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

Joaquin A. Trinanesa,b,c, M. Josefina Olascoagad, Gustavo J. Gonia\*, Nikolai A. Maximenkoe, David A. Griffinf  and Jan Hafnere

aPhysical Oceanography Division, Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL 33149, USA;

bCooperative Institute for Marine and Atmospheric Studies, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL 33149, USA;

cInstituto de Investigaciones Tecnoloxicas, Universidade de Santiago de Compostela, Santiago, 15782, Spain;

dDepartment of Ocean Sciences, Rosenstiel School of Marine and Atmospheric Sciences, University of Miami, Miami, FL 33149, USA;

e International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii, Honolulu, HI 96822, USA;

fCSIRO Oceans and Atmosphere, Hobart, GPO Box 1538 Australia

\*Correspondence to: [Gustavo.Goni@noaa.gov](mailto:Gustavo.Goni@noaa.gov)

*To be submitted to Journal of Operational Oceanography*

May 3, 2016

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

Joaquin A. Trinanes, M. Josefina Olascoaga, Gustavo J. Goni, Nikolai A. Maximenko, Jan Hafner and David A. Griffin

**Summary**

Flight MH370 disappeared in March 2014. Potential location sites of the plane entering the water are being considered within a vast region in 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 correspond to the historical data set of surface drifters that were deployed and/or traveled in the Indian Ocean. These data allow to assess historical trajectories and to identify those drifters that have run ashore 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 bounded 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 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 in 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. We also provide the estimated travel time and probable ashore positions of the plane debris given by the analysis of the historical dataset. The recent discovery in Mozambique of new debris from MH370 and the possible presence of parts of the plane in Mossel Bay (South Africa) are consistent with results presented here and confirm 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, a 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). No debris from the missing airplane has been found in the search area. However, on 31 July 2015, a plane flaperon was found washing up on the shores of Reunion Island, located in the western side of the southern Indian Ocean (SIO). More recently, there were other discoveries linked to the missing plane, in Mozambique, South Africa and Rodrigues Island. The two panels found in Mozambique in Dec 2015 and Feb 2016 have been found consistent with parts of the missing aircraft and are certainly from MH370. Up to this date, no results have been released from the pieces found in South Africa and Rodrigues Island.

***Large Scale Ocean Dynamics in the Indian Ocean***

The search and efforts following the debris discovery led to the analysis of the complex Lagrangian (i.e., of material) ocean circulation capable of connecting distant locations in the SIO. The surface ocean circulation in this region is sustained by a system of major ocean currents that exhibit high seasonal and year-to-year large scale variability, that 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 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, their associated eddy field, which together with the wind field and 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 new and key information on the potential crash site of flight MH370 in the SIO. This study uses two main data sets that are frequently 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 turn into the so-called an 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 surface gravity waves. The average drifter loses the 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 SCUD-Surface Currents from Diagnostic Model (Maximenko and Hafner 2010), that incorporates hydrographic, satellite altimetry, and wind data. The spatial resolution of these velocity fields is of one quarter of a degree and fields are provided on a daily basis. The trajectories of surface and synthetic drifters are used in this study to simulate the displacement in the surface of the SIO of debris that could have potentially belonged to flight MH370.

**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.

***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 generally follow the general circulation of the South Indian Ocean subtropical gyre. Of these 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.

**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).

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 travelled 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 them. These direct trajectories follow a general pattern that includes part of the West Australian Current, and a 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, in 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 improve the coverage, also allows to expand the temporal coverage over periods larger than the lifespan of an average drifter. 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 neighborhood 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 south westwards, 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 to reach the major coastal areas in the Indian Ocean from the search area varies 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.

**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 boxes. There are many regions in the Indian Ocean where at least half of the drifters passing through arrive at the purple box.

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, and areas of the center of the South Indian Ocean 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 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. Other important constraint is determined by the drifter lifetime once the drogue is lost, and that can affect the overall estimates as this factor can significantly change the probability of getting near Reunion Island. The use of indirect trajectories (see above) allows to overcome this limitation.

**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 (a,b,c,d). The trajectories of the synthetic drifters that arrived in the purple box are highlighted in red and black. The trajectories in red correspond to drifters with locations within a radius of 150km centered in Reunion Island. The background colors indicate the percentage of synthetic drifters initially deployed within the search area that travelled in each square box of 1 degree side. Each panel represents a different windage coefficient (from top to bottom and from left to right: 0%, 0.6%, 0.8% and 1%).

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 air friction. High windage values generally correspond for situations where most of the object is above the sea surface. This factor indicates that 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 debris under in this study, the windage coefficient can be variable as the buoyancy decreases over time, and approaches to 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 100km 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 that 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 those 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. Low-windage tracer (blue) was not just drifting slower after reaching Madagascar in 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 happened elsewhere. Other 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:

<Windage(x,y)>= (Windage\*C(x,y,Windage))/(C(x,y,Windage)),

where C(x,y,Windage) is the tracer concentration at location (x,y) for a given windage. The “probable” windage of the flaperon <Windage(x,y)> was estimated close to 0.8%. This calculation, in which tracer concentration was interpreted as a probability density function for a particle movement, demonstrates that by July 2015 majority of high-windage debris has been already 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 (and also references media reports from South Africa and Rodrigues Island).

**Figure 5.** Maps of model solution for multi-windage tracer. Color indicates windage; brightness corresponds to concentration and adjusted to maintain vivid colors. Pink line marks the release location on March 8, 2014.

**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.

Results obtained from this numerical experiment show that debris may wash up in various regions. In the eastern Indian Ocean, some locations in 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 would expand the list of coastal areas in countries where debris could have potentially washed on ground to include those in the east coast of the African continent. These results are confirmed by the analysis of the historical dataset from the Global Drifter Program (Figure 7). The distribution of the landings by country is shown in Table1. 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 50km 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 with also high probability values of having been reached by debris.

**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 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.

|  |  |  |
| --- | --- | --- |
| 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 1.** 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.

**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 and have the same windage coefficients used to construct Figure 4. Each panel represents a different windage coefficient (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 represent the percentage of the synthetic drifters at the time that MH370 disappeared.

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 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 in Reunion Island (Figure 9), the possible sources of debris arriving to the 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 of high probability as source of the debris.

**Figure 9**. Backtrack trajectories of synthetic drifters that reached a small region surrounding Reunion Island at the end of July 2014 obtained from SCUD analysis using the same windage coefficients of Figure 4. 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 represent the percentage of the synthetic drifters at that time in each 1ºx1º cell.

***Discussion and Conclusions***

We present here a methodology based on the use of surface drifters and on the output of the SCUD model to describe 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 force, 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 of 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 the trajectory 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 as to 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) Backward analysis of 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 source of in situ data.

3) A similar procedure to the first step is implemented, using 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 improve the coverage and reduce the bias caused by in situ drifter data, with deployments and observations inhomogeneous in space and time.

4) The synthetic drifters are backtracked in time 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 drifters trajectories indicate that debris that originated in the search region could have travelled to vast areas of the Indian Ocean to even reach the coast 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 in the eastern coast of Africa, Madagascar, and Reunion Island. An analysis of the historical trajectories of surface drifters that arrive 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 also 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 reported in Summer-Fall 2014 from 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 can be used to monitor the movement of debris under different windage coefficients, time-varying buoyancy conditions, and within an operational framework. It also should include small-scale motion (submesoscale to smaller mesoscale) that is present in the real ocean.  It must also take into account the Stokes drift and the wind-driven current shear. 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 proposed here, 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. This work was led by G. Goni, who was funded by NOAA/AOML. J. Trinanes was funded by NOAA/OceanWatch and 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.