Backtracking of the MH370 flaperon from La Réunion

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Summary

This report outlines how the discovery of the MH370 flaperon on La Réunion in July 2015 could help the current search effort for the missing aircraft. The drift of millions of virtual flaperons under the influence of ocean currents and waves were simulated using the most accurate model data available. Under the most common scenario in which the flaperon would originate close to the 7th Arc on 8-9 March 2014 (when the aircraft was lost), the area of high probability for the aircraft crash site is found to be in a region around the arc north of the current priority search area. Recently, several other pieces of debris, some confirmed to belong to MH370, have been collected around the coasts of Mozambique, South Africa, and Mauritius. Unless specific information regarding when these objects made landfall become available, considering these objects will not help to further refine the analysis. However, that the debris were found in the southwestern Indian Ocean does corroborate the results presented here, especially given the general oceanic circulation of the region.

Introduction

On 8 March 2014 Malaysian Airlines flight 370 (MH370) disappeared on its way from Kuala Lumpur, Malaysia to Beijing, China with 239 people on board. Initial analyses from radar and other communication pointed to a deviation of the planned flight path towards a southern route in the Indian Ocean. Detailed analysis of satellite communication, provided in the form of handshakes between engines and satellite, indicated that the plane had last contact along the '7th arc' around the position of the satellite, ranging from Java, Indonesia, to the southern Indian Ocean, southwest of Australia. In the following months, the Joint Agency Coordination Centre (JACC [1]), led by the Australian government, started the search for MH370. Underwater search is on-going with bathymetric surveys by various vessels [2]. Since December 2015, the search has been focussed within a narrow swath along ~700 km of the 7th arc, between 35°S and 40°S[3].

Following the discovery on 29 July 2015 and subsequent identification of a flaperon from the MH370 on the French Indian Ocean island of La Réunion, there has been renewed interest in elucidating the mystery of the disappearance of the MH370 aircraft 16 months earlier. Two questions are of particular interest:

1. Can ocean currents explain a drift of the flaperon from the southeastern Indian Ocean towards La Réunion?
2. If so, how can this information help the search for the missing plane?

Pathways of objects passively transported by ocean currents can be described in a Lagrangian perspective. In this frame of reference, an object starting at a given position and time is moved from that position either forward or backward in time using the velocity description of the ocean currents for each time step. The Global Drifter Program[4] maintains an array of satellite-tracked surface drifting buoys providing information on (near) surface temperature, salinity, winds, atmospheric pressure, and ocean currents. While such observations are invaluable, they are not homogenously available in sufficiently large numbers to provide statistically robust information for operational purposes or estimating the drift of specific items. Surface drifters typically use drogues to represent ocean currents at 15 m depth and deeper; this differs from the surface drift in angle and magnitude. In contrast, after losing their drogues, drifters are prone to additional wind fetch (Poulain et al., 2009). We have therefore opted to use an ocean model to simulate potential pathways that the flaperon could have taken on its way to La Réunion.

[1] http://jacc.gov.au

[2] https://www.atsb.gov.au/media/5668327/ae2014054_mh370__search_areas_30jul2015.pdf

[3] http://jacc.gov.au/media/reports/2015/december/files/AE-2014-054_MH370-Definition_of_Underwater_Search_Areas_3Dec2015_update.pdf

[4] http://www.aoml.noaa.gov/phod/dac/gdp_objectives.php

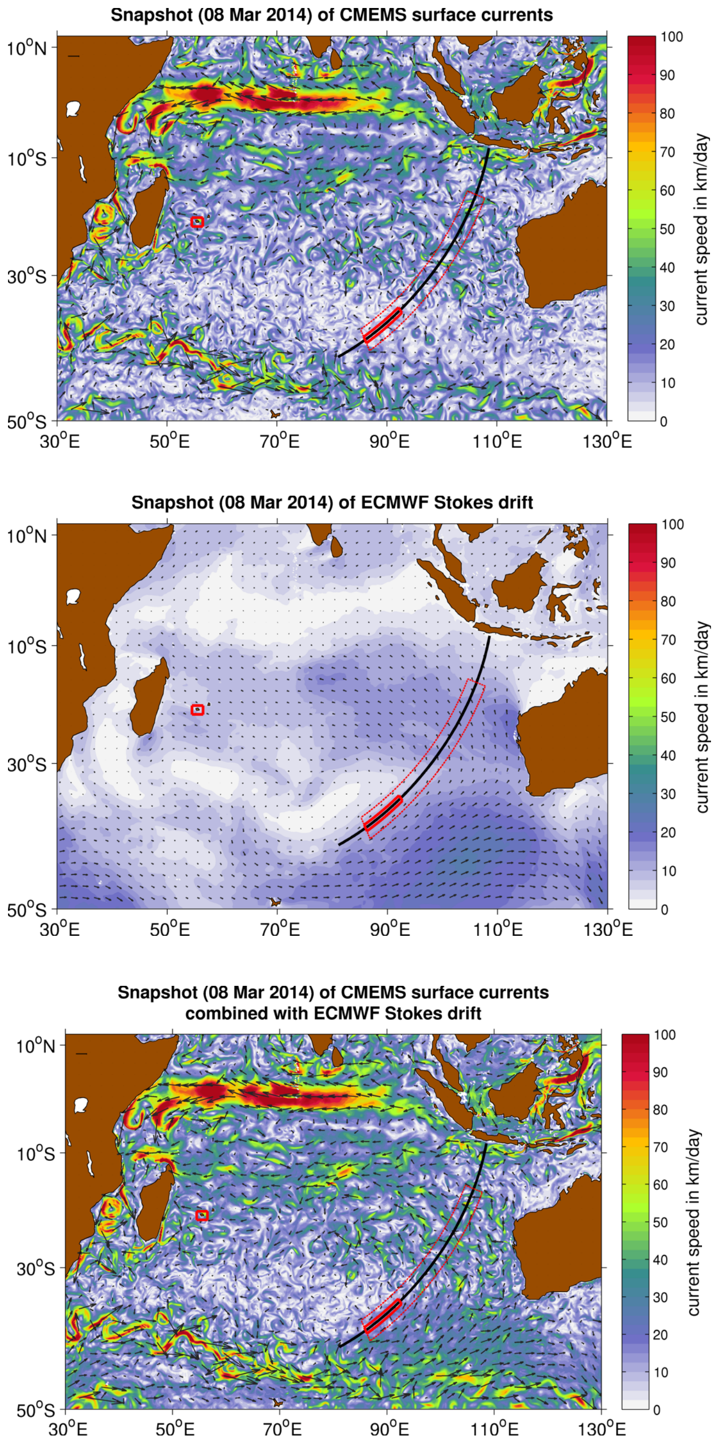

Figure 1: Snapshot for 8 March 2014, on the day MH370 went missing, of surface currents from the *Copernicus Marine Environment Monitoring Service*, upper row), Stokes drift (*European Centre for Medium-Range Weather Forecasts*, middle row), and combination of both (lower row). Shown are direction (arrows shown every 2°) and speed (colour shading in km/day). The black arc indicates the possible location of the aircraft in the eastern Indian Ocean during its last successful automated satellite contact on 8 March 2014 (7^{th} arc). The red dashed framed area marks the wide underwater search area obtained from engine fuel consumption considerations (meridional extent defined in Table 2 of footnote 2); the red solid framed area indicates the current (defined December 2015) priority search area[3]. The island of La Réunion is highlighted by a small red square box.

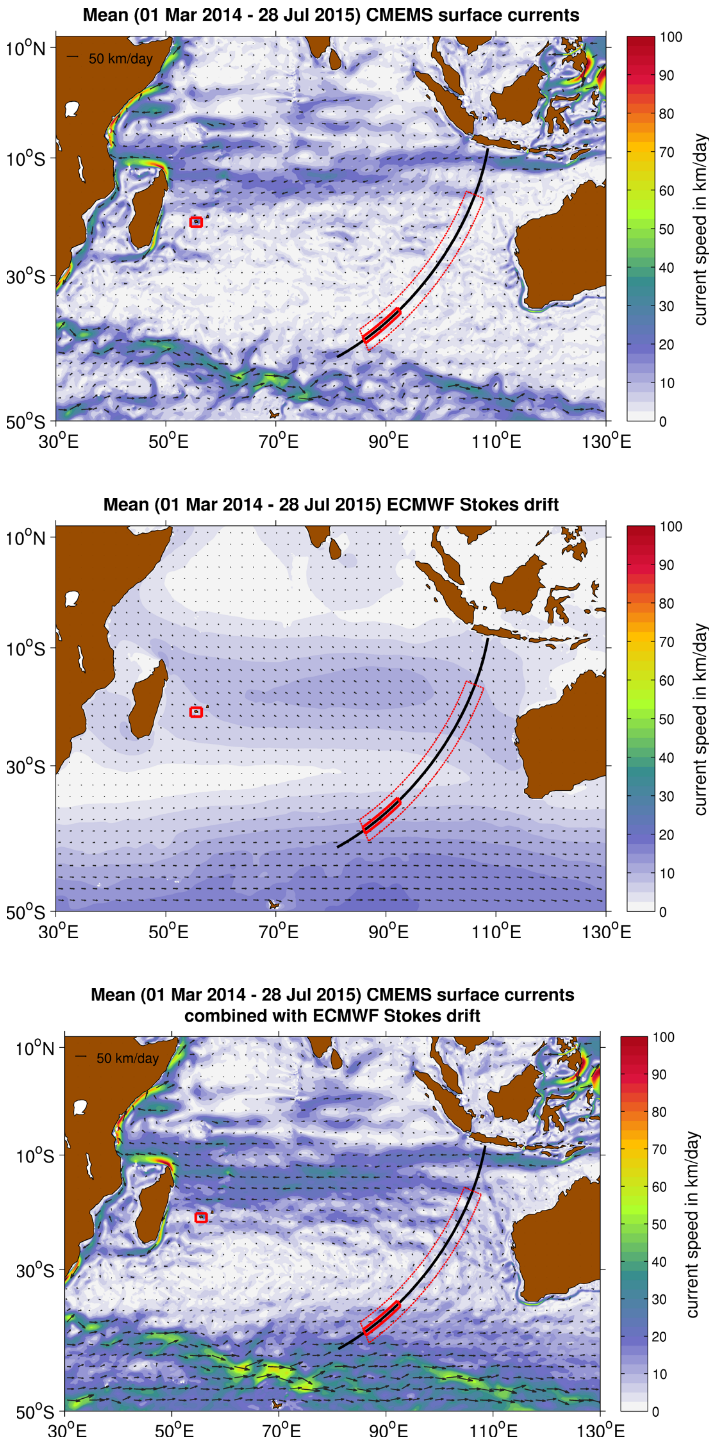

Figure 2: As Figure 1 but as average for the period 1 March 2014 – 28 July 2015

The simulation of pathways within an ocean model is common practice. Ocean models provide coherent descriptions of the flow within which trajectories can be simulated. Such analyses have been previously performed to trace pathways of water masses (Biastoch et al., 2009; Durgadoo et al., 2013), as well as immotile organisms, such as glass eels (Baltazar-Soares et al., 2014) and foraminifera (van Sebille et al., 2015). Typically, such studies are performed using data from ocean models forced by realistic atmospheric fields of the past decades. However, a reliable backtracking of MH370's flaperon requires more up-to-date velocities that cover the period from March 2014 to July 2015.

The flaperon is approximately ~2–3 m long, 1 m wide and perhaps 0.2–0.3 m thick (see photographs[4]). We assume here that it floated horizontally on the surface. It will therefore not simply be advected by the ocean currents in the uppermost 0.2–0.3 m but will also be affected by wind and wave processes. We assume the direct wind stress on the flaperon to be negligible due to its horizontal alignment and low freeboard[5,6]. However, the Lagrangian motion driven by the waves, the 'Stokes drift', cannot be neglected (Röhrs et al., 2012). Stokes drift occurs in the direction of wave propagation as a direct consequence of actual and past wind conditions. Details depend on wave characteristics such as wave height and length, and fetch, hence its estimation requires a wave model.

Data and Methods

In order to determine the origin of the flaperon discovered on La Réunion, it is clear that an accurate and reliable description of surface ocean currents and Stokes drift are required for the period March 2014 – July 2015. The surface currents obtained from the Copernicus Marine Service[7] operational model (produced by Mercator Océan[8]) are combined with simulated Stokes drift to fulfil these requirements.

The starting point is a 1/12° global ocean/sea-ice model, ORCA12, which is based on the NEMO code (Madec, 2012) within the European modelling initiative DRAKKAR[9] (Deshayes et al., 2013), which includes the institutions authoring this report. It covers the global ocean at 1/12° nominal resolution (~9 km grid size in the Indian Ocean) and 50 levels in the vertical, with a surface layer 1 m thick. It is forced by 3-hourly European Centre for Medium-Range Weather Forecasts (ECMWF) operational winds and corresponding heat and freshwater fluxes. Apart from the actual forcing, the operational character comes in through the assimilation of observational data. Using a Kalman filter with SEEK formulation (SAM2v1) and bias correction (3D-Var) with incremental analysis update, a range of satellite and *in-situ* data are used to update and correct the simulated ocean state (Lellouche et al., 2013). In particular, the use of sea surface temperature and sea surface height from satellites provide an accurate description of the upper-ocean hydrography and velocity. Here we use daily average velocities for the period 1 March 2014 to 28 July 2015 from the

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[5] http://jeffwise.net/2015/10/09/the-flaperon-flotation-riddle/

[6] http://www.lemonde.fr/asie-pacifique/article/2015/09/04/le-flaperon-retrouve-a-la-reunion-appartient-bien-au-boeing-777-du-vol-mh370_4746144_3216.html

[7] http://marine.copernicus.eu

[8] www.mercator-ocean.fr

[9] http://www.drakkar-ocean.eu

Copernicus Marine Environment Monitoring Service (CMEMS) global ocean 1/12º physics analysis and forecast model[10] in its most accurate delayed mode.

Data for the wave effect were taken from the ECMWF High RESolution WAve Model (HRES-WAM; ECMWF, 2014) which explicitly simulates the Stokes drift (Breivik et al., 2014). Using an atmospheric forcing consistent with what was used by the Copernicus Marine Service global ocean 1/12º physics analysis and forecast model, the wave model is simulated at global 1/4° resolution. Here we interpolated daily-mean velocities from the ECMWF Stokes drift onto the ORCA12 grid and combined these with the ocean model velocities.

Figure 1 and Figure 2 show current speeds and velocity vectors from the Copernicus Marine Service and ECMWF operational models, as a snapshot to illustrate the temporal variability (08-03-2014), and averaged over the complete period (01 March 2014 to 28 July 2015), respectively. On average the direction of ocean currents, excluding Stokes drift, (upper rows) south of the equator is westward, with the broad South Equatorial Current (SEC) at around 10°S and a more sluggish flow in the subtropical gyre south of it. Stokes drift (middle rows) adds a northwestward, anticlockwise component, which is a direct result of the prevailing southeast trade winds in the southern Indian Ocean. The resulting combined velocities (bottom rows) are particularly important in regions where the background ocean currents are weak, for example in the subtropical gyre off Australia.

A rough estimation shows that the general orientation of the velocities can already explain a drift across the Indian Ocean within the given time period: their magnitude in the order of 0.18 m/s (15 km/day) can easily explain the drift between the eastern Indian Ocean and the island of La Réunion ~6000 km away within ~1 year. However, currents in the Indian Ocean feature (as all other regions of the world ocean) a strong stochastic component, with mesoscale eddies varying in direction and speed on the order of days to months (Chelton et al., 2011). In addition, as a result of the Monsoon circulation, the northern and equatorial Indian Ocean seasonally reverses its surface flows (Schott et al., 2009).

Lagrangian experiments were performed on a NEC high-performance computer at Kiel University using the Ariane[11] software (Blanke et al., 1999). Ariane is designed to carefully consider the ORCA12 grid layout and is widely used at GEOMAR for the spreading of water masses and biological objects (Baltazar-Soares et al., 2014; Biastoch et al., 2009; Durgadoo et al., 2013). Owing to the accurate calculation of streamlines, the code can effectively simulate several millions of trajectories over the desired time period within a few hours of computing time.

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[10] http://marine.copernicus.eu/web/69-interactive-catalogue.php?option=com_csw&view=details&product_id=GLOBAL_ANALYSIS_FORECAST_PHYS_001_002

[11] http://www.univ-brest.fr/lpo/ariane

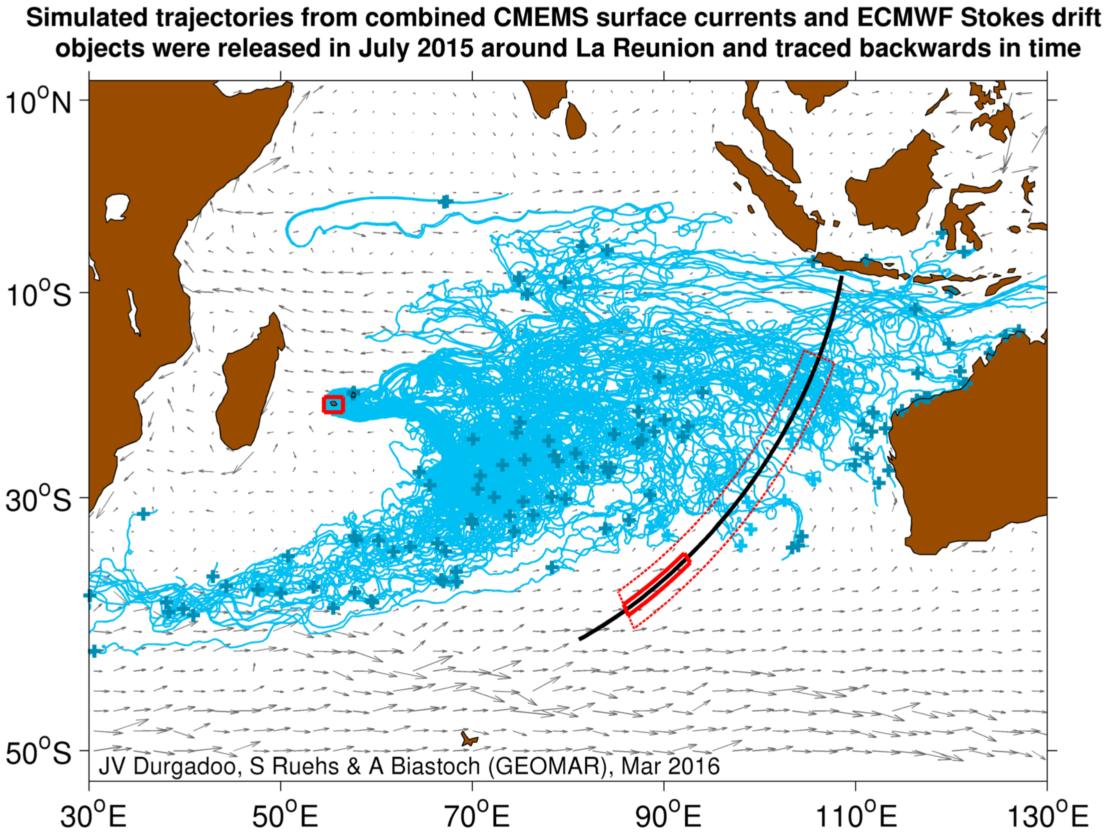

Figure 3: Example of object trajectories starting from La Réunion (red box) in July 2015 and calculated backwards until March 2014. Object positions on 8 March 2014 are highlighted with a +. The 7th arc, wide and priority search areas are overlaid.

The flaperon was modelled as a dimensionless passively floating object. From the anatomy of the 2m-long flaperon, it is safe to assume that it would have been partially submerged and that its drift would be under the influence of surface currents. The flaperon was discovered at St André, north east of the island on 29 July 2015. It is not known how long it had been on the island before its discovery, or how long it had been drifting in the close vicinity of the island before being washed ashore. For this reason, and owing to the turbulent nature of the ocean, which adds an element of chaos (Figure 1), back-tracking a single object from La Réunion will not provide robust information. To account for such uncertainties, "virtual" flaperons (henceforth objects) were released into the Lagrangian software uniformly around La Réunion at a fixed depth of 0.5 m in a 2º x 1.5º box (54.5ºE–56.5ºE; 22ºS–20.5ºS) every hour over the period 1–28 July 2015. In total, more than 5 million objects were used. Each object was back-tracked until 1 March 2014 using the daily mean velocity field.

Figure 3 shows the trajectories of selected objects, with their positions on 8 March 2014 highlighted. The turbulent nature of the ocean is evident; some objects take large detours, others undertake multiple circular paths. It is clear that the possible origin of an object can span a large area.

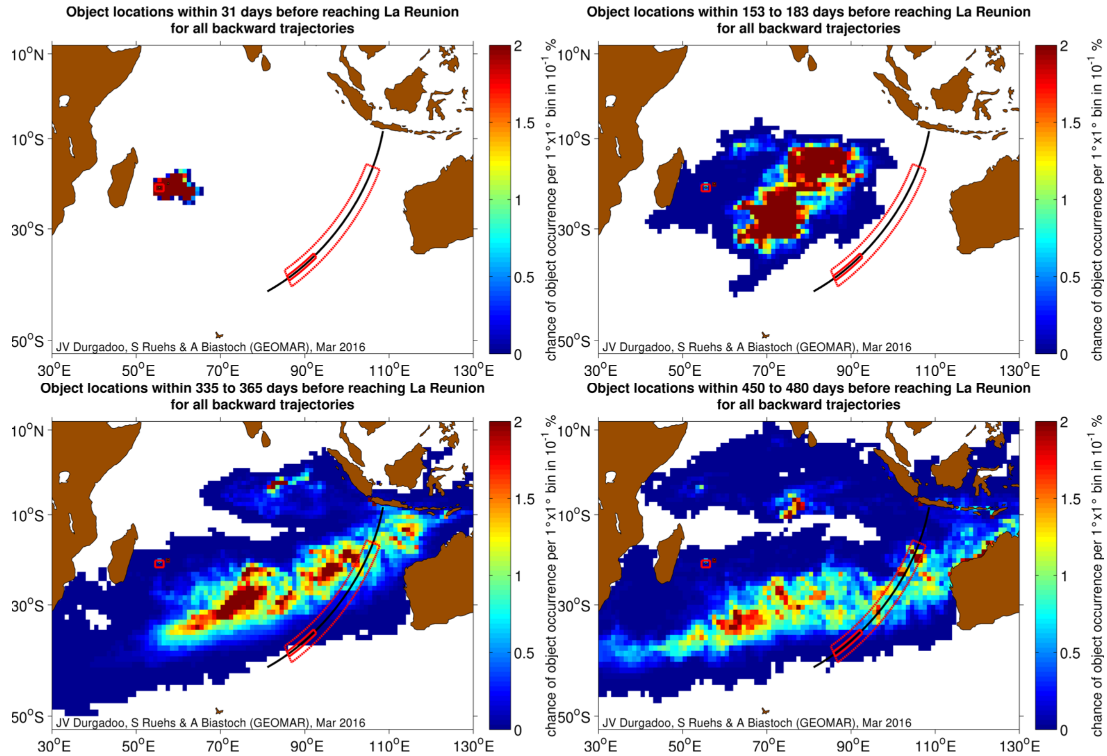

Figure 4: Object locations within different periods before reaching La Réunion (red box). The colour shading shows the object location counts per 1° x 1° bin, divided by the total amount of object location counts in the whole Indian Ocean domain during the respective time period in %. It indicates the chance of objects occupying a particular bin; the values of all bins sum up to 100 %. The 7th arc, wide and priority search areas are overlaid.

To statistically represent the trajectories, daily objects' locations were binned and counted on a 1º x 1º grid for various time periods. A high count within a bin indicates many objects crossing the bin during the particular period and/or few objects occupying the bin for more than one day (e.g. slow crossing velocities, looping within the bin, or larger re-circulations). Subsequently, for each bin, the count was divided by the total amount of object location counts in the whole study domain during the particular time period. Effectively, for a particular bin the higher the ratio (expressed as percentage), the more likely it is that objects occupied it. The values of all bins sum up to 100 %.

Results

The outcome of the backtracking exercise shows objects spreading from the southern and southeastern Indian Ocean towards La Réunion (Figure 4). Ocean currents are primarily responsible for the propagation within the equatorial current system and in the northern

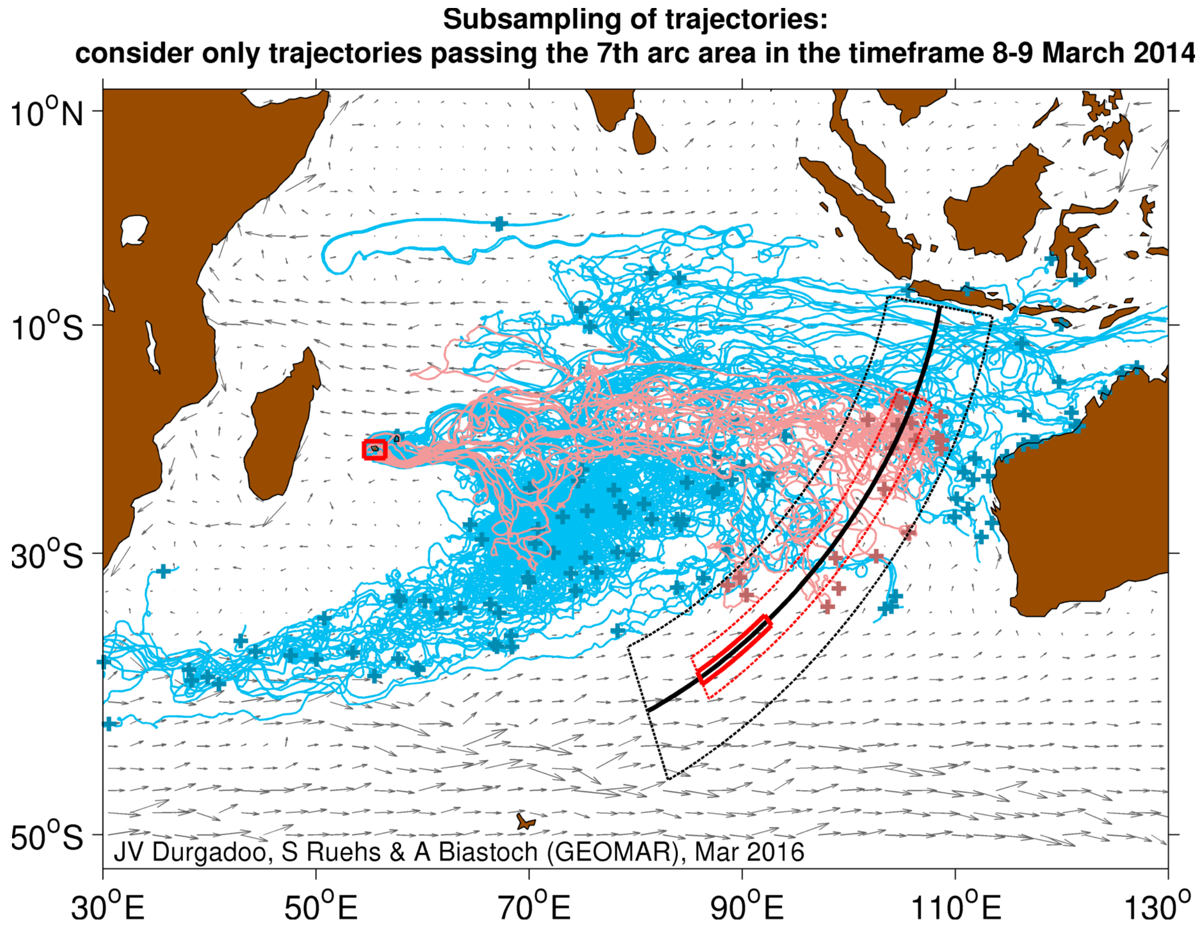

Figure 5: As Figure 3 but with highlighted (red colour) trajectories of those objects which were within 5° on either side of the 7th arc (marked in dashed black) in the timeframe 8–9 March 2014.

Indian Ocean. The additional effect of Stokes drift contributes an anticlockwise flow such that the bulk of the objects found 153–183 days prior reaching La Réunion tend to cluster in two cores: one centred around 15ºS, 80ºE and the other 25ºS, 72ºE. Objects in the former core originate from the eastern tropics and the northern Indian Ocean, whereas objects from the latter originate from the southwestern Indian Ocean. Here again, the effect of eddy stirring is quite prominent, and is evident in the spread of the regions portrayed. 16 months (450–480 days) before reaching La Réunion, objects are concentrated along a broad region extending southwestward from west Australia.

The 7th arc represents the possible location of the MH370 aircraft during its last successful contact with the satellite ground station on 8 March 2014. More than 85 000 square kilometres[12] in the vicinity of this arc have already been searched. In order to achieve a more meaningful description of the possible origin of the flaperon, we refine our analysis with the knowledge that on 8 and 9 March 2014, our simulated object must be somewhere around the 7th arc.

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[12] http://jacc.gov.au/families/operational_reports/opsearch-update-20160203.aspx

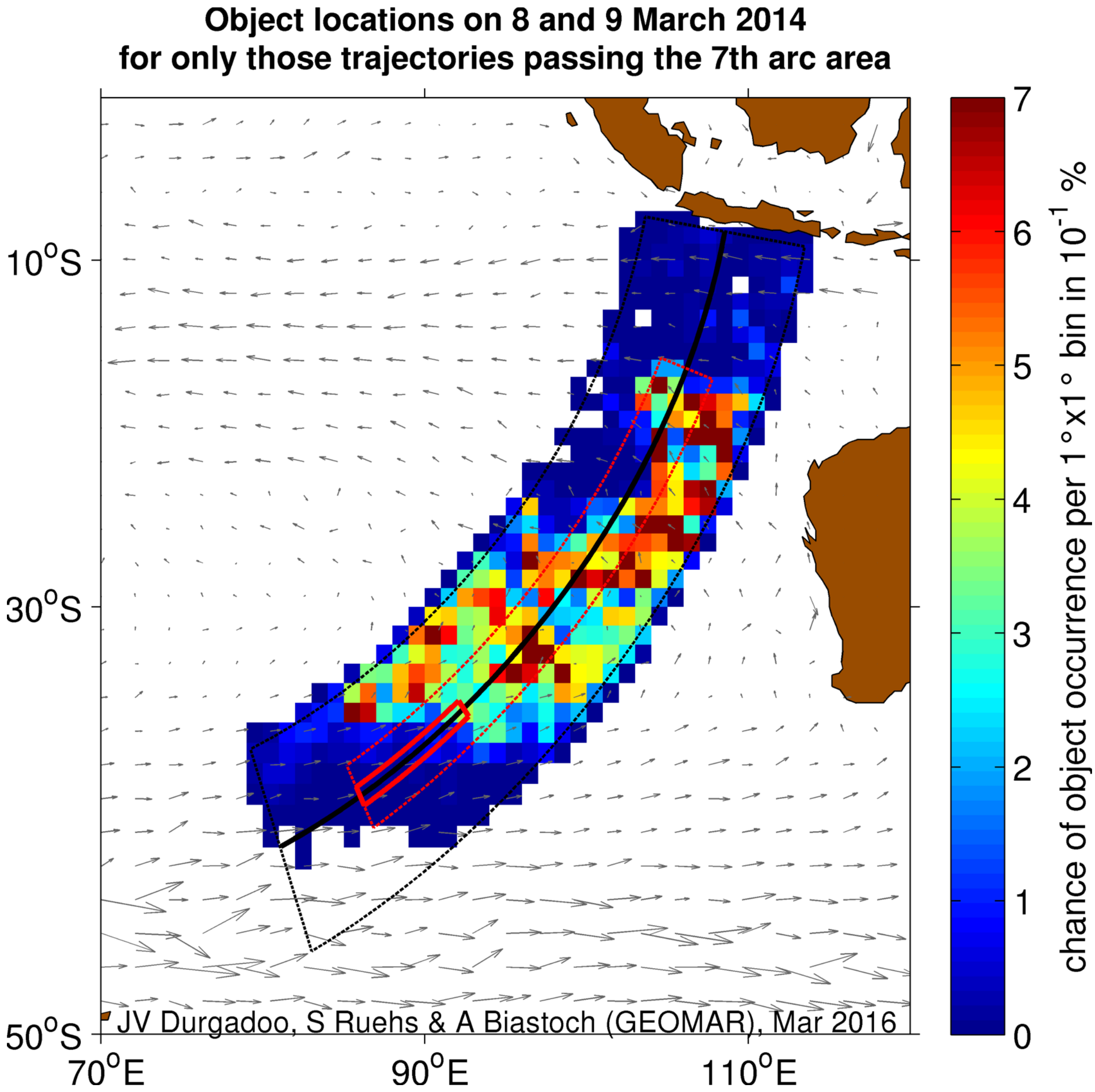

Figure 6: Locations on 8 and 9 March 2014 of only those objects that were within 5º on either side of the 7th arc (as in Figure 4) and reached La Réunion within the period 1–28 June 2015. The colour shading shows the object location counts per 1º x 1º bin divided by the total amount of object location counts in the 7th arc area (dashed black) on 8–9 March 2014 in %. It indicates the chance of objects occupying a particular bin on these two days; the values of all bins sum up to 100 %. The 7th arc, wide and priority search areas are overlaid.

We therefore subsample objects in order to keep only those whose positions on the 8 or 9 March 2014 are within a 5º swath along either side of the 7th arc between the island of Java and 45ºS. This subsampling region is about 3 times larger than the wide search area. About 15 % of the objects (> 800 000 objects) satisfy this criterion, and this is visualised by the red trajectories highlighted in Figure 5 (a subset of the subsample).

Repeating the 1º x 1º binning on the trajectories from the reduced number of objects and only considering the timeframe 8–9 March 2014, Figure 6 was generated. This shows the chance of occurrence of objects that ended up at La Réunion in July 2015, whose origins on

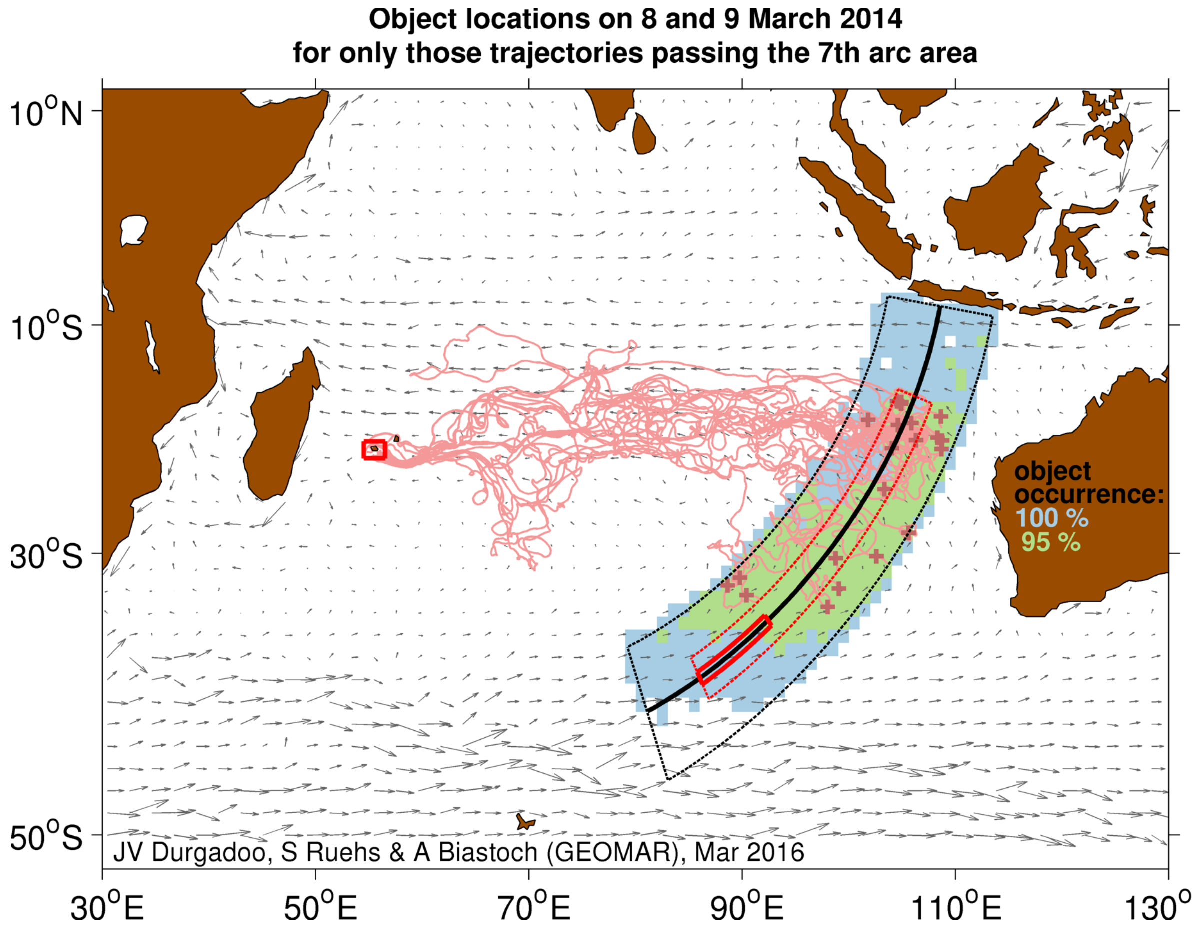

Figure 7: Most likely area where the flaperon found at La Réunion in July 2015 started its drift in the timeframe 8–9 March 2014. The chances of object occurrence displayed in Figure 5 were cumulated recursively above a certain threshold to determine the most likely start area encompassing 95 % of the object occurrences, shaded in green. Examples of possible drift trajectories of the flaperon are displayed in red. The 7th arc, wide and priority search areas are overlaid.

8–9 March 2014 were around the 7th arc. Another way of portraying this information would be to recursively sum the values shown in Figure 6 above a certain threshold (which is incrementally increased) to achieve the most probable region encompassing 95 % of the object occurrence (Figure 7). When the threshold is zero, the entire region is captured (blue area of Figure 7). The 95 % region encompasses approximately 2.5 million square kilometres west of Australia, north of the current priority search area. Based on our analysis, less than 1.3% of the object counts fall into the current priority search area on 8–9 March 2014. However, it is important to note that modelling studies, such as that presented here, are subject to uncertainties. These are discussed further below.

Discussion

The analysis has described the possible trajectories of objects ending at La Réunion in approximately 16 months in order to determine the possible origin of the MH370 flaperon. The following assumptions were made:

- The flaperon floated – in general, an object in the ocean would either float and drift at the surface or sink to the sea-floor and remain at depth. The fact that the flaperon was discovered on land indicates that it drifted at the surface.
- The direct effect of wind on the drift of the flaperon is negligible – in this case, the effect on drift would be dependent on the surface area of the flaperon directly exposed above water. It is uncertain how exactly the flaperon floated. However since growth of barnacles appeared to have occurred uniformly on the flaperon, it is likely that it floated along its horizontal axis. As such, the area exposed above the surface would be minimal, and hence wind fetch would be negligible.
- The flaperon was modelled as a dimensionless object incapable of self-propulsion.

Coming back to the two introductory questions asked, the results suggest that ocean currents and wave effects explain a drift of the flaperon from the southeastern Indian Ocean towards La Réunion. Furthermore, while it is possible that the flaperon originated from the current priority search area, our modelling suggests a more likely origin further to the north, in a region west of Australia around the 7th arc.

Final remarks

The present investigation uses state-of-the-art modelling systems, including the assimilation of available observations into the model circulation patterns, and the effects of wind-waves through the inclusion of Stokes drift. However, as with all such studies, there are uncertainties involved. While the large-scale structure of the Indian Ocean is expected to be reasonably well represented (e.g. the major current pathways and speeds), the real ocean contains smaller scale and rapidly-moving features such as eddies and waves (on the scale of tens to hundreds of km). While the modelling systems in the present study are expected to broadly reproduce the statistics of such features, the actual pathway taken by floating debris moving through the ocean will be determined by the actual day-to-day positions of these features. The ability of our modelling system to correctly represent the size and location of such features every day throughout the study period depends on the availability of large amounts of *in situ* data to constrain the model simulations (similar to weather forecasting in the atmosphere). There are insufficient amounts of real-world data (including data from satellites) available to constrain the model simulations, so that any individual trajectory will be subject to uncertainties. We compensate for this by simulating many trajectories and looking at their statistics.

Other uncertainties arise from not knowing exactly how the flaperon floated in the ocean (and whether any direct wind drift or "sail effect" should be applied to the calculations), and from not knowing precisely how waves interact with the flaperon (e.g. how the shorter waves impact on the flaperon, and the effective depth over which the Stokes drift should be applied). It is not clear that the finite-size flaperon should be transported by the waves at precisely the speed of the surface Stokes drift. A substantial percentage of the surface Stokes drift (typically about a third, Breivik et al., 2014) results from the high frequency tail of the surface wave spectrum. This component decays rapidly with depth, with a decay scale that may be as short as 0.1–0.2 m, so the flaperon may not 'feel' the full surface Stokes drift. On the other hand, these short high-frequency tail waves may break or reflect off the flaperon, giving a radiation stress (Longuet-Higgins, 1977) and enhancing the drift effect. Additionally, some laboratory work (e.g. Huang et al., 2011) has suggested that the waves may cause finite objects to move faster than the Stokes drift. We here choose to simply advect with the full surface Stokes drift, noting that there is some uncertainty.

Nonetheless, we re-iterate that the present study uses state-of-the-art modelling techniques, and the above uncertainties would equally apply to any other similar study. Based on the fortuitous discovery of a single piece of debris, we have attempted to provide insights into possible locations of the crash site using the best tools available, while also acknowledging that there are necessarily limitations in this. Should more information on the debris found at other locations in the Indian Ocean and/or more technical details (e.g. how the flaperon floated) become available, further such simulations could help to narrow down the area of debris origin.

Finally, the results presented here should be considered in conjunction with other independent analyses, such as those arising from the satellite communications and of the barnacles found on the debris.

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Appendix

As mentioned in the final remarks, the trajectory results are sensitive to the inclusion of Stokes drift, but this drift at the surface is thought to be quite accurate (based on verification of modelled wave-spectra against fixed buoy data). As a sensitivity test, Figure A1 shows two cases with 50% and 150% of the ECMWF Stokes drift.

Since the Stokes drift effect reduces with depth, the experiment in which the Stokes drift was increased is less useful. Vertical profiles of Stokes drift are available (Breivik et al 2016) if a more accurate estimate of the flaperon's depth was known. At the limit of halving the Stokes drift, results show trajectories that originate from further north.

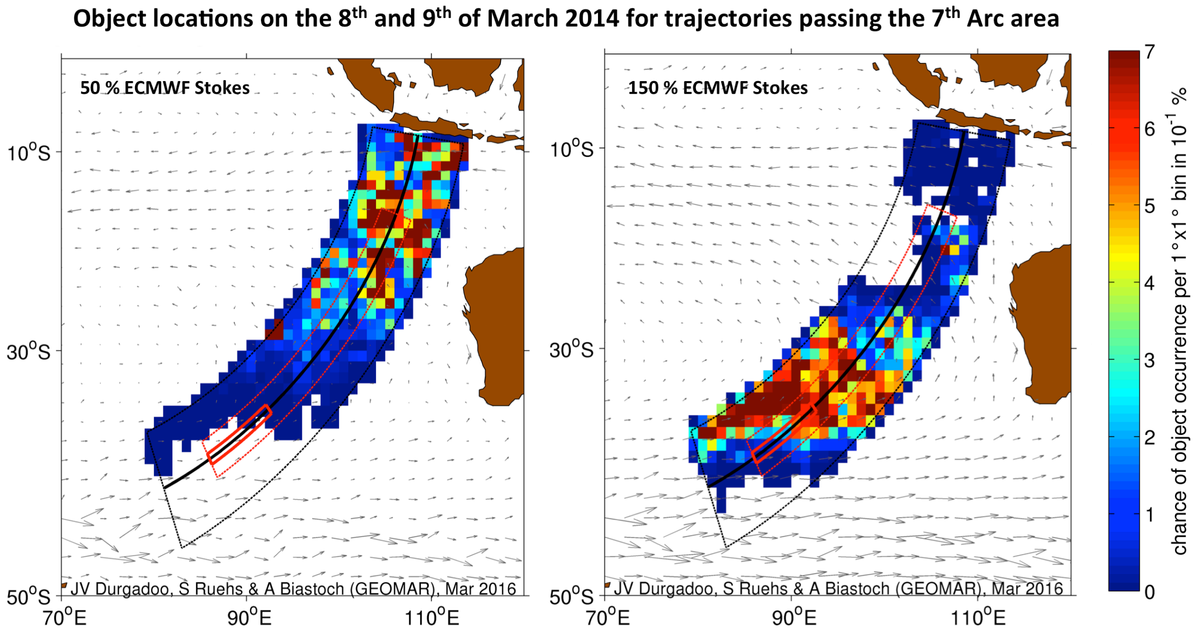

Figure A1: Locations on 8 and 9 March 2014 of only those objects that were within 5º on either side of the 7th arc and reached La Réunion within the period 1–28 June 2015. The colour shading shows the object location counts per 1° x 1° bin, divided by the total amount of object location counts in the 7th arc area (dashed black) on 8–9 March 2014 in %. It indicates the chance of objects occupying a particular bin on these two days; the values of all bins summing up to 100%. The 7th arc, wide and priority search areas are overlaid. Trajectories have been calculated by using surface currents based on CMEMS and 50% (left) and 150% (right) of the ECMWF Stokes drift.

Breivik Ø., J-R. Bidlot, P.A.E.M. Janssen, 2016, A Stokes drift approximation based on the Phillips spectrum, Ocean Modelling, doi:10.1016/j.ocemod.2016.01.005