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Evaluating where and why drifters die

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ABSTRACT

NOAA's Global Drifter Program (GDP) manages a global array of ~1250 active satellite-tracked surface drifting buoys ("drifters") in collaboration with numerous national and international partners. In order to better manage the drifter array and to assess the performance of various drifter manufacturers, it is important to discriminate between drifters that cease transmitting due to internal failure and those that cease due to external factors such as running aground or being picked up. An accurate assessment of where drifters run aground would also allow the observations to be used to more accurately simulate the evolution of floating marine debris, and quantify globally which shores are most prone to the deposit of marine debris. While the drifter Data Assembly Center of the GDP provides a metadata file which includes cause of death, the cause for most drifters is "quit transmitting." In this study it is shown that a significant fraction of these drifters likely ran aground or were picked up, and a statistical estimate that each drifter ran aground or was picked up is derived.

1. Introduction

NOAA's Global Drifter Program (GDP)[1] manages a global array of ∼1250 active satellite-tracked surface drifting buoys (hereafter "drifters") in collaboration with numerous national and international partners. The drifters have a mean lifetime of ∼450 days, requiring the acquisition and deployment of ∼1000 drifters per year to maintain the active array. Drifters die (i.e., cease providing oceanic data) for reasons which can be broadly categorized as internal – for example the drifter quits transmitting due to hull leakage or drained batteries – or external reasons such as running aground or being picked up by a boater. As the GDP and its partners plan deployments, it is important to consider as accurately as possible where these external causes of death are likely to occur. It is also important to consider the causes of death when assessing the performance of drifters from various manufacturers. For example, the GDP calculates the median lifetime of all drifters for each manufacturer deployed in a given year. In principle this should be done only for drifters which died from internal reasons, as drifters which happened to run aground or be picked up soon after deployment should not negatively impact the assessment of the associated manufacturer's drifters. These logistical factors dictate that a careful assessment be made of why and where drifters die.

An accurate assessment of where and why drifters die can also improve scientific appli-

[1] http://www.aoml.noaa.gov/phod/dac

cations of the data. Because the drifters are pseudo-Lagrangian tracers of the ocean surface, their trajectories can be used to estimate the advection and dispersion of oil, plankton and other passive particles. In the simplest such use of these data, all trajectories leaving from an area can be plotted to visualize the downstream fate of particles released in an area. Alternatively, source regions can be visualized by plotting the prior trajectories of drifters that enter a particular area. Such approaches are typically very limited; for example, few drifters may have entered a small region, thus limiting the statistical robustness that can be inferred from their downstream fate. However, if those few trajectories subsequently crossed other trajectories, the number of representative trajectories can be increased by including those trajectories. Because each of those will in turn intersect many more trajectories, an extremely large number of possible trajectories can be derived. Such an approach has been exploited by Brambilla and Talley (2006) and van Sebille et al. (2011), who constructed "composite trajectories" using crossing points and additional criteria intended to follow a particular water mass. Given a model for source regions of marine debris, this type of analysis could be extended to simulate floating plastic, which accumulates in the centers of the major ocean gyres (IPRC, 2008; Law et al., 2010; Maximenko et al., 2011). One of the ways debris is removed from the ocean is by washing ashore, and in principle the model could include this by noting which drifter trajectories ran aground. When a composite trajectory includes one of these "ran aground" trajectories, the simulated debris would be removed from the system. In addition, the location where drifters routinely run aground could be used to identify shores which are particularly exposed to marine debris.

The goal of this paper is to examine where surface drifters run aground, and more generally evaluating why drifters die. We limit our study to the Surface Velocity Program (SVP) type drifter of the GDP (Niiler, 2001; Lumpkin and Pazos, 2007). The drifter Data Assembly Center (DAC) of the GDP records the cause of drifter death in a “directory file” offered at http://www.aoml.noaa.gov/phod/dac/dirall.html. This file is updated approximately every three months. As of June 30, 2010, this file covered 14,554 unique drifters including 1427 that were still alive as of that date. For the remaining 13,127 drifters that had died, the causes of death were:

Ran aground:	3049 (23.2%)
Picked up:	888 (6.8%)
Quit transmitting:	8972 (68.3%)
Unreliable transmissions at end of trajectory:	86 (0.7%)
Bad battery voltage:	37 (0.3%)
Placed in inactive status while still transmitting:	95 (0.7%)

The DAC determines that a drifter is dead after no transmissions have been received for 30 days, after the drifter stops moving, or after its behavior indicates it has been picked up. Every Monday, the DAC updates the status of the drifter array; the software used for this also automatically flags drifters which have moved less than 1 km over the previous seven days or moved at a sustained speed greater than 2 m/s. All drifters which have died in the preceding week are then manually examined for the cause of death. The DAC declares that a drifter has “run aground” when its position data indicates that it has stopped moving, apart from the random jitter introduced by position fix errors (Fig.1c,d), without any evidence that it was picked up first. The DAC determines that a drifter was “picked up” when its trajectory abruptly moves in an artificial manner (such as in straight legs from one point to another), usually accompanied by a large increase in diurnal temperature variations and an abrupt drop in the submergence or tether strain sensors used for drogue detection. A drifter is also declared to have been picked up when its position rapidly moves onto land without intervening location fixes (Fig.1a,b). In many cases, “picked up” drifters are first identified by their non-moving transmissions from their final resting place in a marina or boater’s yard, and the previous behavior is used to manually assess when and where the drifter was picked up. “Unreliable transmissions” may be associated with antennae failures, and are often preceded by poor quality and sporadic location fixes. “Bad battery voltage” was a designation used briefly by the DAC to flag drifters which quit with voltage less than 9V, but is no longer implemented when assessing drifter death. “Placed in inactive status while still transmitting” is done at the request of a few principal investigators to save transmission fees after drifters leave an area of interest or when the drifter is no longer transmitting good sensor data and/or has lost its drogue. Most drifters die due to “quit transmitting”, i.e., the transmissions simply terminate without any change in location indicating why.

[Figure 1 about here.]

The DAC determines when a drogue is lost using submergence or tether strain time series (Lumpkin and Pazos, 2007). Of the 13,127 drifters considered here, 5354 died with the drogue still attached and 7773 died after losing their drogue. The locations of drogue loss (Fig. 2a) include many clustered against windward coastlines such as Brazil and the eastern African coast, suggesting damage during or shortly before running aground. It is plausible that drogue presence could have affected the distribution of deaths by running aground, and merits consideration before collectively treating drogued and undrogued drifter deaths. Fig. 2b,c shows the location of the 1672 drifters that ran aground with drogue attached and of the 1376 drifters that ran aground after losing their drogues. These distributions are not significantly different. Note that this does *not* suggest that an individual drifter with a drogue attached is as likely to run aground as a drifter without one, but only that the distribution of where drifters run aground does not depend significantly upon whether those drifters had drogues attached at the time.

[Figure 2 about here.]

2. Reevaluating the “ran aground” drifters

Fig. 3 shows the locations of all (drogued and undrogued) deaths due to “ran aground”. Most of these deaths are located on or near coastlines. However, there are a few locations visible in Fig. 3 that are not near any land.

[Figure 3 about here.]

Fig. 4a,b shows the histogram of the “ran aground” locations as a function of distance from the nearest coastline, determined from the NOAA Global Self-consistent, Hierarchical, High-resolution Shoreline Database (GSHHS version 2.1), and as a function of depth from the ETOPO1 Global Relief Model. While it is plausible that drifters can “run aground” far from shore if the water is shallower than the bottom of the drogue depth ($\sim$20m), it is unlikely that drifters in an ETOPO1 grid averaging > 100m depth and more than 100km from any shoreline actually ran aground. A total of 222 “ran aground” drifters meet both these criteria (circles in Fig. 3).

[Figure 4 about here.]

These 222 “ran aground” drifters were treated as “quit transmitting” for the remainder of this study, and individually reevaluated for an update of the directory file. In a few cases, the drifters appeared to cease moving due to entering an extremely quiescent location in the ocean, or due to being trapped in a small, non-propagating vortex. These drifters continued motion after having been declared “ran aground”. The subsequent trajectories have now been included in the GDP data base and the cause of death reevaluated. In some high-latitude cases, the drifter may have become frozen in ice. Finally, in a number of cases, the “ran aground” declaration appears to be human error as the trajectory simply terminated without evidence of running aground (i.e., the drifter died by “quit transmitting”). These deaths have been changed to “quit transmitting” in the updated version of the directory file now available on the GDP web page. In this update, 160 (72%) of the 222 were changed to “quit transmitting,” 57 (26%) were changed to “picked up,” often with additional data after the original “quit” location, and two were deemed to have “ran aground” at some point after the original “ran aground” death date.

3. Examining why drifters quit

Fig. 5 shows the spatial distribution of the various death types in deaths per square degree, counted in $2^\circ\times2^\circ$ bins. While the revised “ran aground” are concentrated along the coastlines, the distribution of “picked up” also reflects near-shore fishing activities, particularly concentrated off the coast of Brazil, in the northern Gulf of Guinea, and in the northeastern Indian and western and eastern tropical Pacific basins.

[Figure 5 about here.]

The distribution of “quit transmitting” death locations (Fig. 5) includes a large number concentrated along coastlines (also see Fig. 4c,d). On close inspection, it is clear that a number of these deaths are due to the drifter running aground and immediately ceasing transmission. Because the drifters do not subsequently transmit from a fixed location, they are not flagged as “ran aground” by the DAC; instead, because transmissions cease to be received, they are flagged as “quit transmitting.” For example, many trajectories terminate at the southwestern tip of South America (Fig. 6) where the drifters are presumably running aground (few drifters are picked up in this region).

[Figure 6 about here.]

Because most of the drifter deaths in the directory file are attributed to “quit transmitting,” and some fraction of these represent drifters that actually ran aground and immediately stopped transmitting, it is important to reassess the “quits” to determine which of these actually ran aground or were picked up.

If the death types provided by the DAC are counted in $2^\circ\times2^\circ$ bins (as shown in Fig. 5), then the total number of deaths per square degree D in any given bin can be written as

$$D = D_g + D_{pu} + D_q, \quad (1)$$

where D_g are deaths attributed to "ran aground", D_{pu} are deaths attributed to "picked up", D_q are deaths attributed to "quit transmitting," and we shall ignore the negligible number of deaths due to causes besides these three categories.

Fig. 7 compares the distribution of D_q to the background density of drifter observations N and the mean age of drifters at death. N was calculated by counting in each bin the number of six-hourly drifter observations in the kriged, quality-controlled data set offered by the DAC. The distribution of mean age highlights convergent regions where older drifters tend to accumulate. It is correlated with N because of the increased number of observations collected by these drifters, but the two distributions differ because of the effect of spatially inhomogeneous deployments on N. Away from coastlines, the distribution of D_q resembles that of N more so than mean age at death, suggesting that a large fraction of D_q is caused by internal failures such as hull leakage, battery failure, etc. which are not location-dependent or age-dependent to lowest order.

Anomalously high values of D_q near coastlines are due to drifters that have run aground or were picked up, but have been flagged as "quit transmitting" by the DAC. If D_q^* is the background rate of quit drifters in the absence of any drifters running aground or being picked up, we can write this as $D_q^* = N/r$. The constant r can be estimated by averaging N/D_q in bins with zero grounded or picked up drifters. If the ratio r is plotted as a function of distance from coast for all bins that also satisfy $D_g = D_{pu} = 0$ and $N > 100$ drifter days per square degree (not shown), it is basically constant, with a mean value of 650±7 days (standard error from the standard deviation and number of bins, each assumed to provide an independent estimate). For the subset of these bins that are ≥100 km from the nearest coast, the mean value is not significantly different (654±7 days). Because N has units of drifter days per square degree and D_q^* is the the background number of deaths from quitting per square degree, r is a measure of drifter lifetime in the absence of external causes of death. For comparison, the mean lifetime of all drifters is 384 days, the mean lifetime of drifters identified as "quit transmitting" is 417 days, and the design half-life of a drifter is 450 days. Fig. 7d shows the difference $D_q - N/r$, indicating the deviation "quit transmitting" deaths D_q from the background rate D_q^*.

[Figure 7 about here.]

4. A statistical model for the "quit transmitting" drifters

In the absence of (unavailable) further data on the hundreds of "quit transmitting" drifters creating enhanced values of $D_q - N/r$ (Fig. 7d), we can only make statistical statements about the likelihood that a particular drifter quit due to the background rate or because it actually ran aground or was picked up.

Because we assume that some fraction of the "quit transmitting" drifters actually ran aground or were picked up, an improved estimate of the number of drifters which ran aground, D_g^*, will be greater than or equal to the number D_g identified by the DAC. Similarly, $D_{pu}^* \geq D_{pu}$. This can be expressed as

$$D_g^* = (1 + x_1)\, D_g, \quad D_{pu}^* = (1 + x_2)\, D_{pu}, \tag{2}$$

where constants x_1 and x_2 are both ≥ 0 and superscript $*$ indicates improved estimates of these terms. The background rate of "quit transmitting" drifters, as defined in the previous section, can then be estimated as

$$D_q^* = N/r \sim D_q - x_1 D_g - x_2 D_{pu}, \tag{3}$$

where r=(650±7) days. We solve for the value of the unknown coefficients x_1, x_2 to minimize $(D_q - x_1 D_g - x_2 D_{pu} - N/r)^2$ in all 5109 bins with $N > 100$ observations per square degree. The resulting least squares best fit values are

$$x_1 = 0.240 \pm 0.001, \quad x_2 = 0.430 \pm 0.005. \tag{4}$$

If the background lifetime r is treated as an unknown and determined simultaneously with x_1 and x_2, the results are

$$r = 699 \pm 58 \text{ days}, \quad x_1 = 0.251 \pm 0.042, \quad x_2 = 0.48 \pm 0.13, \tag{5}$$

i.e., not significantly different from the values obtained by first separately solving for r. Our results are not very sensitive to the drogue status of the drifters; if the calculation is repeated for the subset of drifters that were drogued upon dying, the results are:

$$r = 738 \pm 132 \text{ days}, \quad x_1 = 0.237 \pm 0.082, \quad x_2 = 0.31 \pm 0.29, \tag{6}$$

and if calculated only for drifters that were undrogued,

$$r = 733 \pm 100 \text{ days}, \quad x_1 = 0.255 \pm 0.068, \quad x_2 = 0.45 \pm 0.16, \tag{7}$$

not significantly different from the overall results but with larger error bars due to the smaller sample sizes.

Fig. 8 shows D_q for drogued+undrogued drifters (repeated from Fig. 5c), the distribution described by the best-fit model D_q^*, the difference between these two, and the deaths in D_q^* which are attributed to running aground or being picked up. The residual $D_q - D_q^*$ is an unstructured field of noise except for excessively large values against the Antarctic Peninsula and in the East China Sea. Excessive “quit transmitting” against the Antarctic Peninsula is likely due to interaction with ice away from the coastlines (not captured by the term $x_1 D_g$) destroying the drifters, while the elevated number of "quits" in the East China Sea (elevated above the level expected from those seen as "picked up") may be caused by an elevated number of vessels accidentally striking the drifters, or by boaters more likely there than elsewhere to destroy a drifter rather than recover it (thus violating the assumption of a global constant value for x_2).

[Figure 8 about here.]

With these results, we may reassess how many drifters ran aground, how many were picked up, and how many quit transmitting due to internal reasons. Compared to the original numbers given earlier in this paper (original values in parentheses), the reassessed numbers are:

Ran aground:	3520 (3049)
Picked up:	1260 (888)
Quit transmitting at background rate:	8129 (8972)

From our best-fit model for the distribution of "quit transmitting" drifters, we can assess the statistical odds that a particular drifter which "quit transmitting" actually ran aground or was picked up. In each bin, the total number of "quit transmitting" drifters is $D_q = N/r + x_1 D_g + x_2 D_{pu}$, of which $x_1 D_g$ actually ran aground and $x_2 D_{pu}$ were picked up. Then the spatially-varying field

$$\frac{x_1 D_g}{N/r + x_1 D_g + x_2 D_{pu}}, \tag{8}$$

interpolated to the location of a "quit" drifter, gives the odds that it actually ran aground, while the field

$$\frac{x_2 D_{pu}}{N/r + x_1 D_g + x_2 D_{pu}}, \tag{9}$$

gives the odds that it actually was picked up. We have applied this to all drifters in the directory file, generating a new metadata file which gives the odds that each drifter ran aground or was picked up. This file is available at:

`http://www.aoml.noaa.gov/phod/dac/drifter_deaths.html`

In this file, the chance p_g that a drifter ran aground will be 0 for drifters which were identified as "picked up", 1 for drifters identified as "ran aground", and will be in the range $0 \leq p_g < 1$ for drifters identified as "quit transmitting." Similarly, the chance p_{pu} that a drifter was picked up will be 0 for drifters which were identified as "ran aground", 1 for drifters identified as "picked up", and will be in the range $0 \leq p_{pu} < 1$ for drifters identified as "quit transmitting."

5. Application to Marine Floating Debris

Improved information on where drifters run aground can be used to estimate where floating marine debris is likely to be deposited by ocean currents, under the assumption that the debris follows the water like a drifter (i.e., that shear in the upper 15 m is negligible). One way of formulating this problem is documented in Maximenko et al. (2011). In this approach, the advective and turbulent processes that govern particle spreading are assumed to be stationary. In this case, the probability distribution function P that describes how all drifters within a bin will subsequently enter neighboring bins a fixed time T later can be applied at any time to a simulated particle in that bin. Maximenko et al. (2011) calculated this for 1/2° bins with a time step of five days and calculated the spatial distribution of P (see their Fig. 3 for examples of P at various locations in the Pacific Ocean). Starting in May 2005, the same methodology, with five degree bins and a time step of 90d, has been used by R. Lumpkin to make 90-day forecasts of the global drifter array.[2]

As shown by Maximenko et al. (2011), the concentration of a tracer C can be projected forward in time by iteratively solving

$$C(\boldsymbol{x}, t+T) = \int C(\boldsymbol{x}, t) P(\boldsymbol{x}, T) d\boldsymbol{x} + S(\boldsymbol{x}), \qquad (10)$$

[2]See http://www.aoml.noaa.gov/phod/graphics/dacdata/forecast90d.gif

where S represents sources or sinks of C. Maximenko et al. (2011) used this to simulate the evolution of marine debris from an initially homogeneous distribution, with all drifter death locations used as sinks for the tracer. However, these deaths include many drifters which were picked up or quit transmitting from internal causes which ideally should not be included in a simulation of marine debris.

With the results of this study, we can repeat the calculation of Maximenko et al. (2011) but include as sinks only those drifters which ran aground. Drifters which "quit transmitting" with a chance of running aground between 0 and 1 contribute to this chance in the bins where they quit. Fig. 9 shows the resulting concentration of floating marine debris after 10 years of integration, starting from a uniform distribution at a concentration of unity. The vertical bars indicate the grounded concentration on land, with relative heights indicating how much debris has run aground in that bin and colors corresponding to $10\times$ the value in the color scale for floating debris. These results indicate remarkably larger marine debris impact on the coastlines of Alaska and Washington compared to California and most of Oregon, southern Chile compared to Argentina, Brazil compared to northern Chile, and eastern South Africa compared to western South Africa. In addition, they suggest that many mid-latitude islands are particularly threatened locations for deposit of floating marine debris. Note that, while the locations of the bars are supported by real drifters that ran aground, the heights of the bars will likely change in more realistic model runs with the debris sources distributed inhomogeneously along the coastlines.

[Figure 9 about here.]

6. Conclusions

By better understanding why and where drifters die, management of the global array can be improved: deployment locations can be chosen that optimize drifter lifetime, regions where large numbers of drifters are picked up can be targeted for educational outreach efforts, and simulations of the array's evolution can more accurately represent the places that drifters are likely to run aground or be picked up. This information can also be used in a statistical model in which individual trajectories can be processed in a probabilistic way to simulate ocean advection of a particle floating at the ocean surface.

In order to improve our understanding of drifter death causes, we have examined the relevant metadata file, known as the directory file, maintained by the Global Drifter Program's Data Assembly Center (DAC). We identified 222 deaths flagged as "ran aground" which were far from any land or shallow water. The DAC has reassessed the cause of death for these drifters and concluded that 26% of the 222 have been switched to "picked up" and 72% have been switched to "quit". These revised death causes now appear in the updated directory file publicly available at the DAC web page.

In the directory file, the vast majority of drifters die due to “quit transmitting.” The distribution of these deaths (Fig. 7a) reflects the background density of the data (Fig. 7b), but is enhanced in coastal and shallow regions where drifters are frequently picked up or run aground. This indicates that a significant fraction of the drifters that “quit transmitting” did so due to interaction with land or boaters. The fraction of “quit” drifters that ran aground or were picked up can be estimated with a statistical best-fit model (equation 3) based on the distributions of the various causes of drifter death. We conclude that the total number of drifters that ran aground is 24% greater than indicted in the DAC metadata, while the number that were picked up is greater by 43%. Using this best-fit model, we can assess the statistical odds that each individual drifter which “quit transmitting” actually ran aground or was picked up. We have applied this to all drifters in the DAC metadata, generating a new metadata file available at:

`http://www.aoml.noaa.gov/phod/dac/drifter_deaths.html`

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List of Figures

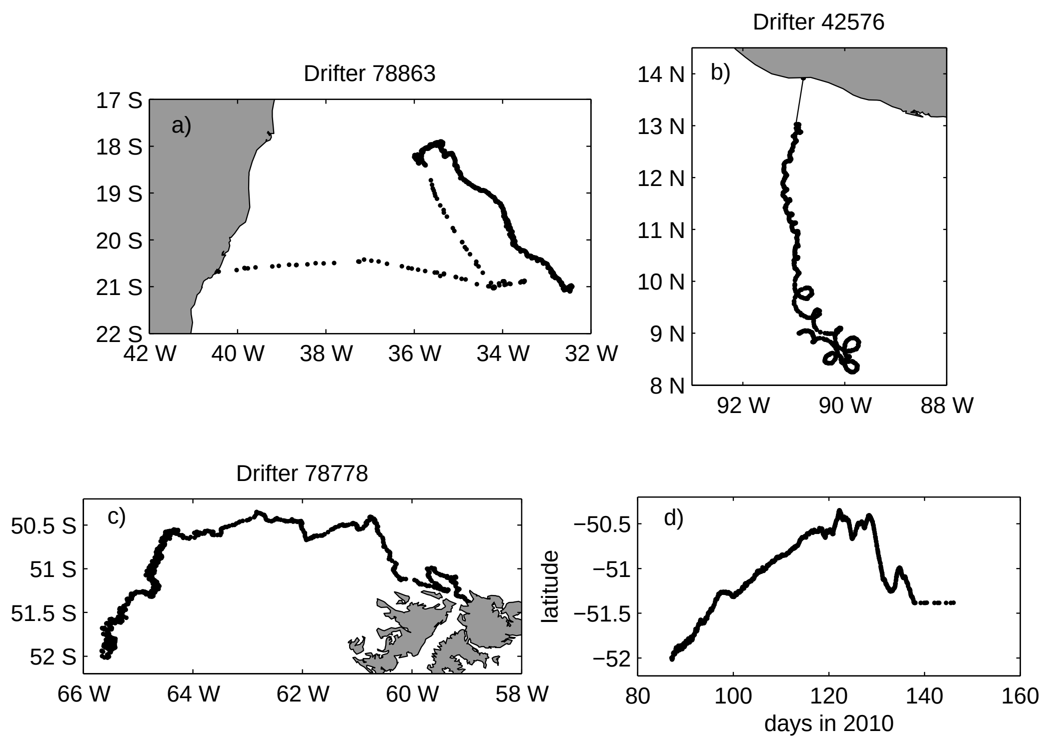
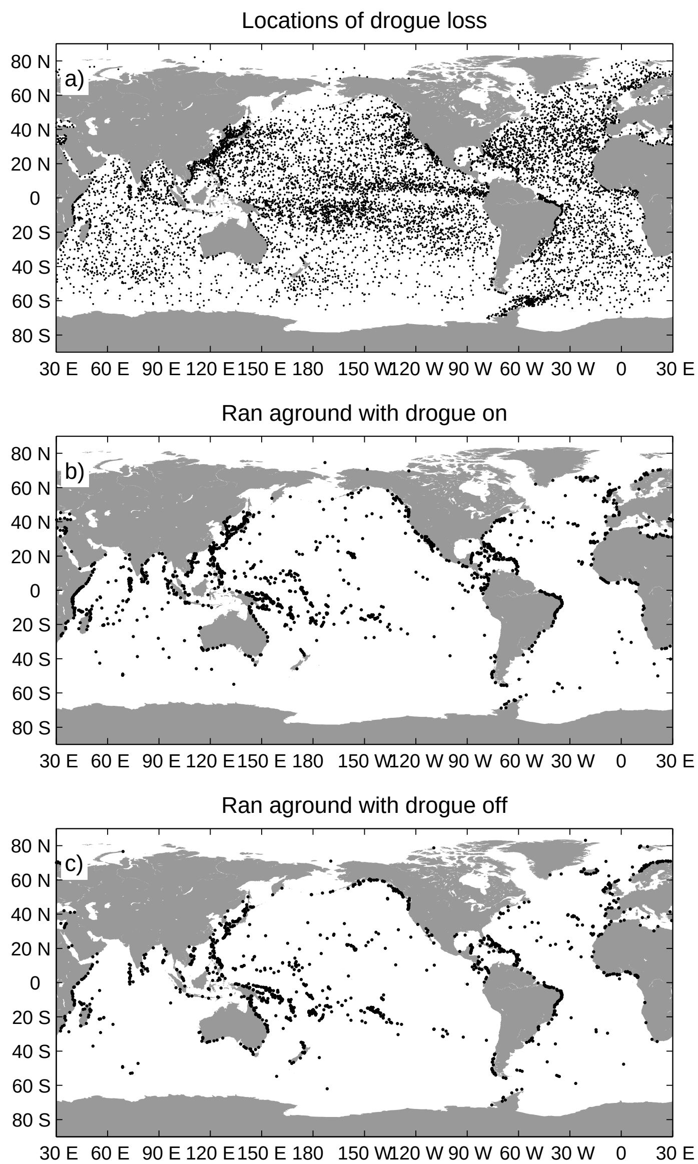


Figure 1: Examples of drifters that were picked up or ran aground. (a) Drifter 78863 was picked up by a vessel and carried southeast at >2 m/s, then west to the Brazilian coast at >3 m/s. (b) Drifter 42576 made an abrupt jump from the ocean to the land at a speed which must have exceeded 5.5 m/s, and remained on the land thereafter. (c) Drifter 78778 ran aground on the Falkland Islands, as also seen in its time series of latitude vs. days in 2010 (d).



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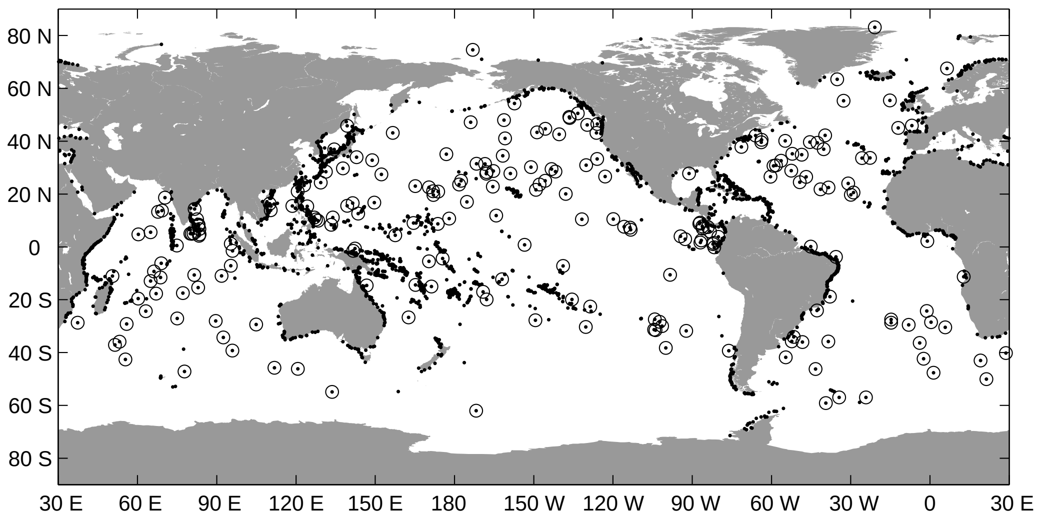
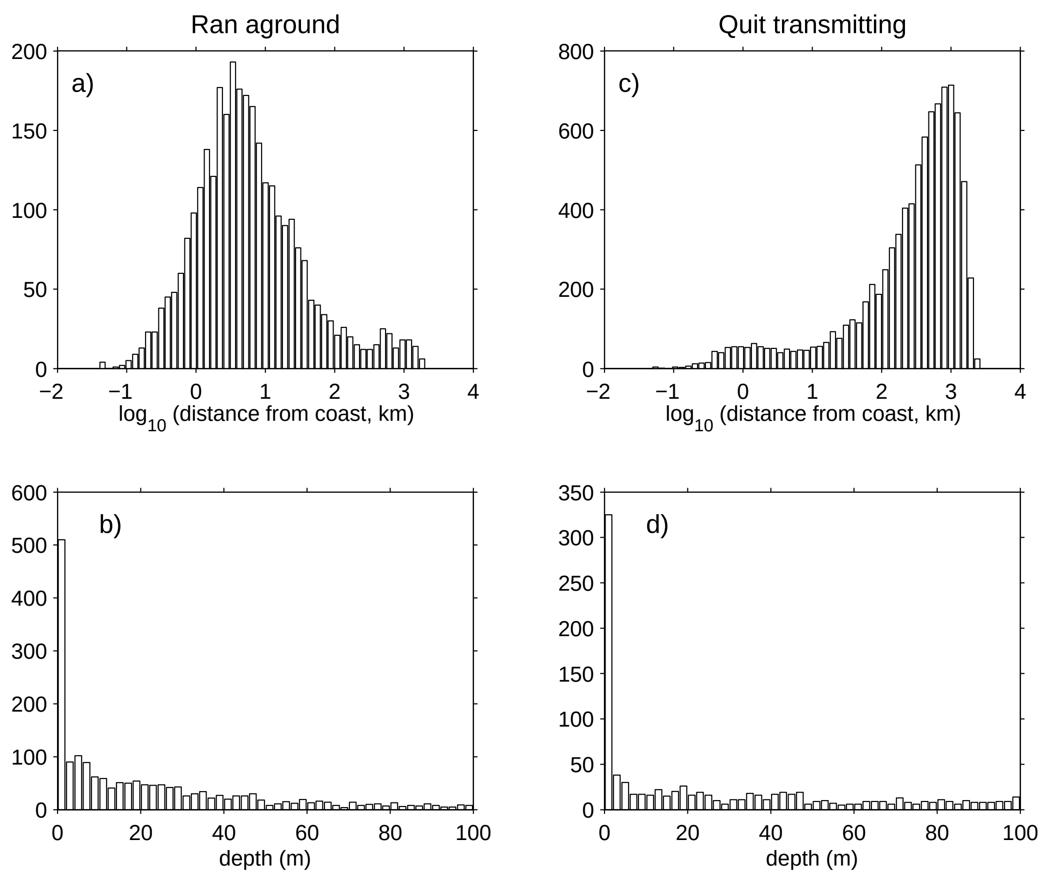


Figure 3: Locations of 3049 "ran aground" death locations. Circles indicate the 222 locations in water >100m deep and >100km from the nearest coast.



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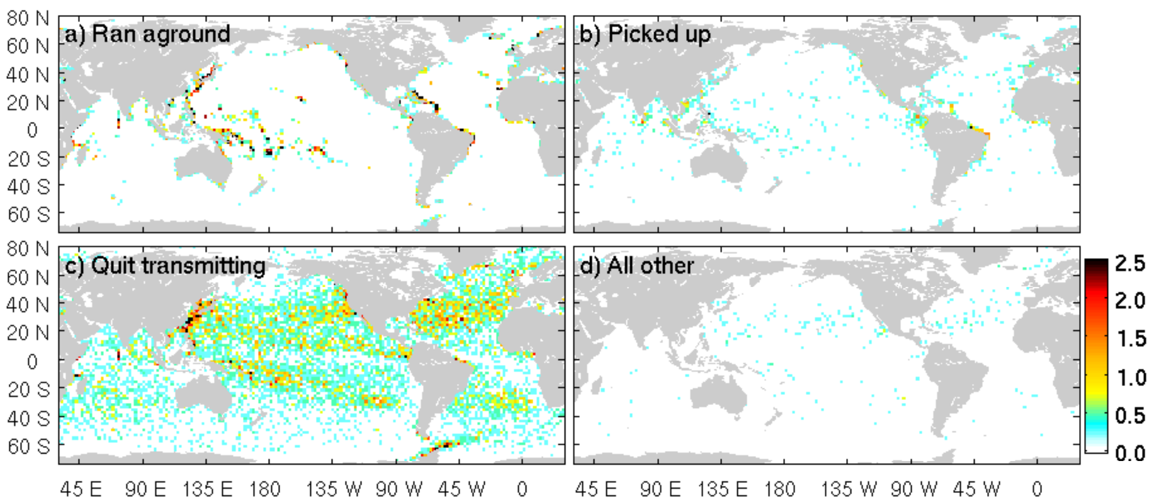

Figure 5: Spatial distribution of deaths from various causes, in deaths per square degree, counted in $2^\circ \times 2^\circ$ bins.

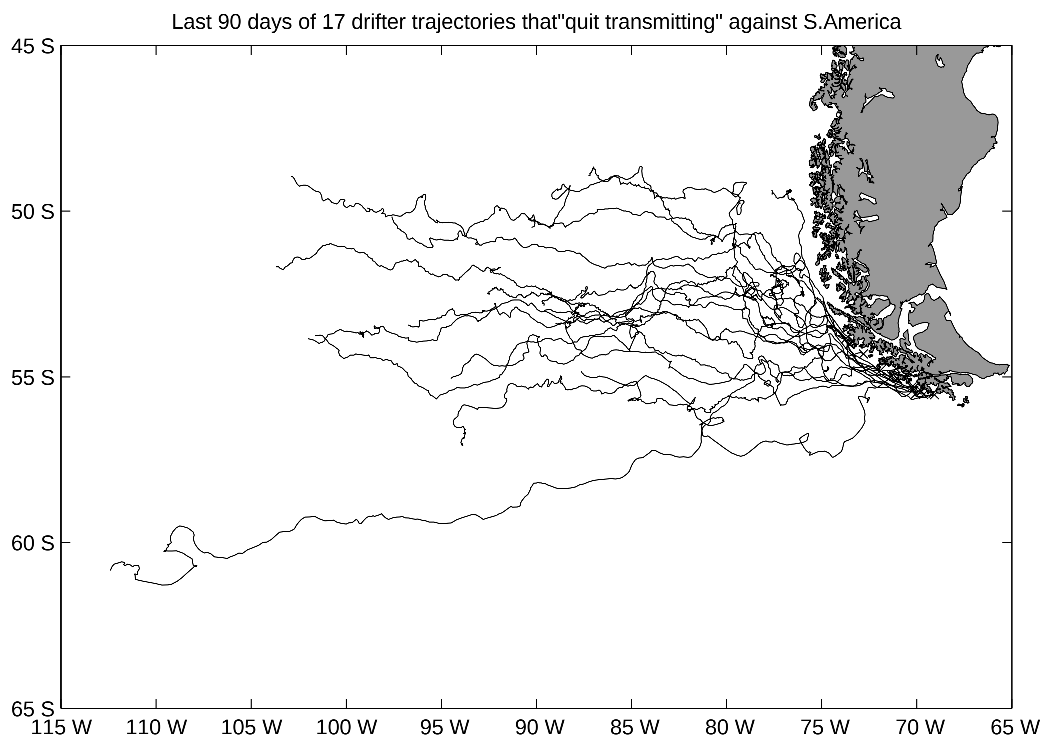

Figure 6: Final 90 days of trajectories for drifters flagged as “quit transmitting” which terminated against the southwest coast of South America.

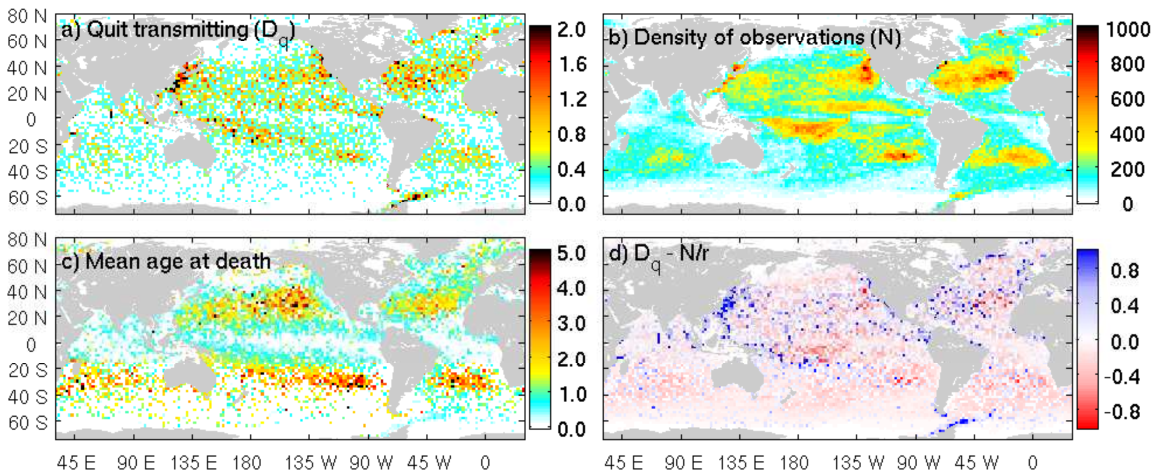

Figure 7: a) Spatial distribution of D_q, deaths per square degree flagged as "quit transmitting". b) N, the number of six-hourly drifter observations per square degree. c) Average age of drifters at death (years). d) $D_q - N/r$ with r =650 days.

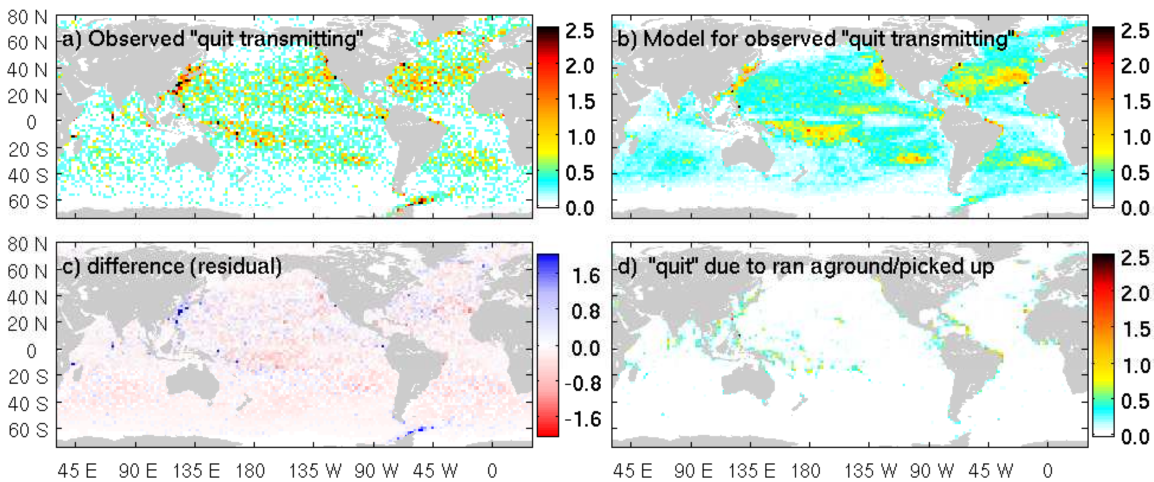

Figure 8: a) D_q, the observed distribution of "quit transmitting" deaths (deaths per square degree). b) modeled distribution (see text). c) residual (top left minus top right). d) estimated distribution of "quit transmitting" deaths caused by drifters running aground or being picked up.

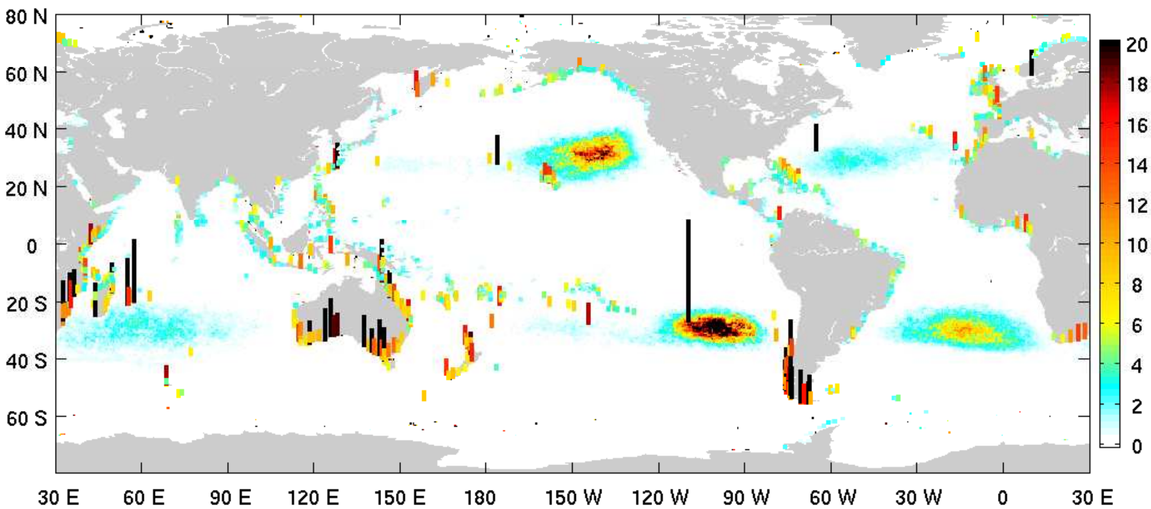

Figure 9: Distribution of the concentration of floating marine debris in arbitrary units, after 10 years of integration from an initially homogeneous distribution of concentration unity. Vertical bars indicate the concentration of material that has washed ashore, with color corresponding to 10× the value in the color bar.