# Adrift.org.au – a free, quick and easy tool to quantitatively study planktonic surface drift in the global ocean

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**Abstract:**

Almost all organisms in the ocean are impacted by ocean currents. Hence, there is growing interest by marine ecologists in using objective methods to assess current drift and its implications for marine connectivity. Here, an online tool – hosted at adrift.org.au – is introduced that allows for a simple, quantitative assessment of drift patterns and transit time scales on the global scale. The tool is based on a statistical transition matrix representation of the observed trajectories of more than 15 thousand surface drifters. Users can select any point in the ocean and obtain the evolution of the probability density distribution for a tracer released at that point, both forward and backward in time, for a maximum interval of 10 years. It is envisioned that this tool will be used in research and teaching, especially where estimates of drift patterns and transit times are required quickly.

**Keywords:** Ocean circulation, dispersion, drifting buoys

## 1. Introduction

Many organisms in the ocean are planktonic for either their entire lifespan or during some stage of their life cycle (e.g. Suthers and Rissik, 2009). This means that these species – including bacteria (e.g. Wilkins et al., 2013), foraminifera (e.g. Weyl, 1978) and jellyfish (e.g. Dawson et al., 2005) as well as eggs and larvae of fish (Aiken et al., 2011; e.g. Cowen et al., 2006; White et al., 2010), crustaceans (e.g. Griffin et al., 2001) and algae (e.g. Coleman et al., 2013) – can drift and disperse over long distances during their life. In addition, stronger swimmers such as nekton, including large fish, turtles, marine mammals and penguins may have their movements impacted by currents that can alter their speed of travel or carry individuals off-course (see Chapman et al., 2011 for a review).

Understanding this pelagic drift is important for studying (genetic) connectivity, species invasion, biogeography or for explaining animal behaviour (such as in some species of turtle; Scott et al., 2014). Given this broad impact of ocean currents, it is not surprising that biologists have had a long interest in assessing the implications of current drift for their particular species or ecosystems of interest. Many decades ago, marine biologists used simple schematics of ocean currents to assess ocean drift (Carr, 1967), thereby ignoring the variability in currents and details such as eddies. As ocean current models and trajectories of drifting buoys started to becomes available, there were efforts by biologists to use these tools (e.g. Hays and Marsh, 1997).

Studies in the early 1990s were constrained by the limitations of the models and the availability and extent of buoy trajectories. The last 20 years have seen advances in both areas. Ocean models are now widely used by biologists (Cowen et al., 2006; e.g. Hays et al., 2013; Kough et al., 2013; Naro-Maciel et al., 2014; Paris et al., 2005; Simpson et al., 2013; Staaterman et al., 2012). However, these ocean models still do not reproduce all the details and variability in actual ocean currents and require a skills set to implement that is often outside the experience of marine ecologists (Fossette et al., 2012). At the same time, the freely available data-set of global Lagrangian drifter trajectories has grown hugely (http://www.aoml.noaa.gov/phod/dac/index.php) and this is now a relatively straightforward resource for biologists to use in its simplest form of plotting individual trajectories (Monzon-Argueello et al., 2010).

Here I describe a freely available, quick and simple online tool for studying the pathways and time scales of ocean surface drift based on empirical data. The tool uses Lagrangian drifter data but goes well beyond plotting individual trajectories. Rather, the tool splices together all the possible drift scenarios in the Lagrangian drifter dataset so that the full extent of drift scenarios is generated and quantified. This easy-to-implement approach promises to have very wide utility (van Sebille et al., 2011; 2012a), although there are some caveats (including the lack of control over exact depth habitat of the organisms and the absence of mortality or settling/beaching, see also the Discussions and Conclusion section) that might limit the merit of the tool for certain research questions.

The website adrift.org.au is fronted by an easy-to-use interface (Figure 1) where researchers can study the movement (in a probabilistic sense) of passive particles from any point in the ocean, both forward and backward in time. While adrift.org.au is framed in terms of marine plastics, the results are equally representative for many planktonic species in the upper few meters of the ocean. Output from the website can be downloaded in comma separated values (csv) format for easy import into data analysis programs like Microsoft Excel, R, python or Mathworks Matlab.

## 2. The methodology behind adrift.org.au

### *2.1 The surface drifter data*

The numerical engine behind adrift.org.au is built on an updated version of the methodology described in (van Sebille et al., 2012a), which is similar to that presented in (Maximenko et al., 2012). In these studies, the trajectories of surface drifters (Niiler, 2001), as aggregated in the NOAA Global Drifting Buoy Program (Lumpkin, 2003; Lumpkin et al., 2012), were used to study the formation and evolution of the marine garbage patches. In total, more than 24 million locations from 17,494 individual surface drifter trajectories and spanning a time period between 1979 and 2013 are used on adrift.org.au. The drifter geolocations are available every 6 hours, and more than 85% of the ocean surface has had more than 100 location fixes per 1° x 1° degree grid cell during that 34 year period (van Sebille et al., 2011). See Figure 2 for an example of the density of drifter trajectories.

The buoys are deployed with a drogue centered at 15m depth, which is there to make the buoys less prone to windage effects and hence more closely follow the (upper-ocean) Ekman transport. However, many buoys lose their drogue at some point, affecting their paths (Grodsky et al., 2011; Poulain et al., 2009).

Within the data set used here, 48% of all data used is of buoys with a drogue and 52% is of buoys without a drogue, making the data representative for anything that drifts in the upper 15m of the ocean. Maximenko et al. (2012) showed that although the details of the pathways of drogued and undrogued buoys are different, the evolution of the two types of buoys is similar on longer timescales and larger spatial scales. Furthermore, it can be argued that neutrally buoyant particles that constantly change depth within the mixed layer will have pathways that are a mix of both the drogued and undrogued buoys.

### *2.2 The global transition matrix*

As in Van Sebille et al. (2012a), the drifter trajectories are converted into a set of six transition matrices (Dellnitz et al., 2009; Froyland et al., 2007) that represent, for each surface grid cell on the ocean, the fractional distribution of tracer two months later. More specifically (see also Figure 3), each individual drifter trajectory is binned onto a 1° x 1° degree array of grid cells. For each trajectory and then within each trajectory for each day $t$, the number of times a buoy crosses from grid cell $i$ at time $t$ to grid cell $j$ at time $t + \Delta t$ is added to the crossing matrix $\mathbf{C}_b(i,j)$. Here, we use $\Delta t$ = 2 months and a grid size of 1°, which are the same values as used in Van Sebille et al. (2012a). The choice for a 1° x 1° grid is an optimum between the size of the matrix (and hence computational effort) and the ability to resolve fronts, as also shown in Van Sebille et al. (2011). The choice for $\Delta t$ = 2 months ensures both a sufficient number of off-diagonal crossings (which requires a $\Delta t$ larger than 1 month) and a good representation of seasonality (which requires a $\Delta t$ smaller than 3 months). The seasonal cycle in the circulation is resolved by classifying the time of year each crossing occurred and then adding that crossing to one of six crossing matrices for each two-month period (Jan-Feb for $\mathbf{C}_1$, Mar-Apr for $\mathbf{C}_2$, …, Nov-Dec for $\mathbf{C}_6$).

The crossing matrices $\mathbf{C}_b$ are converted to transition matrices $\mathbf{P}_b$ by row-normalizing them (i.e. making the sum of each row $i$ equal to 1.0). The entries in the rows of $\mathbf{P}_b$ can be interpreted as a 2-dimensional probability distribution of a virtual tracer two month after it is released from a grid cell. Ocean grid cells that buoys have never reached or have never exited from are removed from the transition matrix. The total number of ocean grid cells that remains in this way is $N$ = 33,654, and they are ordered from south to north. The transition matrix for the months January and February ($\mathbf{P}_1$, Figure 2b) is rather diagonal and sparse, indicating that for each grid cell (each row in $\mathbf{P}_\mathrm{b}$), there are only a limited amount of grid cells within the vicinity that are reachable in two months. This transition matrix also shows that dispersion is larger in the Southern Ocean around 60°S than anywhere else, largely because of the large speeds and eddy activity there.

The general idea of the tool is that each transition matrix calculates the probabilities that a particle that is in one grid cell at time $t$ has moved to any of the grid cells by time $t$ + 2 months. This calculation is then repeated through time, so that for a particle at $t$ + 2 months that has moved to a new grid cell, the subsequent probability of moving to all other cells is estimated and so forth. Numerically, the evolution of the probabilities $v$ from any point in the ocean can be computed by solving the iterative vector-matrix multiplication $v_{t+2\mathrm{months}} = v_t \times \mathbf{P}_b$ where the bimonthly counter $b$ is cycled through.

The initial condition on adrift.org.au is that $v_{t=0} = 0$ everywhere except for the entry $i$ that represents the grid cell where the user clicked, which is $v_{t=0}(i) = 1$. Releases in different two-month periods can be simulated by using a different initial value of the counter $b$ at $t = 0$. Because of the row-normalisation, the virtual tracer is conserved throughout the iteration, meaning that the total probability of the particles being somewhere in the ocean will always be 1. This means that the tool doesn't account for mortality, beaching or other ways in which a particle might leave the ocean.

*2.3 Hybrid transition matrices for regional experiments*

While the surface drifter data set is adequate for the study of tracer evolution in the open ocean, where the number of samples is generally large, it is not sufficient in some regional seas such as for instance the Indonesian Archipelago or the Strait of Gibraltar. In the 30 years since the global drifter program started, for example, there has never once been a surface buoy that has crossed the Indonesian Archipelago (Lumpkin et al., 2012).

Because of this lack of observational data in some regional areas, hybrid transition matrices $\mathbf{P}_b$ are created for the regional experiments only. These hybrid transition matrices are formed from a combination of both the observational drifting buoy trajectories and a set of virtual particles released within a numerical ocean circulation model. The model is the eddy resolving OFES model data set (Masumoto et al., 2004), with a horizontal resolution of 0.1° and 54 vertical levels. This model, although lacking the sub-mesoscale structures that do affect the drifting buoys, has been shown to accurately reproduce the circulation in many areas of the global ocean (Masumoto et al., 2004; Sasaki et al., 2008), as well as in specific regions such as around Australia (van Sebille et al., 2012b). For the analysis here, the 2-dimensional horizontal velocity at 15 m depth (the nominal depth of the surface drifters) from the model has been used. A total of 455,236 virtual particles were released within the velocity fields in the year 1980, on a 1° x ° grid and every 30 days. The locations of the particles were saved every 6 hours, and the particles were advected for a total of 365 days, using the Connectivity Modeling System version 1.1 (Paris et al., 2013).

The trajectories of the virtual particles were also converted into a crossing matrix $\mathbf{C}_{b\text{model}}$. Before normalizing the crossing matrices, however, they were entry-wise added together as $\mathbf{C}_b(i,j)_{\text{hybrid}} = \mathbf{C}_b(i,j)_{\text{model}} + w * \mathbf{C}_b(i,j)_{\text{obs}}$, using a weighing factor $w$ of 10. This weighing factor ensures that, in the regional transition matrices, the hybrid transition distribution is very similar to the observed transition distribution for regions where sufficient surface drifters are available, and that the model trajectories are only used in regions where observed drifter coverage is inadequate.

## 3. Using adrift.org.au

Users of adrift.org.au are presented with a map of the global ocean. The mouse is used to select a point somewhere in the ocean that represents the start point of the particles. After a few seconds, an animated simulation is produced that shows how tracer from that location spreads through the ocean (Figure 1). Each frame in the animation represents an interval of 2 months, and the total animation runs for 10 years, a time ceiling currently dictated by limits on the computational resources.

The simulation represents the evolution of a large number of free drifting, neutrally buoyant particles, with the color scale indicating the percentage of particles in each 1° x 1° grid cell at each time interval. As dispersion causes the density of particles to decrease rapidly in the ocean, the colour scale (bottom right) has a maximum value of 1% of the total amount of particles. The value in each grid cell can be viewed as a probability that a particle is found in that grid cell, a certain amount of time after being released.

The particles can be tracked both forward in time (the default) and backwards in time, by toggling the switch on the map. In the latter case, the animation shows the probability distribution of where particles at the selected location have come from. There is also an option on the map to zoom into specific regions. Currently, only the Mediterranean and the seas around Australia are available, but new regions will be added in the future.

After the animation has finished, users are able to download the simulation data in a comma separated values (csv) format as (year, month, latitude, longitude, probability). These files can be loaded into other software and used to further investigate the quantitative spreading of the particles (see also Section 4). Users who want to have more precise control of where the particles are released can alter the start location manually in the browser's address bar, using the format adrift.org.au/map?lat=LAT&lng=LNG&startmon=MON, where LAT and LNG are numerical values of latitude and longitude, respectively, and MON is the three-letter abbreviation of the month. Note that, since the method works with bimonthly increments, JAN is the same as FEB, APR is the same as MAR, etc.

## 4. An example: drift times across the North Atlantic

As an example of how adrift.org.au can be used, the fastest-possible drift across the North Atlantic from the US East Coast is examined. For this, the simulation at adrift.org.au/map?lat=35&lng=-75&center=251.4&startmon=Jan has been downloaded in csv format. Some simple manipulation of the csv file allows for the creation of a map that for example shows the shortest transit times from Cape Hatteras to any point in the Atlantic Ocean (Figure 4). On this map, which is coloured on a logarithmic scale to highlight differences in timing in the first few months after release, regions that are white cannot be reached within 10 years.

The cyclonic circulation of the subtropical gyre is very clear in the map, with transit time scales of less than 2 years in the Gulf Stream extension and North Atlantic Current, increasing to 2 to 4 years on the southern flank of the subtropical gyre around 20°S. Fastest times to cross the North Atlantic and reach Europe are in the order of 1.5 years, which agrees well with direct analysis of the drifter trajectories (Brambilla and Talley, 2006) and numerical ocean modelling studies (Baltazar-Soares et al., 2014). As also found in these studies, as well as in another recent numerical ocean modelling study (Burkholder and Lozier, 2014), there is very little mixing between the subtropical gyre and the subpolar gyre, with a very sharp front between the North Atlantic Current and the subpolar gyre to the northwest. This suggests, as was also shown in van Sebille et al. (2011), that the effect of spurious cross-frontal diffusion in the transition matrix approach is limited.

Note that the map in Figure 4 is rather noisy in some regions such as the Gulf of Mexico and northeast of Iceland. This is related to very low probabilities to reach these grid points from Cape Hatteras. If a more smoothed version of this figure is required, grid cells with very low probability of reaching could be blanked out. The analysis using adrift.org.au shows that it is possible to reach the Barents Sea, but that from Cape Hatteras it takes at least three to four years to reach that area.

An analysis such as this one can be very useful as a way for marine biologist to quickly get an idea of the dispersion range of a particular species, given the span of its planktonic life. Note that in this example any particle density greater than 0 was taken as significant. It is relatively straightforward to change the analysis to include a threshold probability; for example a one in a thousand chance of reaching a certain area.

## 5. Discussions and Conclusion

Adrift.org.au is a free, easy to use tool that can help marine biologists and ecologists quickly assess drift pathways in the global ocean. Although the website started as a public outreach tool, the methodology behind the website is scientifically robust. The narrative of the website is whimsical (featuring lots of rubber ducks: a reference to the story of the container full of bath toys lost at sea - Ebbesmeyer and Scigliano, 2009) and focuses on the problem of marine litter. However, the tool can be used beyond the study of pathways of plastics. The drift of many different substances, including planktonic marine organisms, can be studied using the same statistical analysis of observational drifting buoy trajectories.

The method is different from most other tracking tools available (e.g. Condie, 2005; Lett et al., 2008; Paris et al., 2013) in that - for the global version - it is based entirely on empirical data. While this means that there are no errors associated with numerical ocean models or the choices for parameters associated with running virtual particles in these models (Putman and He, 2013; Simons et al., 2013), the method does have some caveats that users should be aware of. These include the fact that a mix both drogued and undrogued drifters is used and that therefore the user doesn't have control of the exact depth habitat of the organisms. It is hoped that, as the global drifter dataset increases in size, coverage will within a few years be sufficient to construct transition matrices of the drogued and undrogued drifters separately, so that users can choose which depth scenario most suits their needs.

The method behind adrift.org.au is also different from most other tracking methods in that pathways are inherently statistical, and that contrary to direct integration methods users don't get individual trajectories to analyze. Finally, the limits of the observed data set mean that the resolution of the global run is only 1° x 1°, which is relatively coarse for organisms with short drift durations. Nevertheless, it is hoped that adrift.org.au is a valuable addition to the landscape of tracking tools and that the site will be used by scientists, both in their teaching and their research, who are interested in how ocean currents shape ecosystems.

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## Figures

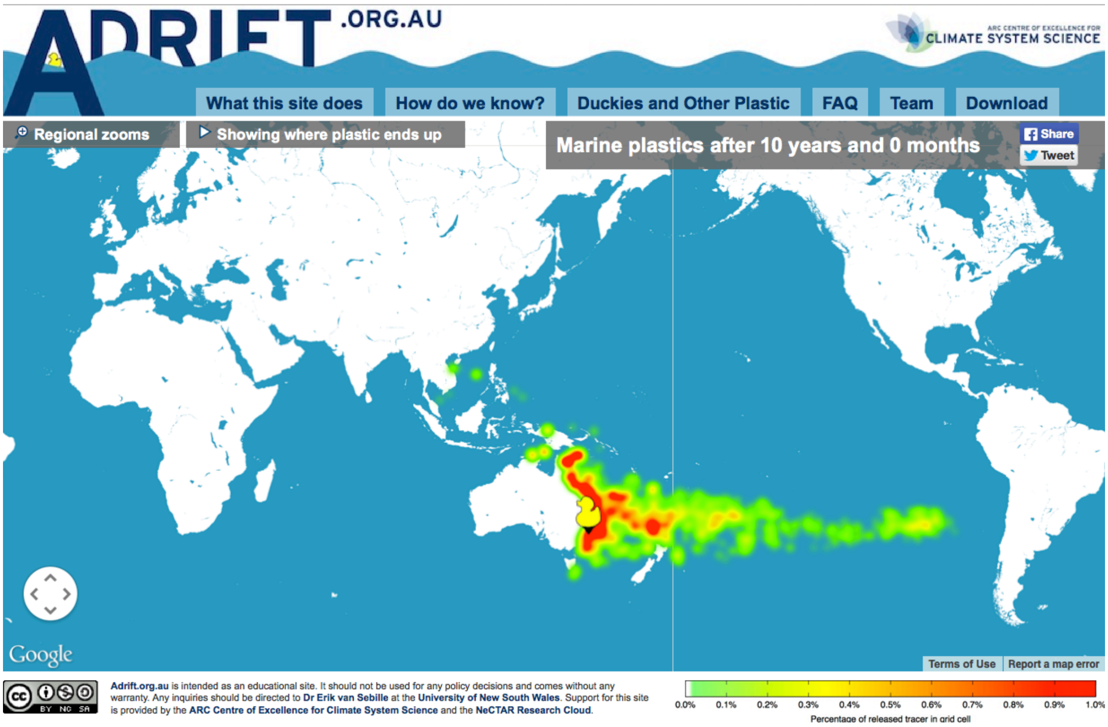


**Figure 1:** Screenshot of adrift.org.au, showing the distribution of tracer released from a grid cell close to Sydney (where the black tip of the yellow duck points) after 10 years. Colors are in percentages of the initial release, and capped at 1% to visually highlight regions with relatively low concentrations. The download button in the top right corner allows for the retrieval of a csv file that contains the data from the simulation.

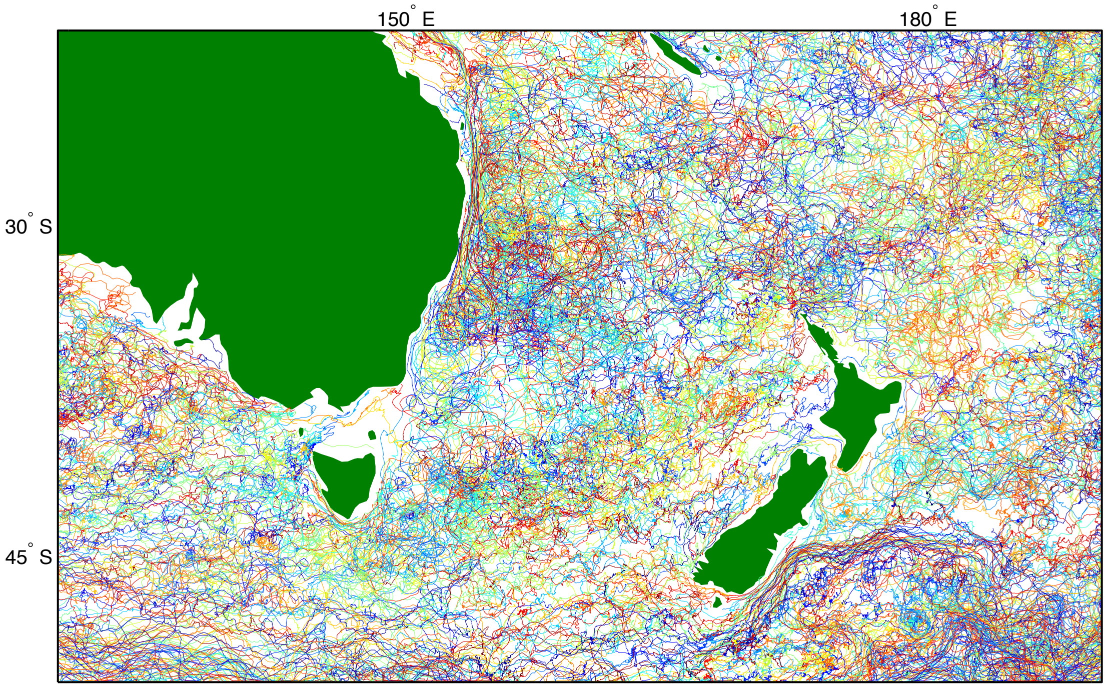


**Figure 2**: A map of all surface drifter trajectories ever to have passed through the area between Eastern Australia and New Zealand. Each drifter has a unique, randomly assigned, color. The drifters are geolocated every six hours. Although there are some regions with fairly low coverage (such as Bass Strait between southeast Australia and Tasmania, overall coverage is higher than 100 fixes per 1° x ° grid cell. This is typical for most of the global ocean.

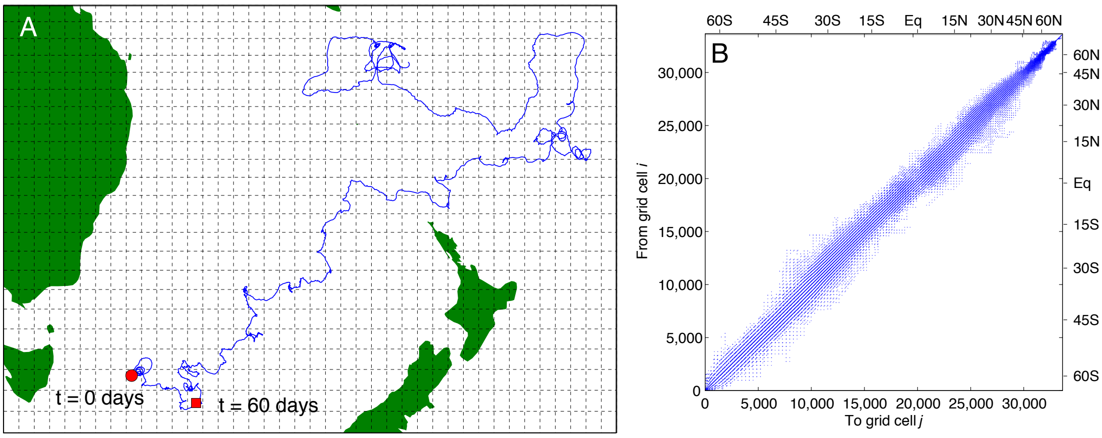


**Figure 3:** Depiction of the methodology to construct the transition matrix $\mathbf{P}_b$, which is used to propagate the distribution of tracer forward in time. The $\mathbf{P}_b(i,j)$ matrix is a row-normalized version of the crossing matrix $\mathbf{C}_b(i,j)$ which holds, for each pair of cells *i* and *j*, the number of times a surface drifter has moved from *i* to *j* in the two-month period *b*. a) Example how, for one drifter trajectory, two points are taken 60 days apart. This is done for each day along the trajectory. b) Depiction of the non-zero entries (in blue) of $\mathbf{P}_1$, the global transition matrix for the months January and February. This matrix shows for a particular row (grid cell *i*), which columns (grid cells *j*) can be reached within 2 months. The ordering of the 33,654 grid cells is from south to north, and the ticks on the top and right of the panel show where some latitudes are located. Because there are more ocean grid cells in the Southern Hemisphere, this scale is non-linear.

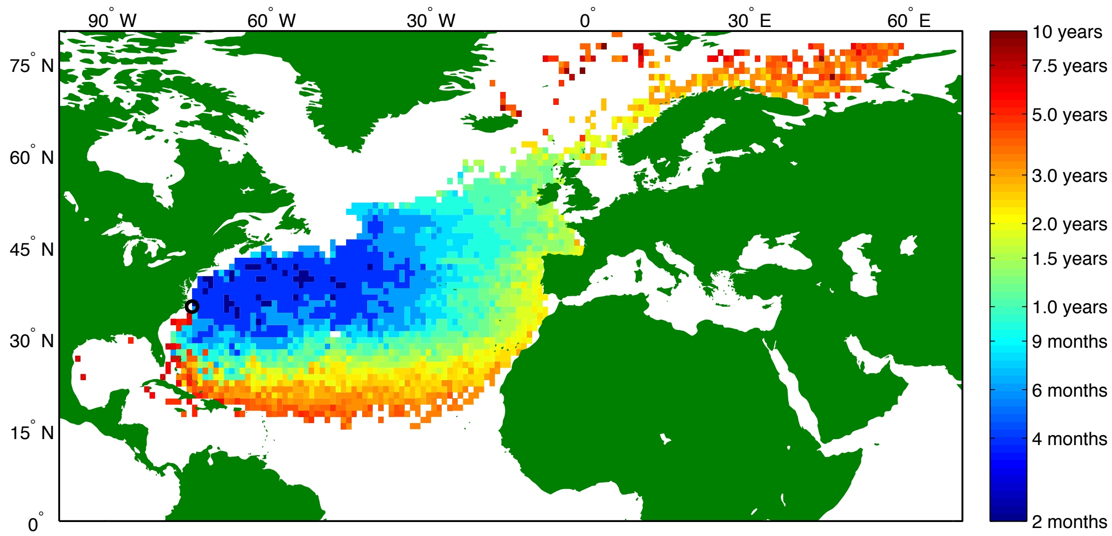


**Figure 4:** Map of the minimum time it takes a particle released from Cape Hatteras (black circle) and passively drifting on the ocean surface to reach other areas in the North Atlantic. White areas cannot be reached in ten years, according to this analysis based on the observed surface buoy trajectories. Note that the color scale is logarithmic.