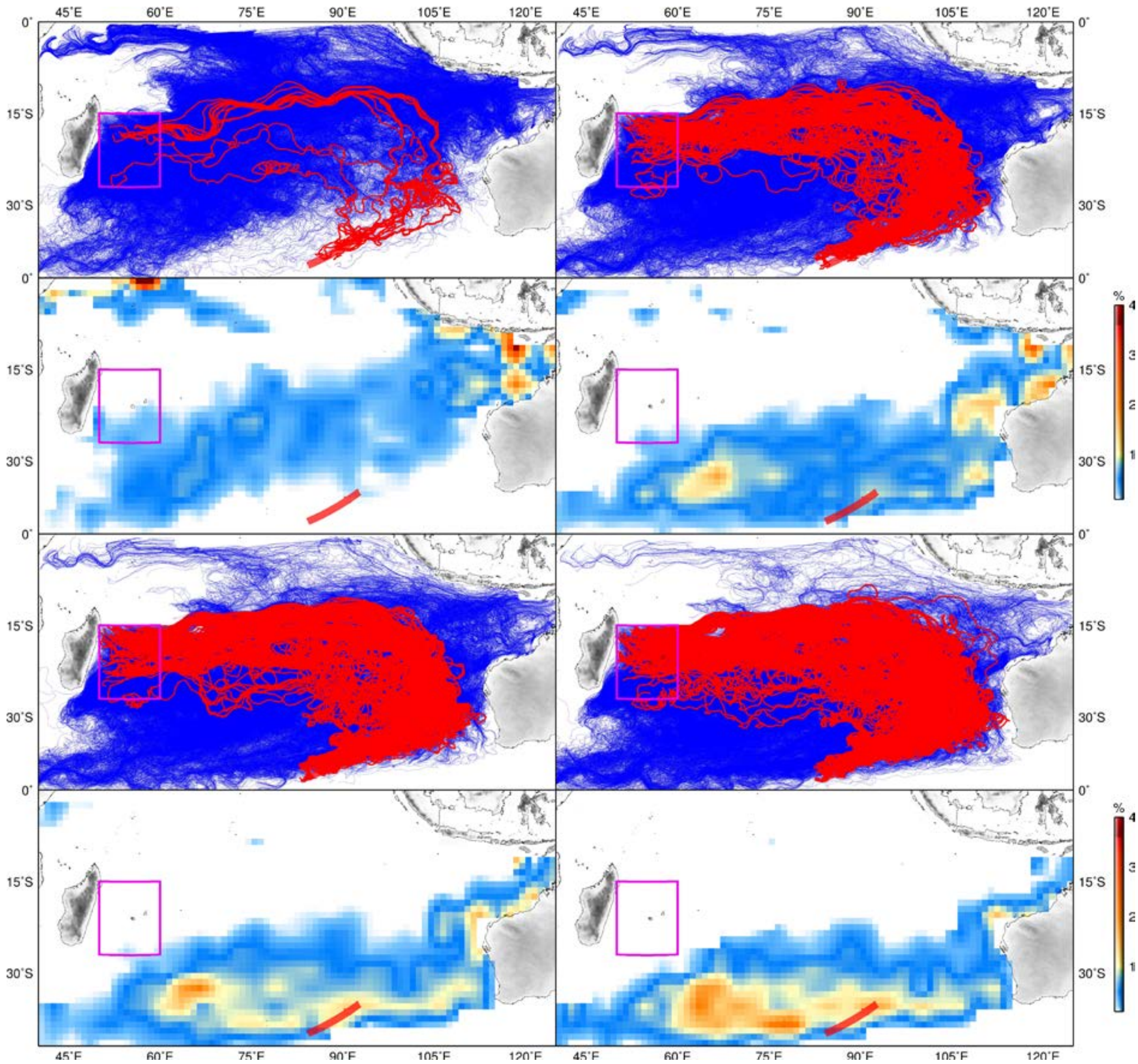

Figure 8. Backtracked trajectories of synthetic drifters that reached the region around Reunion Island (purple box) at the end of July 2014. These figures were constructed using a SCUD analysis for four different windage coefficients (from top to bottom and from left to right: 0%, 0.6%, 0.8%, and 1%). The red trajectories correspond with 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 flight MH370 disappeared.

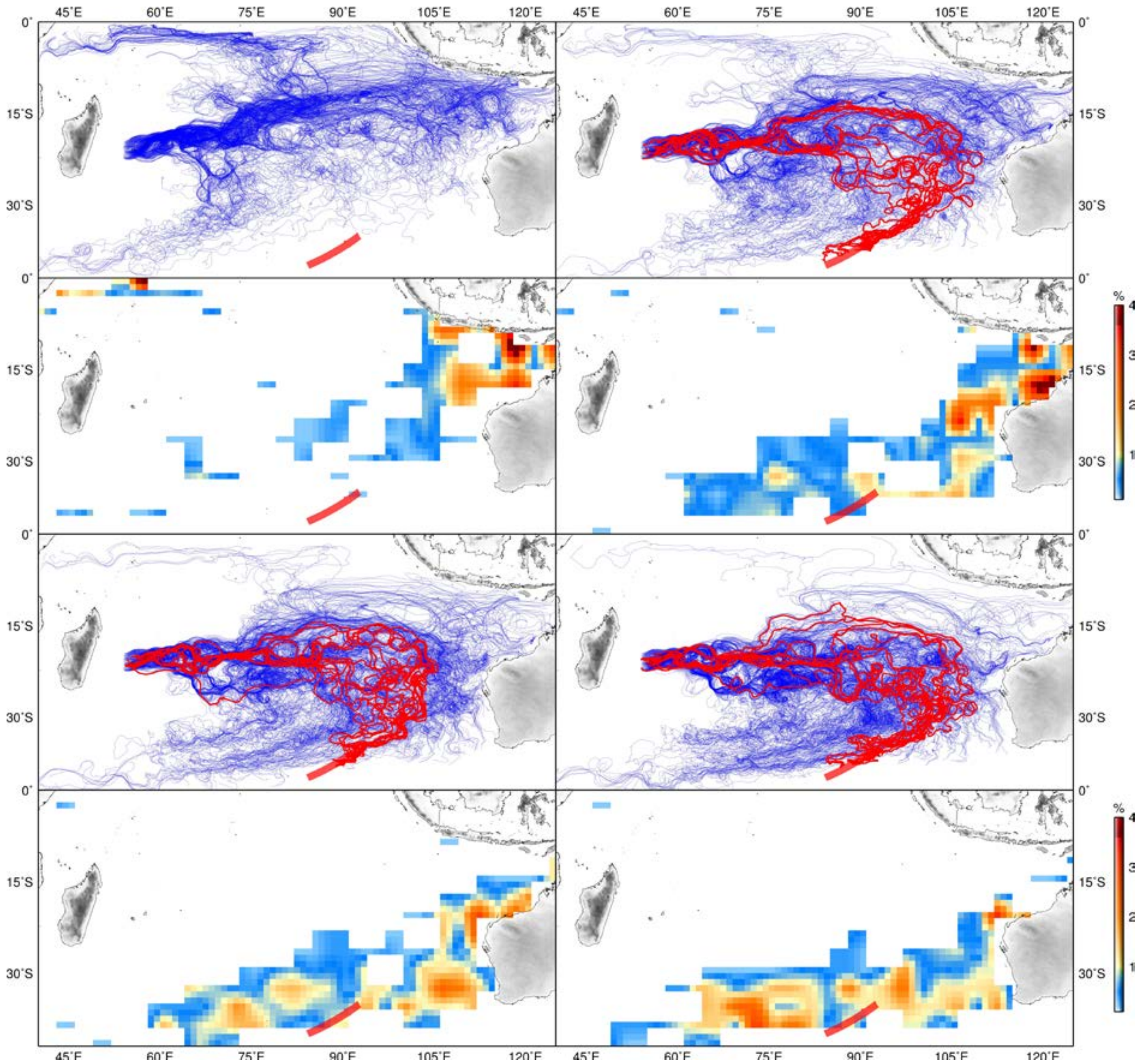

Figure 9. Backtracked trajectories of synthetic drifters that reached a small region surrounding Reunion Island at the end of July 2014 obtained from a SCUD analysis for four different windage coefficients (from top to bottom and from left to right: 0%, 0.6%, 0.8%, and 1%). The red trajectories correspond with the synthetic drifters that at the time of the disappearance of flight MH370 were within 100 km of 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 1º x 1º cell.

Table 1. Summary of debris found to date that has been confirmed (or almost certainly confirmed) as being from flight MH370.

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

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