# 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. 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 because of internal failure and those that cease because of 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 to 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 that includes cause of death, the identified cause for most drifters is simply ''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

The National Oceanographic and Atmospheric Administration's (NOAA's) Global Drifter Program (GDP; http://www.aoml.noaa.gov/phod/dac) 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 that can be broadly categorized as internal (e.g., the drifter quits transmitting because of hull leakage or drained batteries) or external (e.g., 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 that died from internal reasons, since drifters that 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 applications 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

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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. 2012). 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 locations where drifters routinely run aground could be used to identify shores that are particularly exposed to marine debris.

The goal of this paper is to examine where surface drifters run aground and, more generally, to evaluate 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 available online (at http://www.aoml.noaa.gov/phod/dac/dirall.html). This file is updated approximately every three months. As of 30 June 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 given as follows:

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 that have moved less than 1 km over the previous 7 days or moved at a sustained speed greater than 2 m $s^{-1}$. All drifters that 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 indicate that it has stopped moving, apart from the random jitter introduced by position fix errors (Figs. 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 (Figs. 1a,b). In many cases, ''picked up'' drifters are first identified by their nonmoving 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 antenna 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 that quit with voltage less than 9V, but this category 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).

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 this merits consideration before collectively treating drogued and undrogued drifter deaths. Figures 2b and 2c show the location of the 1672 drifters that ran aground with drogue attached and 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

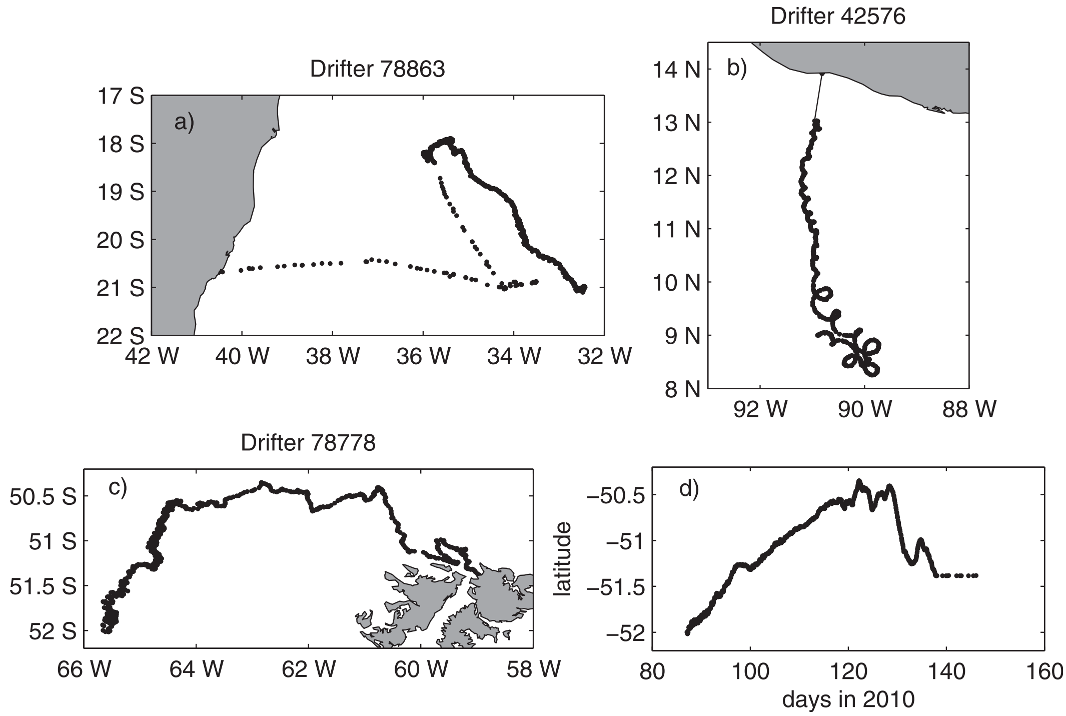


FIG. 1. Examples of drifters that were picked up or ran aground. (a) Drifter 78863 was picked up by a vessel and carried southeast at >2 m s$^{-1}$, then west to the Brazilian coast at >3 m s$^{-1}$. (b) Drifter 42576 made an abrupt jump from the ocean to the land at a speed that must have exceeded 5.5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

distribution of where drifters run aground does not depend significantly upon whether those drifters had drogues attached at the time.

## 2. Reevaluating the ''ran aground'' drifters

Figure 3 shows the locations of all (drogued and undrogued) deaths classified as ''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.

Figures 4a and 4b show 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 1 arc-min 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 (~20 m), it is unlikely that drifters in an ETOPO1 grid averaging >100-m depth and more than 100 km from any shoreline actually ran aground. A total of 222 ''ran aground'' drifters meet both these criteria (circles in Fig. 3).

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 because of entering an extremely quiescent location in the ocean, or being trapped in a small, nonpropagating vortex. These drifters continued motion after having been declared ''ran aground.'' The subsequent trajectories have now been included in the GDP database 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 run aground at some point after the original ''ran aground'' death date.

## 3. Examining why drifters quit

Figure 5 shows the spatial distribution of the various death types in deaths per square degree, counted in 2° × 2° bins. While the revised ''ran aground''

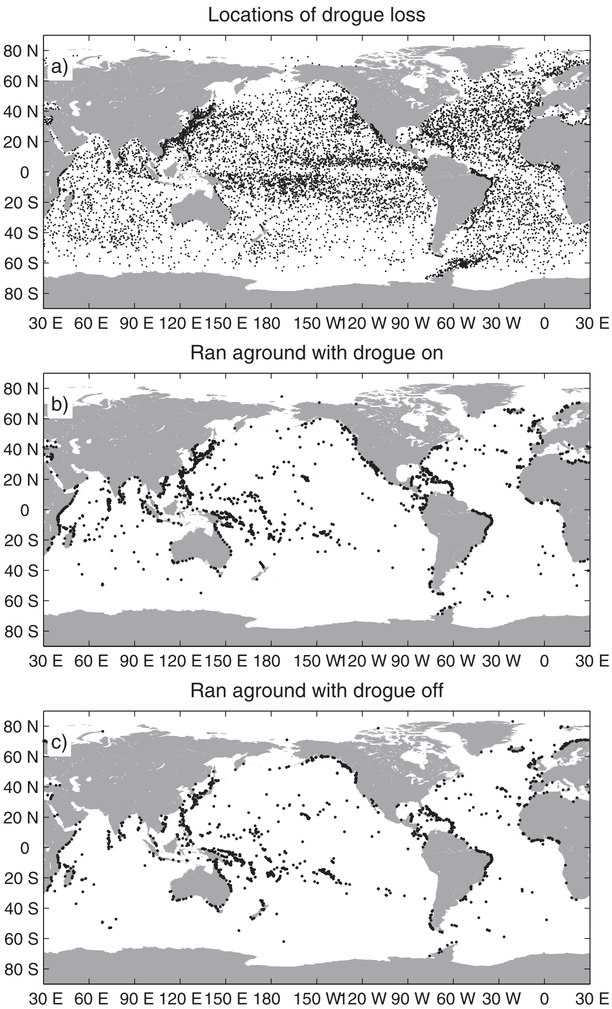


FIG. 2. (a) Locations of drogue loss for 5354 drifters. (b) Locations of 1672 ''ran aground'' death locations for drifters with drogues on. (c) Locations of 1376 ''ran aground'' death locations for drifters with drogues off.

instances are concentrated along the coastlines, the distribution of ''picked up'' data also reflects nearshore 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.

The distribution of ''quit transmitting'' death locations (Fig. 5) includes a large number concentrated along coastlines (also see Figs. 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

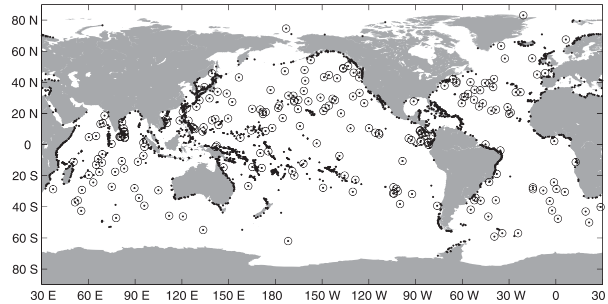


FIG. 3. Locations of 3049 ''ran aground'' death locations. Circles indicate the 222 locations in water >100 m deep and >100 km from the nearest coast.

South America (Fig. 6) where the drifters are presumably running aground (few drifters are picked up in this region).

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 $2° \times 2°$ bins (as shown in Fig. 5), then the total number of deaths per square degree $D$ in any given bin can be written as

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

where $D_g$ are deaths attributed to ''ran aground,'' $D_{\mathrm{pu}}$ 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 other than these three categories.

Figure 7 compares the distribution of $D_q$ to the background density of drifter observations $N$ and the mean age of drifters at death. Note that $N$ was calculated by counting in each bin the number of 6-hourly drifter observations in the kriged, quality-controlled dataset 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

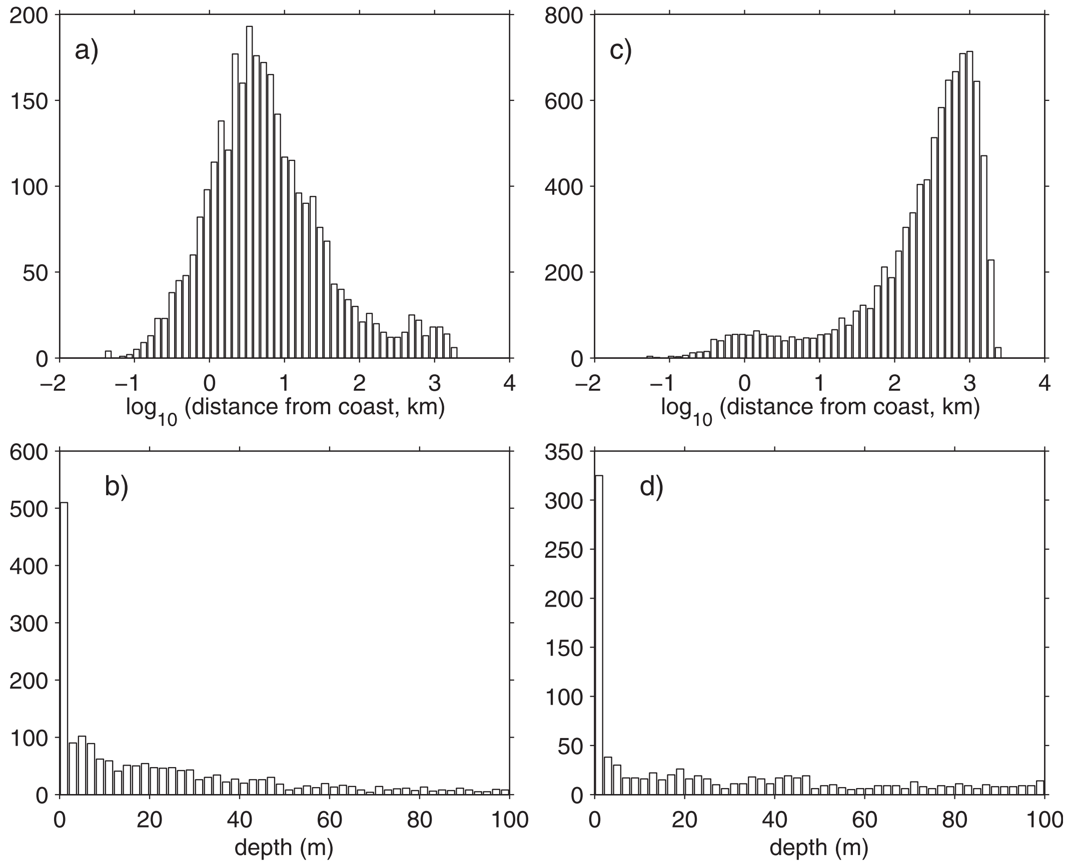


FIG. 4. (left) Histograms of ''ran aground'' and (right) ''quit transmitting'' death locations as a function of (a) distance from coast and (b) depth (depths >100 m not shown).

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

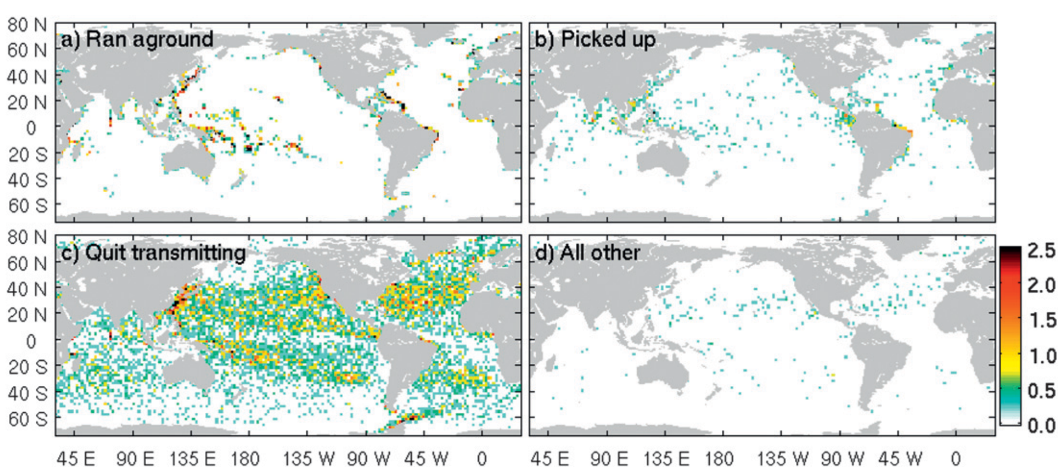


FIG. 5. (a)–(d) Spatial distribution of deaths from various causes, in deaths per square degree, counted in 2° × 2° bins.

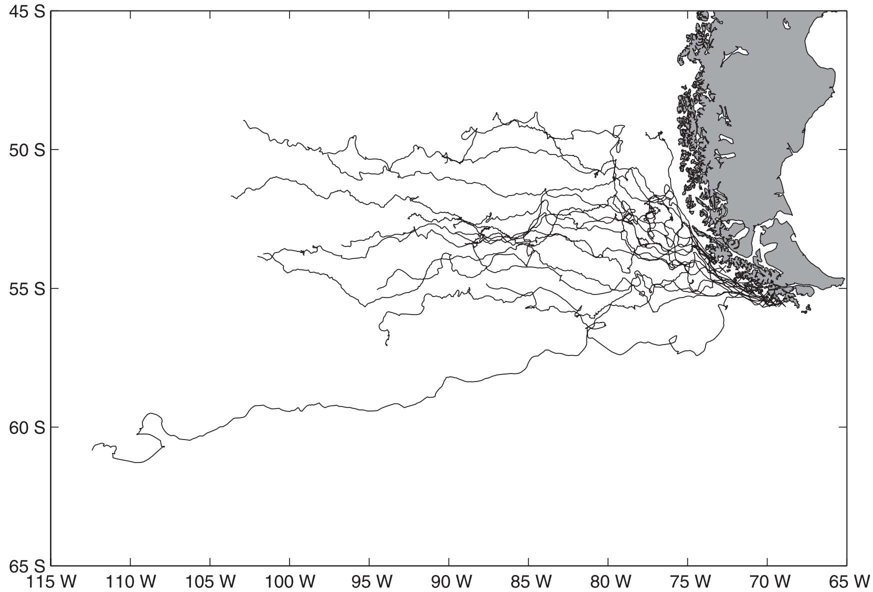


FIG. 6. Final 90 days of trajectories for drifters flagged as ''quit transmitting'' that terminated against the southwest coast of South America.

units of drifter days per square degree and $D_q^*$ is 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. Figure 7d shows the difference $D_q - N/r$, indicating the deviation of ''quit transmitting'' deaths $D_q$ from the background rate $D_q^*$.

## 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 because of 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 that 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

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

where constants $x_1$ and $x_2$ are both $\geq 0$ and a superscript asterisk (*) indicates improved estimates of these terms.

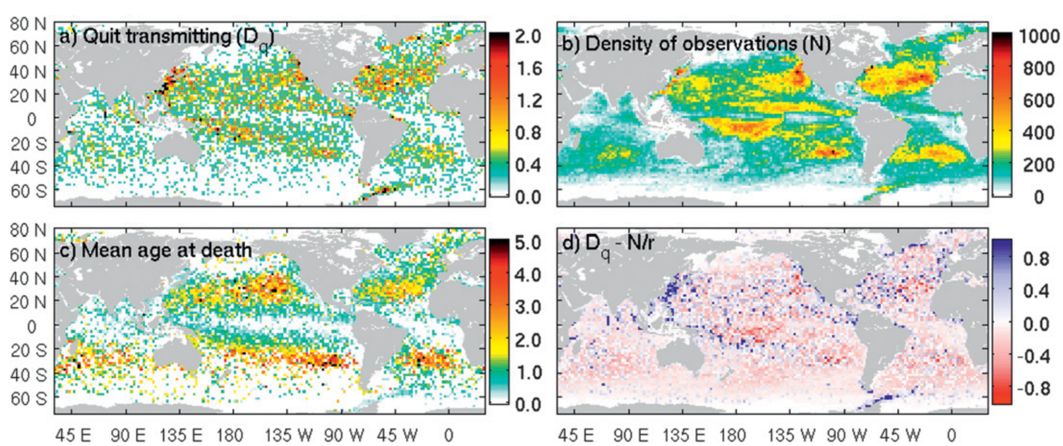


FIG. 7. (a) Spatial distribution of $D_q$, deaths per square degree flagged as ''quit transmitting''; (b) $N$, the number of 6-hourly drifter observations per square degree; (c) average age of drifters at death (yr); and (d) $D_q - N/r$ with $r = 650$ days.

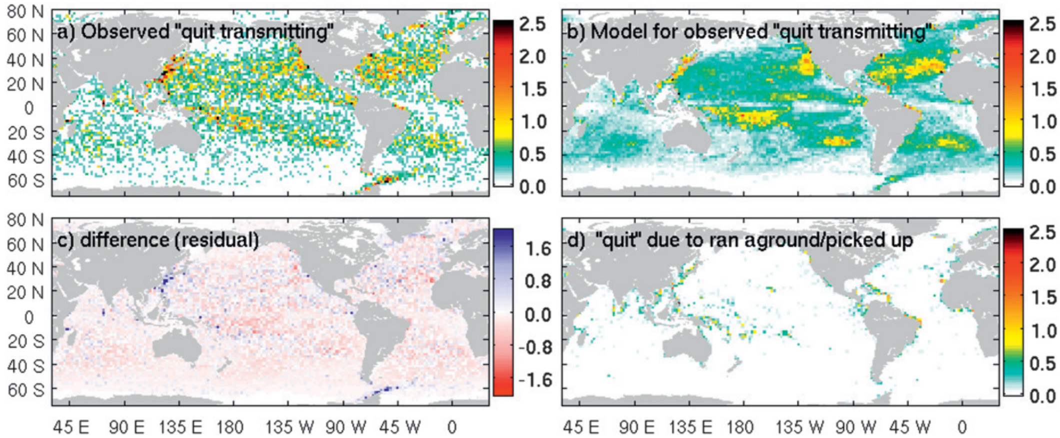


FIG. 8. (a) The observed distribution of ''quit transmitting'' deaths $D_q$ (deaths per square degree). (b) Modeled distribution (see text). (c) Residual (top left minus top right). (d) Estimated distribution of ''quit transmitting'' deaths caused by drifters running aground or being picked up.

The background rate of ''quit transmitting'' drifters, as defined in the previous section, can then be estimated as

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

where $r = (650 \pm 7)$ days. We solve for the value of the unknown coefficients $x_1$, $x_2$ to minimize $(D_q - x_1 D_g - x_2 D_{\rm pu} - N/r)^2$ 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, the results are

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

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

Figure 8 shows $D_q$ for all (drogued and 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 $D_q^*$ that 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'' values near the Antarctic Peninsula are 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 $x_2$).

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

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 that ''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

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

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

$$\frac{x_2 D_{pu}}{N/r + x_1 D_g + x_2 D_{pu}} \qquad (9)$$

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 that gives the odds that each drifter ran aground or was picked up. This file is available online (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 that were identified as "picked up" and 1 for drifters identified as "ran aground", and will be in the range $0 \le p_g < 1$ for drifters identified as "quit transmitting." Similarly, the chance $p_{pu}$ that a drifter was picked up will be 0 for drifters identified as "ran aground" and 1 for drifters identified as "picked up", and will be in the range $0 \le p_{pu} < 1$ 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. (2012). 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. (2012) calculated this for ½° bins with a time step of 5 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 5° bins and a time step of 90 days, has been used by R. Lumpkin to make 90-day forecasts of the global drifter array (see http://www.aoml.noaa.gov/phod/graphics/dacdata/forecast90d.gif).

As shown by Maximenko et al. (2012), the concentration of a tracer $C$ at position $\boldsymbol{x}$ and time $t$ can be projected forward in time by iteratively solving

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

where $S$ represents sources or sinks of $C$. Maximenko et al. (2012) 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 that were picked up or quit transmitting from internal causes that 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. (2012) but include as sinks only those drifters that ran aground. Drifters that "quit transmitting" with a chance of running aground between 0 and 1 contribute to this chance in the bins where they quit. Figure 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 midlatitude 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.

## 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.

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" that were far from any land or shallow water. The DAC has reassessed the cause

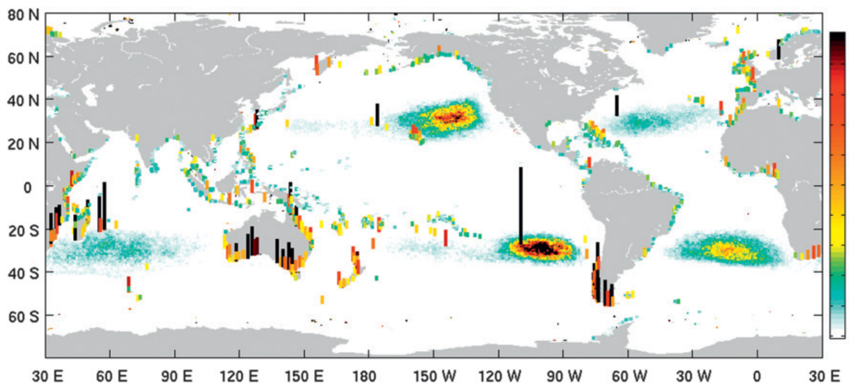


FIG. 9. Distribution of the concentration of floating marine debris in arbitrary units, after 10 years of integration from an initially homogeneous distribution of concentration unity. Vertical bars indicate the concentration of material that has washed ashore, with color corresponding to 10 times the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

of death for these drifters: 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 because of 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 [Eq. (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 that ''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 online (at http://www.aoml.noaa.gov/phod/dac/drifter_deaths.html).

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