

A brute force approach to find the MH370

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1 Introduction

Malaysia Airlines Flight 370 (MH370/MAS370), a Boeing 777-200ER, disappeared from radar on 8th March 2014. The flight was operated by Malaysia Airlines and was on the way from Kuala Lumpur International Airport in Malaysia to its destination, Beijing Capital International Airport in China. The aircraft had 227 passengers and 12 crew members on board. The investigation into the disappearance has been a multinational effort. The primary responsibility fell to Malaysia, as the state of registry and operation of MH370. On 31st March 2014, the Malaysian Government accepted the Government of Australia's offer to lead the search and recovery operation in the southern Indian Ocean, and the US through the FBI also aided the Malaysian government's search. In recent years, private companies have submitted search proposals to the Malaysian government based on new data analysis and technology. Despite these extensive efforts, the plane remains missing, and the investigation continues.

1.1 Context

Despite advanced technology and search techniques, the aircraft has not been found. The search for the missing airplane became the most expensive search in the history of aviation. The initial search focused on the South China Sea and Andaman Sea. Later, an analysis of the aircraft's automated communications with an Inmarsat satellite indicated that the plane had traveled far southward over the southern Indian Ocean. Several researches have been conducted to locate the missing flight. For instance, scientists from Bangor University used detailed computer models of the ocean to trace debris back through the currents to the potential crash site. A team from the University of Liverpool is analyzing data relating to an amateur radio technology called Weak Signal Propagation Reporter (WSPR) to see if it could be used to track the final flightpath of the aircraft. Despite these efforts, the mystery of MH370 remains unsolved.

2 Proposed approach

The approach we propose consists in avoiding the bifurcation difficulty due to forward-tracking trajectory determination [9]. These difficulties lead to the need for very high accuracy drifting models, and very accurate databases, to determine the correct trajectory when bifurcations appear.

Our method is a kind of "bruteforce" approach, where a lot of potential crash areas are tested, in each we depose debris we let drift. With this approach the difficulty of flow trajectory bifurcation doesn't exist. However, this kind of approach need a massive computing time, due to the number of particules to simulate, the number of potential areas to test, and the time during which the debris need to drift ($\simeq 3$ to 4 years).

For each tested area, two debris characteristics are used to determine a "score", which is a metric to compute the correlation between simulation and characteristics (position and date of discovery) of actually found debris on the coasts. This metric

has to take into account the minimal distance of all the debris with all of the 17 spots, and the time when these debris wash up on the coasts.

The score at a time t of a spot is determined with a classical spatio-temporal metric, applied on the closest debris to the spot i , knowing the time t_f when debris was effectively found on the coast :

$$s_i^2 = \|\vec{X}_{debris,i} - \vec{X}_{spot}\|^2 + c^2(t - t_f)^2, \quad (1)$$

with a total score for the tested crash area : $s = \sum_i s_i$.

The difference between time when debris is found and the time it wash up on the coast is not known, a variability on $(t - t_f)$ has been added to take this uncertainty into account, replacing $t - t_f$ with $\max(|t - t_f - 86400 * 3|, 0)$, which cancels out this term at ± 3 days after t_f .

The c velocity has to be chosen to have coherent impact on distance and time, it has been taken as equal to 1 m/s , which is the magnitude of estimated u_{RMS} of the flow contained in the database we use.

The list of debris used to compute the score in each possible crash area are those which comes certainly from the MH370. They are listed in Tab. 1.

| number of item in [1] | longitude (°) | latitude (°) | estimated epoch time of coast discovery [s] | estimated date & time [GMT] |
|-----------------------|---------------|--------------|---|-----------------------------|
| 1 | -20.874858 | 55.4440279 | 1438171200 | 29 Jul 2015 12:00:00 |
| 2 | -23.993213 | 35.5016507 | 1451217600 | 27 Dec 2015 12:00:00 |
| 3 | -21.988463 | 35.3250454 | 1456574400 | 27 Feb 2016 12:00:00 |
| 4 | -34.183320 | 22.1591920 | 1458648000 | 22 Mar 2016 12:00:00 |
| 5 | -19.705962 | 63.5026922 | 1459339200 | 30 Mar 2016 12:00:00 |
| 6 | -24.963743 | 34.1939515 | 1461499200 | 24 Apr 2016 12:00:00 |
| 7 | -26.349411 | 32.9332389 | 1462017600 | 30 Apr 2016 12:00:00 |
| 8 | -20.524751 | 57.5322694 | 1464091200 | 24 May 2016 12:00:00 |
| 9 | -25.766419 | 32.7737308 | 1463918400 | 22 May 2016 12:00:00 |
| 10 | -20.024275 | 57.700481 | 1462881600 | 10 May 2016 12:00:00 |
| 11 | -16.867631 | 49.954899 | 1465214400 | 06 Jun 2016 12:00:00 |
| 16 | -16.204192 | 49.855412 | 1465732800 | 12 Jun 2016 12:00:00 |
| 19 | -5.0390147 | 39.869753 | 1466424000 | 20 Jun 2016 12:00:00 |
| 20 | -26.893192 | 32.891843 | 1466510400 | 21 Jun 2016 12:00:00 |
| 22 | -24.650029 | 35.095237 | 1472212800 | 26 Aug 2016 12:00:00 |
| 26 | -34.218715 | 21.981328 | 1482494400 | 23 Dec 2016 12:00:00 |
| 27 | -32.097776 | 29.067921 | 1485518400 | 27 Jan 2017 12:00:00 |

Table 1: List of debris used for the study.

2.1 Drifting model

Since it is unnecessary to consider the bifurcations in back-trajectory computing, a very high-accurate drifting model is not necessary in our case.

The classical drifting model is given by [2] :

$$\vec{V}_d = \vec{V}_{water} + \vec{V}_S + \vec{V}_W + \vec{V}_D + \vec{V}', \quad (2)$$

where \vec{V}_{water} is the ocean surface current, \vec{V}_S is the wave-induced Stokes drift, \vec{V}_W is the local wind velocity correction term and \vec{V}_D is a correction term due to wind drag on the emerged part of the debris (windage). \vec{V}' is fluctuating velocity noise, to take into account the uncertainty of models and simulation.

Furthermore, the global ocean / atmosphere database has a resolution of fraction of degrees, every hours minimum. The small effects, due to local turbulence or waves, are unattainable. Except for the item 1 which has been recovered (Right flaperon, cf. [1]), all the other items have a size in order of decimeters ([1, 3] and updates : [4, 5, 6, 7, 8]). To have Stokes significant effect, the debris size need to be to the order of the surface wavelength of the ocean [2]. Overmore, the corrected and non corrected drift models applied to this part of the airplane didn't show significant difference in the models for most of debris (for the the smallest one, some small differences can appear on the flaperon : fig. 8 & 9 of [9]).

However, as the dispersion on the surface of the ocean quickly became high [10], due to the surface and atmospheric turbulence, a very high number of lagrangian particles have to be considered to cover the maximum of different trajectories and liquid/gas coupling, to maximize the chance to observe some debris close to the real trajectory it follows.

For this both reasons, in the present study, a very high-level of \vec{V}' has been taken to counterbalance the uncertainty induced by this coarse level of measurement, and to accounts for the uncertainty on Stokes effect. Air velocity has been decoupled from waves, and has been estimated with real mesurments [3].

This model has been implemented, englobing \vec{V}_{water} and effect of wind \vec{V}_W and \vec{V}_D in a different form. For a debris with its density $\rho_d \ll \rho_{water}$, the debris velocities are considered to be the same than atmospheric velocity, on the surface of water. In another way, if its density $\rho_d \simeq \rho_{water}$ ($\rho_d < \rho_{water}$), its velocity will be close to the water velocity : the wind impact is null. To consider all the intermediary cases, a coefficient $\alpha \in [0, 1]$ is randomly given to each particule, with $\vec{V}_{flow} = \alpha \vec{V}_{air} + (1 - \alpha) \vec{V}_{water}$. To cover all the possible cases, a huge number of particles have to be simulated to statistically cover the maximum number of trajectories with a large interval of α .

Which induce this simple model, given in eq. 3.

$$\vec{V}_{part} = \alpha \vec{V}_{air} + (1 - \alpha) \vec{V}_{water} + \vec{V}'. \quad (3)$$

The estimation of \vec{V}_{air} and \vec{V}_{water} are obtained by classical spatial and temporal linear interpolation of known surface of water velocity and surface of atmospher velocity, described by fig. 1.

The interpolation algorithm is the following :

- compute $c_t \in [0, 1]$,
- compute $c_{x,1}$ and $c_{x,2} \in [0, 1]$,

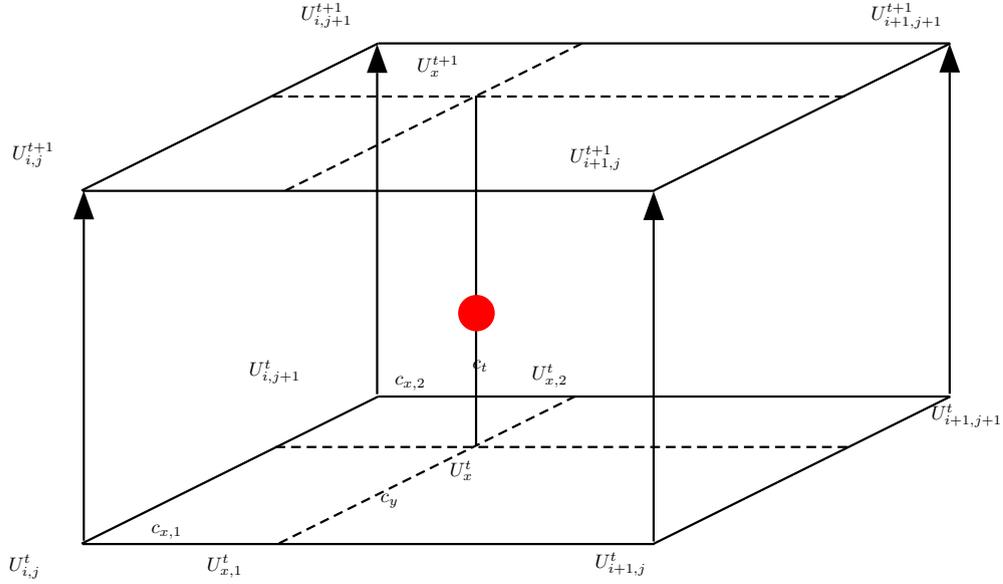


Figure 1: Linear spacial and temporal interpolation.

- compute $c_y \in [0, 1]$,
- compute $U_{x,1}^t = U_{i,j}^t + c_{x,1}(U_{i+1,j}^t - U_{i,j}^t)$ and $U_{x,2}^t = U_{i,j+1}^t + c_{x,2}(U_{i+1,j+1}^t - U_{i,j+1}^t)$,
- compute $U_x^t = U_{x,1}^t + c_y(U_{x,2}^t - U_{x,1}^t)$,
- compute all these values for $t + 1$,
- compute $V_{water} = U_x^t + c_t(U_x^{t+1} - U_x^t)$

The fluctuation part \vec{V} has been tuned to very high values, to take into account the uncertainty on the Stokes and other effects. The u_{RMS} on the database used is estimated to $\simeq 0.14$ m/s. The $\vec{V}_{air}(\vec{X}_{part})$ we implement is set to a random value between ± 0.5 m/s = ± 3.57 u_{RMS} , in a random direction, with new randomly generated value every hour. This very high value is assumed to encompass all the uncertainties.

2.2 Algorithms

The databases used for this study are :

- atmosphere surface velocity, from MERRA (NASA), (lat - lon - date) from -53.50 - 3.75 - 03/08/2014 to 17.50 - 128.75 - 01/29/2017, with a resolution of 0.625×0.5 degree \times 1 h,
- ocean surface velocity, from Copernicus (EU), (lat - lon - date) from -53.625 - 3.625 - 03/01/2014 to 17.875 - 128.875 - 02/01/2017, with a resolution of 0.25×0.25 degree \times 3 h.

Due to the number of interpolations to perform, the code has been developed in Fortran 2003, with MPI/OMP hybrid parallelization. A lot of optimizations have been performed to reduce the computing time of the largest time-consuming step :

- compute the 2 + 1 D interpolations, performed one time per hour and per debris,
- compute the score of each spot on the coasts, which need to find the closest debris, every day of simulation.

For the first one, a conversion (X,Y) \rightarrow (lat,lon) is used to convert the debris to project it in rectangular patterns, to reduce the computing time used to determine which (lat,lon) polygone of the database has to be used. A differential approach is used to detect when the debris change of polygone, instead of recomputing it at each iteration. However, the interpolation coefficients need to be recomputed at each iteration.

To optimize the second, a closest neighbour approach is used to minimize the number of couple (spots,debris) to check to determine the minimal distance of all debris for each spot.

2.3 Simulations & results

The parameters used for the simulation are resumed in the tab. 2.

| Parameter | Value |
|---------------------------------|--------------------------------------|
| Number of debris / spot | 10^6 |
| Size of a spot | $10 \text{ km} \times 10 \text{ km}$ |
| Time step | 1 h |
| Min latitude/longitude of study | $-20.54 \rightarrow 93.38$ |
| Max latitude/longitude of study | $-17.75 \rightarrow 129.10$ |
| Number of spots | 3.10^5 |

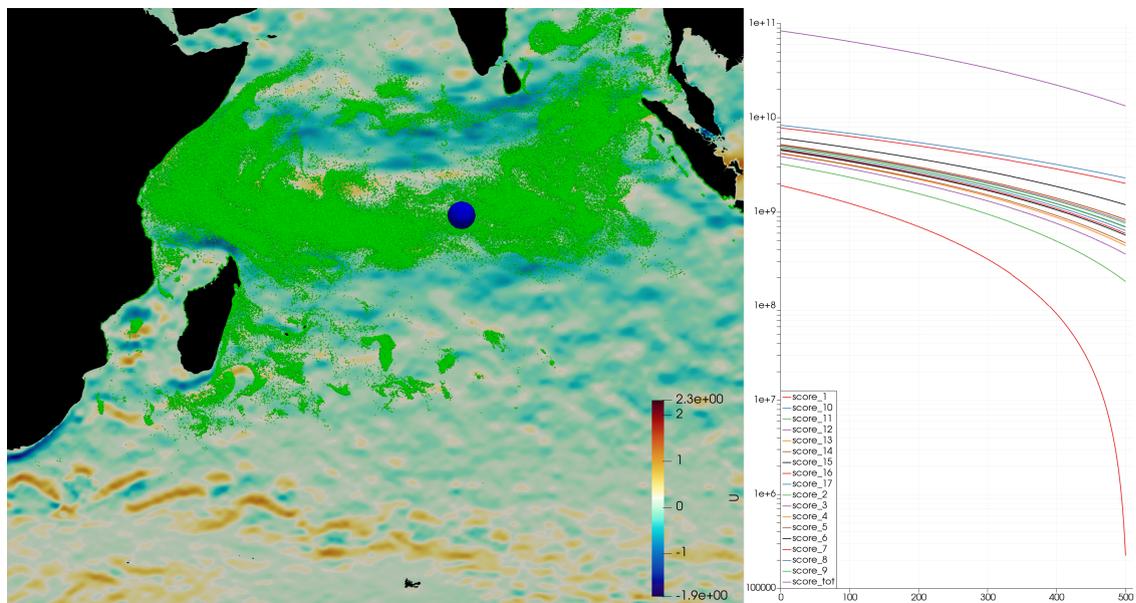
Table 2: Characteristics of the simulations to perform

The estimated number of interpolation to perform is $\simeq 3.10^5 \times 10^6 \times (24 \times 10^3)$ hours = $7.2 \cdot 10^{15}$.

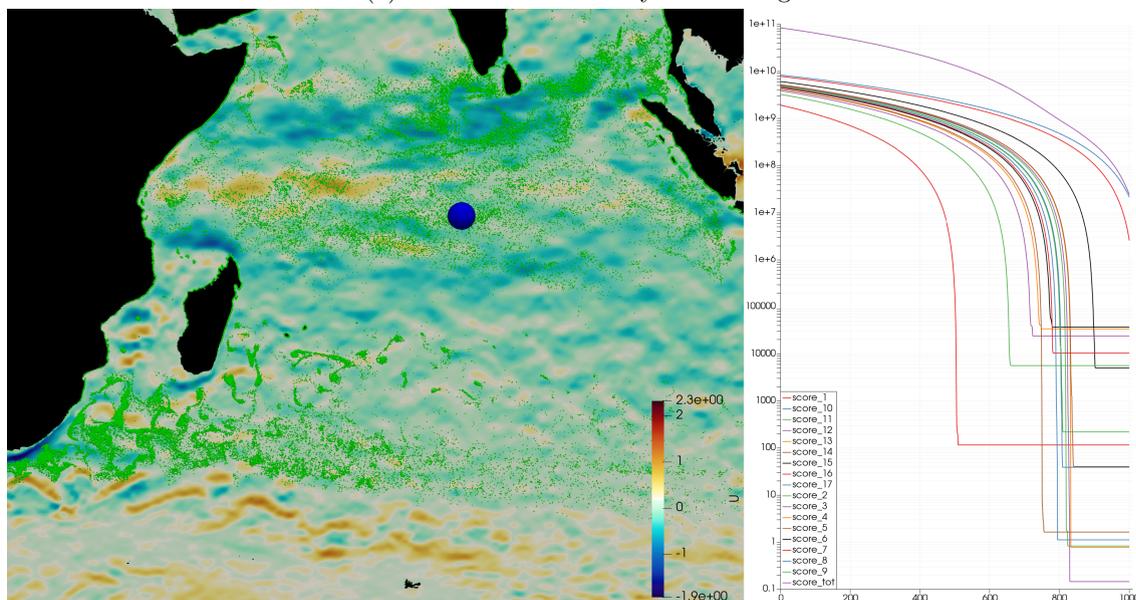
Two screenshots of one simulation over the 3.10^5 , performed with initial crash area at $[-7.52223, 74.81737]$ are shown in fig. 2 as examples.

These simulation have been perform, consuming $\simeq 2.10^6$ hours of CPU time. The most interesting result, is to observe that, despite the high-level noise injected in the drift model, all these simulations show a very small surface ($\simeq 200$ crash areas tested) with very low level of scores (lower is better). These spots, for all of it, have scores bellow 230, which means $\simeq 13$ on average, per spot. It means that for each of theses 17 spots, some debris arrive in the coast in the interval between :

- the same day (± 3 days), at a radius of 13 km ,
- exactly on the spot, at ± 6 days.



(a) Results after 500 days of drifting



(b) Results after 1000 days of drifting

Figure 2: Screenshot of one simulation with one tested crash area at $[-7.52223, 74.81737]$ (in blue). On the left : the debris are in green, spots in yellow, with the ocean velocity magnitude at this time. On the right : scores of each debris and the cumulated sum. This is an example, not the best result obtained.

This area can be estimated to a rectangle of $1450 \times 670 \text{ km}$ for a high level of confidence ($\simeq 91\%$, for all results $< 1.e5$), and decrease as the surface to explore reduces in size, for exemple to $\simeq 22\%$ for a surface of $500 \times 340 \text{ km}$. The level of confidence (i.e. % of explorable areas with all scores $< 1.e5$) is described in the figure 3. The global result with the lower (is better) global result is shown in the fig. ??.

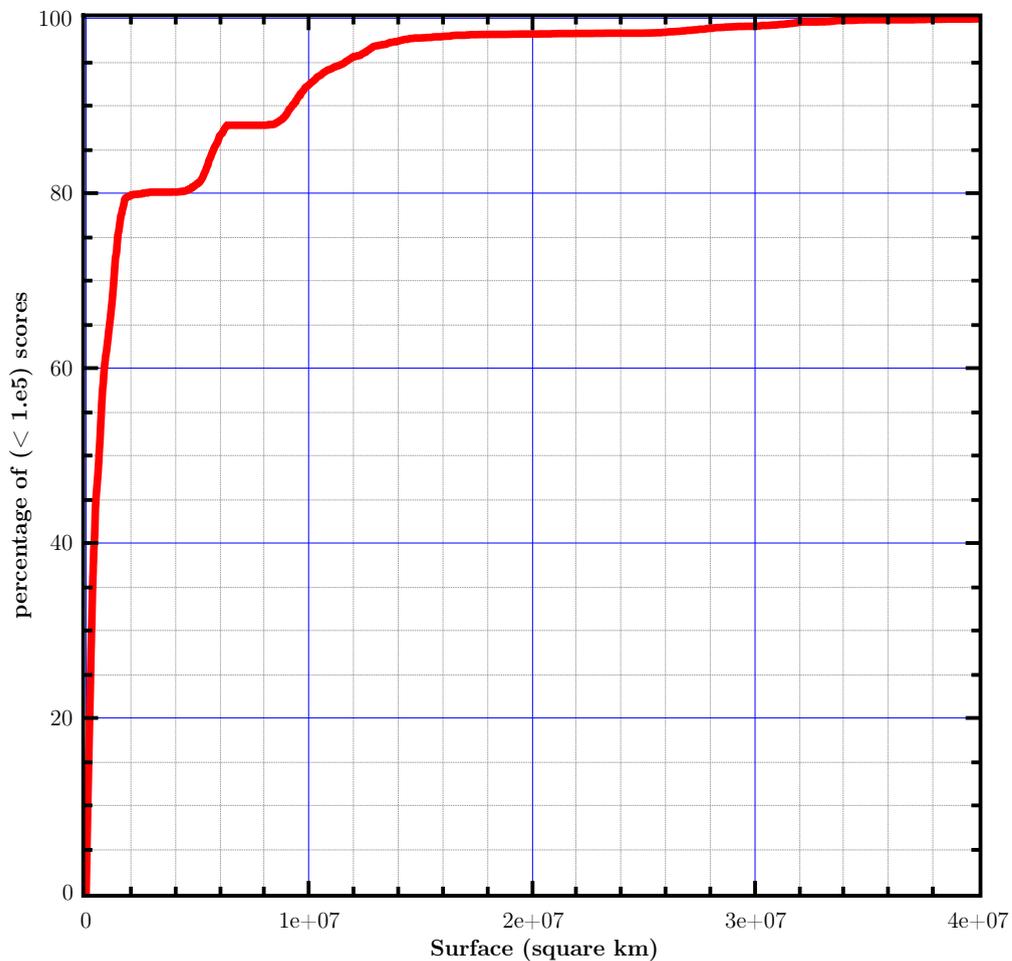


Figure 3: % of explorable areas with scores $< 1.e5$.

References

- [1] Safety Investigation Team for MH370. Safety Investigation Report, Malaysia Airlines Boeing B777-200ER (9M-MRO). March 2014.
- [2] T. Tamtare, D. Dumont, and C. Chavanne. The stokes drift in ocean surface drift prediction. *Journal of operational Oceanography*, 3:156 – 168, 2022.
- [3] ATSB Transport Safety Report. MH370 - search and debris examination update. November 2016.
- [4] ATSB Transport Safety Report Debris examination update No. 1. Identification of two items of debris recovered from beaches in mozambique. April 2016.
- [5] ATSB Transport Safety Report Debris examination update No. 2. Identification of two items of debris recovered from beaches in south africa and mauritius. May 2016.

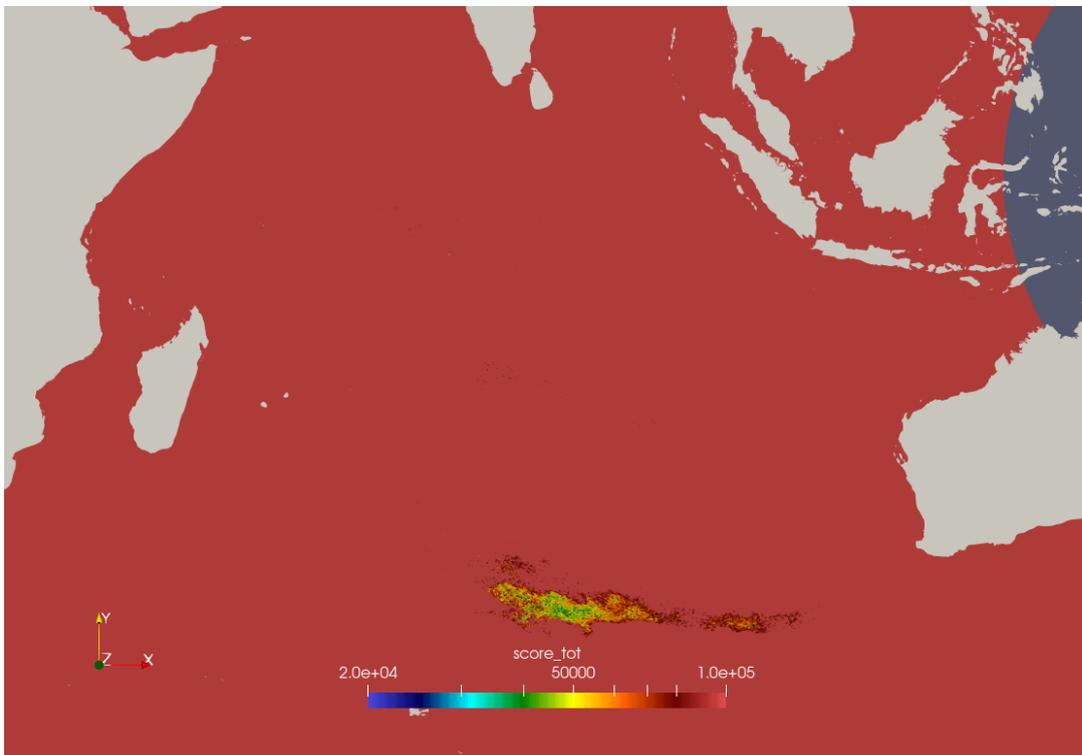


Figure 4: Best score over the $3e5$ simulations.

- [6] ATSB Transport Safety Report Debris examination update No. 3. Identification of large flap section recovered off the tanzanian coast. September 2016.
- [7] ATSB Transport Safety Report Debris examination update No. 4. Preliminary examination of two items of debris recovered near sainte luce, madagascar.
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- [10] Andrew C. Poje, Tamay M. Ozgokmen, Darek J. Bogucki, and A. D. Kirwan. Evidence of a forward energy cascade and kolmogorov self-similarity in submesoscale ocean surface drifter observations. *Physics of Fluids*, 29, 2017.