Debris Accumulation Scenarios in Washington State from the March 2011 Tōhoku Tsunami

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Cover photo of debris in the coastal waters off Japan, taken shortly after the 2011 Tohoku tsunami. Image Credit: U.S. Navy

Abstract

The Japanese government estimates that approximately 5 million tons of debris washed out to sea after the Tōhoku tsunami that struck Japan on March 11, 2011. Of that mass, about 1.5 million tons probably floated away from the near-coastal environment and could be transported to the beaches fringing the northeast Pacific Ocean, including the coast of Washington state. The debris has been difficult to track and represents a potential human and environmental hazard that results in concern about the type and volume of tsunami-generated materials that may wash ashore over the next few years. This analysis uses evidence from oceanographic studies and models to identify likely pathways and sinks for debris and estimate the fraction that might land in Washington. Results suggest that at least 75 percent of the floating debris will not make landfall and will end up in the Pacific Sub-Tropical Convergence Zone. The remaining debris may make landfall, and observations suggest that most is likely to land along the coast of Alaska over multiple years as debris is entrained in and redistributed from the Sub-Arctic Gyre. In Washington, this analysis suggests that most of the debris that makes landfall will do so relatively rapidly (within 3-4 years). It is unlikely, however, that all of the debris will come ashore in any one year. We estimate that no more than 138,000 tons is likely to land along the coast of Oregon, Washington and British Columbia in any single year, with 11,000 tons as a more probable amount. If distributed evenly along the full length of tidal shoreline, this mass of debris would amount to between 0.5 and 6.7 tons/mile of beach, or about 1-13 times the current estimated "baseline" debris delivery to the outer coast of Washington state. Additionally, we estimate that this elevated level of debris accumulation will occur for a relatively short amount of time (1-2 years). Individual beaches may receive significantly more or less accumulation due to local oceanographic effects. While it is likely that tsunami debris will continue to make landfall for years to come, the levels of accumulation in Washington will probably not appreciably exceed the existing debris baseline beyond 2015.

Background

Perceived as a problem in Washington state for decades, potential impacts of marine debris include wildlife interactions, habitat degradation, a reduction in the aesthetic quality of the shoreline and risks to human and environmental health (Environmental Protection Agency, 2011). While a number of individuals and organizations have worked to remove debris from Washington's beaches for some time (Washington Coast Savers, 2012), the possibility of an increased flow of debris due to the March 2011 Tōhoku tsunami has galvanized the public and media and generated interest among federal and state agencies (e.g., National Oceanic and Atmospheric Administration (NOAA); Environmental Protection Agency (EPA); Washington departments of Natural Resources, Ecology, Fish and Wildlife, Health and Emergency Management; tribal governments; local governments; and nongovernmental organizations).

The tsunami was devastating to communities in Japan and swept to sea an estimated 5 million tons of debris, of which approximately 1.5 million tons is estimated to be floating debris that could potentially recruit to beaches on the West Coast of North America (NOAA Marine Debris Program, 2012). Indeed, tsunami debris has already been confirmed from beaches fringing the northeast Pacific Ocean (Mullen, 2012). There is growing concern that significant quantities of debris, above and beyond "normal" background levels, could represent a true human or ecological hazard. Marine debris generally is very difficult to track in the open ocean (Mace, 2012), and the effort to track the debris from the Tōhoku tsunami has been similarly challenging (NOAA Marine Debris Program, 2012).

Continued difficulties in tracking Tōhoku tsunami debris warrant the use of other approaches for predicting its impact. There are numerous specific management questions associated with this debris: Will there be toxic material? When and where will large items like ships or whole buildings make landfall? Will the debris carry invasive species? However, the fundamental question considered in this report is, "Where, and in what quantities, will debris make landfall?" This question is important for those tasked with managing this debris as a solid-waste problem, for natural resources damage assessment, and for developing removal strategies. The objectives of this analysis are to:

1. Review available published literature on patterns and processes driving the distribution of debris in the north Pacific; and
2. Integrate the collected information to formulate a range of scenarios regarding the potential mass of beached tsunami debris expected on the coast of Washington.

A Note Regarding Uncertainty

This analysis attempts to quantify ranges of the mass of debris associated with the Tōhoku tsunami expected to reach the shores of Washington state. The goal is to support efforts to plan for elevated volumes of debris and address questions such as: Will the tsunami debris overtax the existing network of largely community-based clean-up efforts? Will additional support be required to support disposal? Will a larger clean-up effort, perhaps including on-the-ground responders, be required? This is fundamentally a quantitative analysis, and the final conclusions are based on the underlying assumption that the volumes used as input are reasonable estimates. Unfortunately, there is significant uncertainty in this assumption. For example, throughout the paper we use the figure of 1.5 million tons of floating debris generated by the tsunami, but this is only an estimate. The actual mass of debris floating in the Pacific Ocean from the Tōhoku tsunami could be quite a bit less, or more, than this rough estimate made by Japanese officials after the event. Similarly, a baseline estimate of the current debris load to Washington's Pacific coast beaches is used to provide context for the quantitative estimates of tsunami debris making landfall. This figure (0.5 tons/mile) was estimated using data collected by volunteers during the Olympic Coast Clean-up (Washington Coast Savers, 2012) but includes uncertainty derived from the estimations of debris weight and the length of beach cleaned during those clean-ups. Additional information from the Grassroots Garbage Gang, which routinely cleans 22-28 miles of beach on Long Beach Peninsula on the southwest Washington coast, suggests that the beaches there accumulate on the order of 0.25-0.60 tons/mile during the winter (*www.ourbeach.org*). These estimates provide a point of comparison and allow the reader to visualize the possible debris scenarios in the context of the "normal" debris load. At the same time it is essential to recognize that they are uncertain.

Patterns of Beached Debris

The Worst-Case Scenario

It is instructive to put the estimate of the mass of floating debris from the Tōhoku tsunami into context. A million-and-a-half tons is a significant quantity. As a first step toward deriving scenarios for planning, we can imagine a worst-case scenario: all of that debris washing up at one time evenly distributed along the entire West Coast of North America (from Alaska to Baja). While the length of any coast can vary depending on how it is measured (the so-called coastline paradox), we will use the very coarse estimate of the length of the general sea coast as described by NOAA's National Ocean Service, which ignores islands, embayments and complex coastal features. For the entire West Coast of North America, the estimate of the general seacoast length used here is 8,544 miles (Table 1). Under this scenario we could expect about 175 tons of debris per mile of beach, or about 350 times the estimated debris baseline of 0.5 tons/mile/year (Washington Coast Savers, 2012).

Table 1. Length of the "General Sea Coast" (ignoring islands, embayments and complex coastal features) and the full "tidal shoreline" of the U.S. mainland West Coast, Alaska, British Columbia and the Baja Peninsula. "NOAA NOS" refers to NOAA's National Ocean Service.

Location	General Sea Coast (mi)	Tidal Shoreline (mi)	Source
Oregon	296	1410	NOAA NOS
Washington	157	3026	NOAA NOS
Alaska	5580	31,383	NOAA NOS
California	840	3427	NOAA NOS
British Columbia	600	15,985	CA Dept of Energy, Mines and Resources, Survey and Mapping Branch
Baja Peninsula (Pacific Side)	1071	Not Available	Google Earth
Total	8,544	>55,231	

The worst-case scenario is, of course, highly improbable, since it is reasonable to expect that the amount of debris making landfall will vary in both time and space. Indeed, there is a clear suggestion from past investigations that landfall of debris may stretch into years or even decades (Ebbesmeyer et al., 2007), that some may distribute outside of the north Pacific (Ebbesmeyer, 2004), and that much of it may never make landfall at all (Ingraham et al., 2001; Pichel et al., 2007; Lebreton et al., 2012; Maximenko et al., 2012). It is therefore likely that the actual mass of debris making landfall, per year and per mile, will be quite a bit less than is implied by the worst-case scenario described above.

First Revision: The 2 Percent Axiom

The worst-case scenario described above can be improved upon by turning to a hypothesis proposed by debris-tracker and oceanographer Dr. Curtis Ebbesmeyer for estimating the recovery of "tracers": As the distance from the tracer release point to the area of landfall increases, the percentage of tracers that are actually recovered on the beach will decrease. For distances greater than 1000 miles, Dr. Ebbesmeyer suggests a general estimate of about 2 percent of the initial number of tracers is likely to be recovered (Ebbesmeyer et al., 1994; Hiedorn, 2010). This rough estimate will be referred to below as the 2 percent axiom.

The 2 percent axiom is based on empirical evidence. In May of 1990, approximately 80,000 Nike shoes were accidentally lost from a container ship about 500 miles south of Dutch Harbor, Alaska, and 1,600 miles northwest of Washington state (Figure 1). Approximately 1,600 (2.6 percent) of those shoes had been recovered and confirmed from the coasts of Alaska, British Columbia, Oregon and Washington by 1994, with unconfirmed reports of thousands more (Ebbesmeyer et al., 1992, 1994). Next, the recovery rate of 4,518 bottles released between 1957 and 1959 at Ocean Station Papa, an oceanographic monitoring station (Figure 1), was 2.7 percent by 1992 (Ebbesmeyer et al., 1992). Of a second series of drift bottle releases (N=663) occurring between 1960 and 1966, a total of 16 (2.4 percent) were recovered by 1994 (Ebbesmeyer et al., 1994). Finally, another

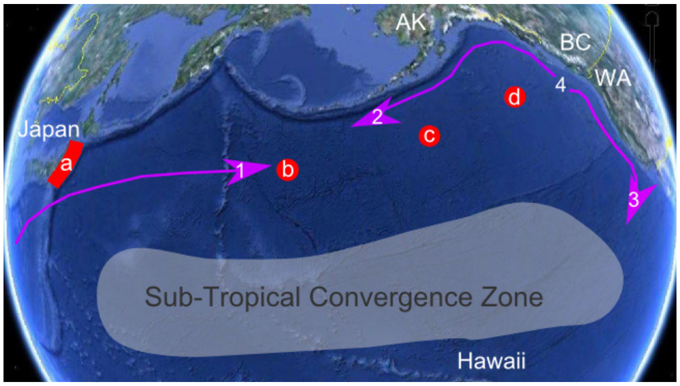

Figure 1. The north Pacific Ocean, with release points for debris or tracers discussed in the text, including the Tōhoku tsunami (a), the 1992 spill of 28,800 plastic toys (b), the 1990 spill of ~80,000 Nike shoes (c), and glass bottles deployed at Ocean Station Papa (d). Purple arrows describe long-term mean currents, including the Kuroshio (1), the Alaska (2) and the California (3) currents, and (4) marks the general location of the Alaska and California currents. Image: Google Earth.

unplanned release of 28,800 plastic toy animals occurred in January 1992 about 500 miles south of Adak, Alaska, and 2,500 miles west of Washington (Figure 1). By 1994, about 400 (1.4 percent) of those toys had been reported from the coast of Alaska (Ebbesmeyer et al., 1994), and by 2007, some 500 more toys had been confirmed, bringing the total recovery rate to 3.3 percent (Ebbesmeyer et al., 2007).

It is likely that the 2 percent axiom will underestimate the amount of debris that actually makes landfall, though. First, it is derived primarily from landings on coasts fringing the northeast Pacific Ocean (Alaska, British Columbia, Oregon and Washington). This stretch of coast is where the beachcombers that recover and monitor items reported in the cited investigations are most active, suggesting that landfalls in other locations may go unreported to the researchers who are tracking debris. Next, this section of coast includes very remote beaches, and tracers that wash up may never be seen, much less recovered and reported to investigators. Since 1979, more than 14,000 satellite-tracked oceanographic "drifters" have been released across the global ocean, and their movement patterns indicate that approximately 20 percent are driven ashore over time (Lumpkin et al., 2012). These drifters do not require physical recovery and may suggest a more accurate estimate of the fraction of floating debris that can be expected to come ashore. Regardless, the 2 percent axiom provides a potentially useful starting point for estimating potential tsunami debris impacts along the coasts of Alaska, British Columbia, Oregon and Washington.

Second Revision: Debris Sinks in the North Pacific

Before applying the 2 percent axiom to the debris from the Tōhoku tsunami, it is useful to consider other relevant questions regarding the eventual fate of debris: If the 2 percent axiom is correct, where does the other 98 percent of tracers end up? Since they are never recovered, the answer to that question cannot be certain, but the largest fraction may remain in the Pacific Ocean without ever making landfall. Ingraham and Ebbesmeyer (2001) seeded a virtual Pacific Ocean with 113 uniformly spaced tracers within the OSCURS model environment and then tracked them over two 12-year intervals beginning in 1965 and 1977. For both model runs, a vast swath of the sub-tropical Pacific (south of 42° N) accumulated approximately 75 percent of the virtual tracers after 12 years. Additional work applying oceanographic models to the problem of identifying the fate of marine debris has corroborated the idea that the sub-tropical Pacific is a dominant sink for marine debris in the Pacific Ocean (Lebreton et al., 2012; Potemra, 2012). This area has been characterized as the Sub-Tropical Convergence Zone (Figure 1), or, colloquially, as the "North Pacific Garbage Patch" (Environmental Protection Agency, 2011). Over time, debris in this area probably breaks into increasingly small pieces and concentrates both on the surface and at depth (Environmental Protection Agency, 2011), but probably does not makes landfall.

Numerical model results can include a great deal of (often) uncharacterized uncertainty and must therefore be interpreted cautiously, but in this instance, there is empirical evidence to support the general conclusion that a great deal of marine debris accumulates in the Sub-Tropical Convergence Zone. Maximenko et al. (2012) suggest, based on an analysis of satellite-tracked drifters released all over the global ocean, that over long time-scales (greater than 10 years, for example) and without continued inputs of debris, the sub-tropical Pacific Ocean would probably act as a sink for much of the debris afloat in the Pacific Ocean (Figure 2). Additionally, a marine debris survey of the global ocean suggested that a majority of the debris observed in the north Pacific Ocean was located in the Sub-tropical Convergence Zone (Figure 3) (Matsumura et al., 1997), a pattern corroborated more recently by Pichel et al. (2007). This hypothesis is further supported by Lumpkin et al. (2012), who analyzed the location and age of "death" of satellite-tracked drifters released since 1979 as part of the Global Drifter Program. They found that nearly all drifters more than three years old that stopped working for no apparent reason did so in the sub-tropical Pacific or in one of the other gyres of the global ocean.

If the assumption is adopted that accumulation in the sub-tropical Pacific Ocean accounts for about 75 percent of the missing tracers, and around 2 percent are recovered by beachcombers, what of the remainder? Some of the tracers probably leave the north Pacific Ocean and end up in other ocean basins (Ebbesmeyer, 2004; Lumpkin et al., 2012). Based on various unconfirmed reports of tracked debris (Ebbesmeyer et al., 1992, 1994) and trajectories of satellite-tracked drifters (Lumpkin et al., 2012), it seems probable that many tracers wash up on beaches in various parts of the north Pacific unnoticed and unquantified. Many may be incorporated into beach sediment, thrown high up into piles of wrack or logs, or crushed against cliffs or rocks. It is therefore possible that the 2 percent axiom, based largely on recovered tracers in a relatively small swath of coast in the northeast Pacific, will underestimate the actual mass of debris that comes ashore. It seems reasonable to assume that the largest mass of debris will accumulate in the sub-tropical Pacific (about 75 percent is assumed here based on the discussion above), but the possibility that as much as 25 percent of the debris may come ashore in the northeast Pacific Ocean (defined here as the shoreline of Alaska, British Columbia, Washington and Oregon) cannot be excluded. We will therefore adopt a range of 2 and 25 percent and assume that it will define the uncertainty for the quantity of debris that can be expected to make landfall on the shores of the northeast Pacific Ocean.

In summary, these empirical and model results suggest that over multiple years, the dominant portion of the debris that approaches the coast of the northeast Pacific may be deflected northward and make landfall in British Columbia and southeast Alaska. Based primarily on the work of Lumpkin et al. (2012), it seems reasonable to assume that that at least half of the debris that makes landfall on the coast of the northeast Pacific ocean will end up on the coast of Alaska, and that the actual ratio is likely to be much higher. Given the available data, though, it is impossible to exclude the possibility of a similar fraction of the debris washing up on more southerly beaches (British Columbia, Oregon and Washington). In particular, the influence of near coastal winds may promote debris landfall on the coast of Washington.

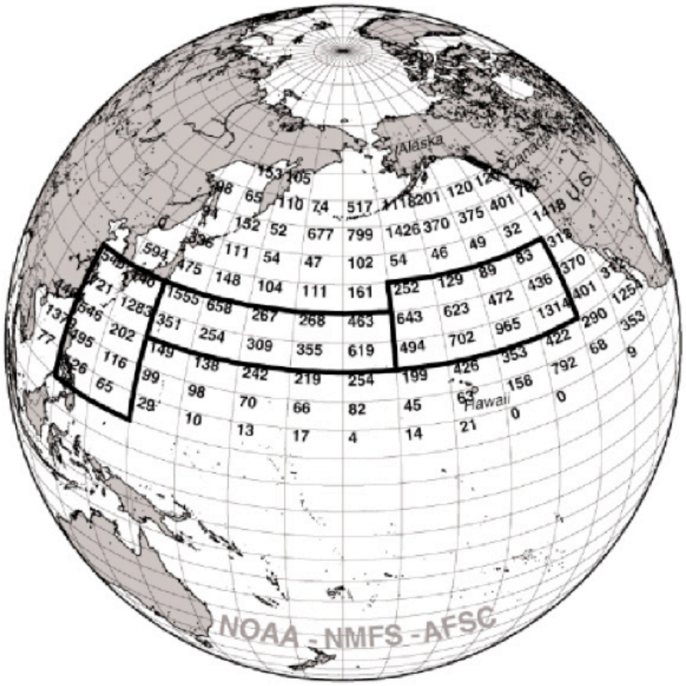

Figure 3. Density of floating marine debris (# of items per square nautical mile) based on observations reported by Matsumura and Nasu (1997). Figure from Ingraham and Ebbesmeyer (2001). Black boxes are OSCURS tracking regions as described in Ingraham and Ebbesmeyer (2001)

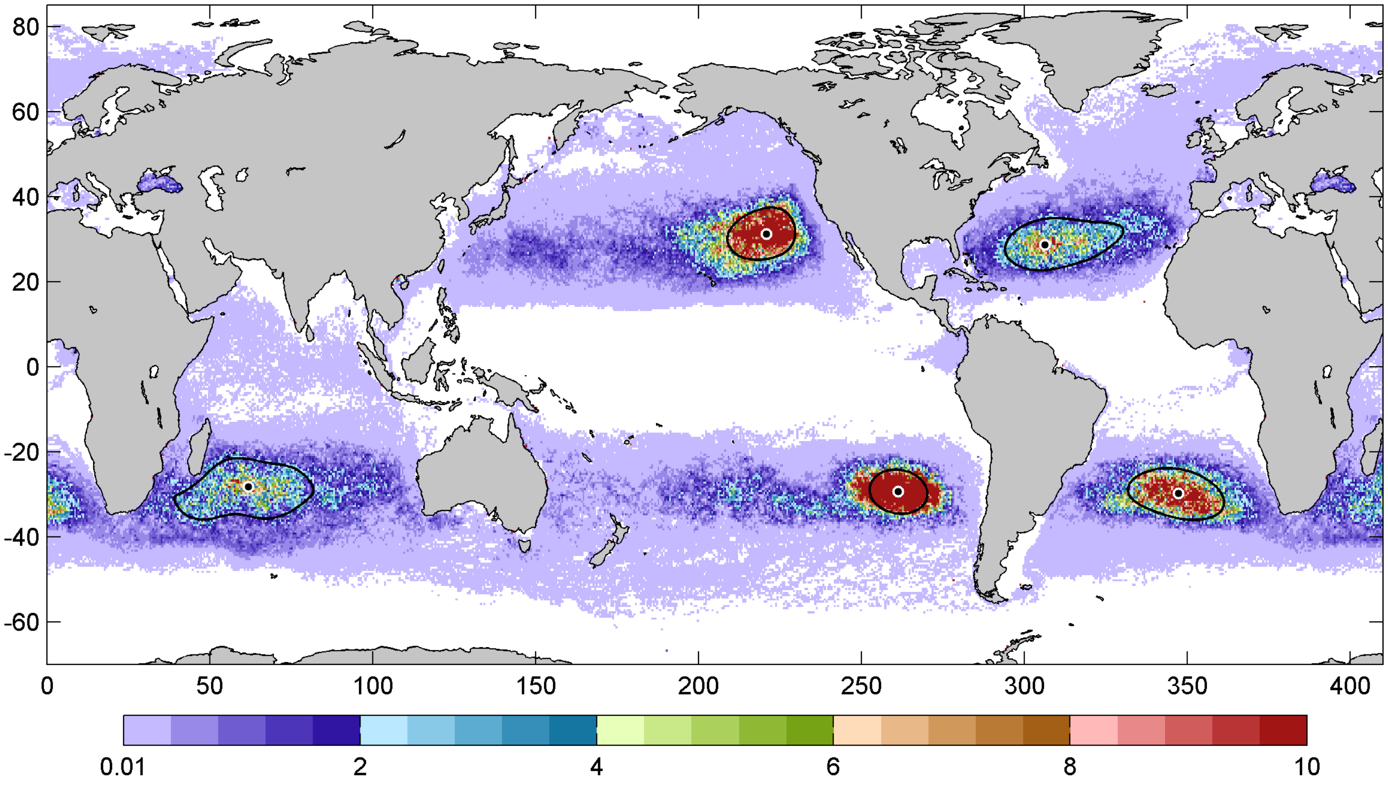

Figure 2. Map of the modeled concentration of oceanographic drifters after 10 years, starting from a uniform global distribution with a starting concentration of 1 (units are arbitrary). Dots mark the positions of the five maxima in concentration (associated with subtropical convergence zones), and contour lines show the boundary of one-half of this maximum value. Figure adapted from Maximenko et al. (2012)

Third Revision: Spatial Patterns along the Northeast Pacific Coast

The initial worst-case scenario assumed an even distribution of debris along the shoreline of the northeast Pacific Ocean that is almost certainly an over-simplification. Within the huge stretch of shoreline, from beyond Kodiak Island to southern Oregon, are there spatial patterns suggesting areas that might be more prone to accumulations of debris? Ingraham et al. (1998) show that the latitude of debris deposition on beaches is probably broadly controlled by annual climate patterns in the north Pacific and can vary considerably year-to-year. Ebbesmeyer and Ingraham (1992) modeled float trajectories of virtual tracers released at the location of the actual 1990 spill of thousands of Nike shoes for five different years (1951, 1973, 1982, 1988 and 1990) representing five different climate conditions in the north Pacific. Their results suggest that landfall in British Columbia and southeast Alaska is expected under most climate conditions for these tracers (Figure 4). For a larger set of simulations starting on May 27 of each year from 1946-1990, the latitude of first landfall was usually north of 48° N (the approximate latitude of Neah Bay, Washington) and always north of 45° N (the approximate latitude of Lincoln Beach, Oregon), with a mean latitude of 55° N (approximately the latitude of Ketchikan, Alaska) for all releases and all years (Figure 4b). Modeled trajectories for virtual tracers released during the winter at Station Papa (Figure 1) in the northeast Pacific also typically deflect to the north or head straight west (toward Vancouver Island) under nearly all climate conditions (Ingraham et al., 1998).

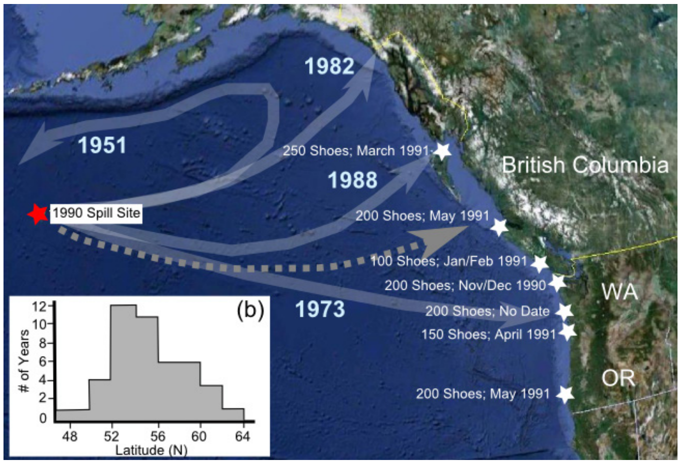

Figure 4. Simulated average trajectories for ~80,000 shoes released on May 27, based on OSCURS model hindcasts. The grey dotted line is the estimated average trajectory for 1990 (the actual year of the spill), and white stars mark the general locations where 2.6 percent of the shoes were recovered by beachcombers. The four lighter arrows represent estimated average trajectories from four other years representing various distinct climate conditions in the northeast Pacific Ocean. A histogram (b) shows the latitude of first landfall for simulated releases on May 27 for 45 years (1946-1990). Figure adapted from Ebbesmeyer and Ingraham (1992) using a base image from Google Earth.

Empirical data supporting this pattern are mixed, however. After the 1992 spill of 28,800 plastic toys (Figure 1), about 400 plastic toys were recovered within two years in southeast Alaska, between Coronation Island and Glacier Bay, suggesting a pattern of deflection to the north (Ebbesmeyer et al., 1994). By contrast, for the 1990 Nike shoe spill, the impact point on the coast calculated from the mean drift trajectory was near the northern end of Vancouver Island (Lerche et al., 1995), but most recovered shoes made landfall south of that point (Figure 4). The discrepancy may reflect the timing of the approach of the shoes toward the coast. If the mass of shoes approached the coast during summer, for example, deflection to the south may be more likely, due to seasonal north winds. Trajectories calculated from satellite-tracked drifters released around the globe between 1979 and 2007 also suggest a broad area of divergence (shown in Figure 1) around the central Oregon and Washington coast, where drifters moving under the influence of currents head either north or south (Maximenko et al., 2012), probably under the influence of the northward flowing Alaska Current or the southward flowing California Current.

It is unclear if the flow divergence described by Maximenko et al. (2012), around the latitude of Washington state between the northward flowing Alaska current and the southward flowing California current (Figure 1), would support or discourage the deposition of debris on Washington beaches. Large-scale surface currents may not be the mechanism by which debris is directly delivered to the shores of Washington state. Instead, short-term wind may play a dominant role (Ebbesmeyer et al., 1994; Howell et al., 2012; Maximenko et al., 2012). This suggests that the debris "windage" factor (the degree to which debris floats above the water's surface and is exposed to wind) may partially control its eventual deposition location on the coast of the northeast Pacific Ocean. This hypothesis is supported by the results of Poterma (2012), who analyzed a suite of general circulation ocean models for their applicability to marine debris tracking. Virtual particles released near the coast of Washington in these models almost always travelled south and eventually away from the coast, under the influence of average large-scale currents. The investigator notes, however, that these models only incorporate wind as mean long-term fields and that the influence of "real" time-varying wind can change the motion of "virtual" particles dramatically. This observation is corroborated by high resolution oceanographic models of the Washington coast, which suggest that near-coastal winds play a pivotal role in setting up on-shore directed currents (Dr. Parker McCready, University of Washington, personal communication). The movement of particles in these models toward the Washington coast is often associated with strong westerly or, in particular, southwesterly near-coastal winds.

Lumpkin et al. (2012) provide perhaps one of the most useful empirical analyses suggesting which parts of the northeast Pacific coast might be expected to accumulate debris. Extending the analysis of Maximenko et al. (2012), they incorporate information about where those drifters ran aground. Their results suggest that the coast of Alaska is the epicenter of drifter groundings in the northeast Pacific (Figure 5). In some cases, drifters may effectively model the behavior of marine debris, and these observations may provide insight into the most likely landing areas for tsunami debris in the northeast Pacific. It should be noted, however, that because this dataset collates drifter trajectories from

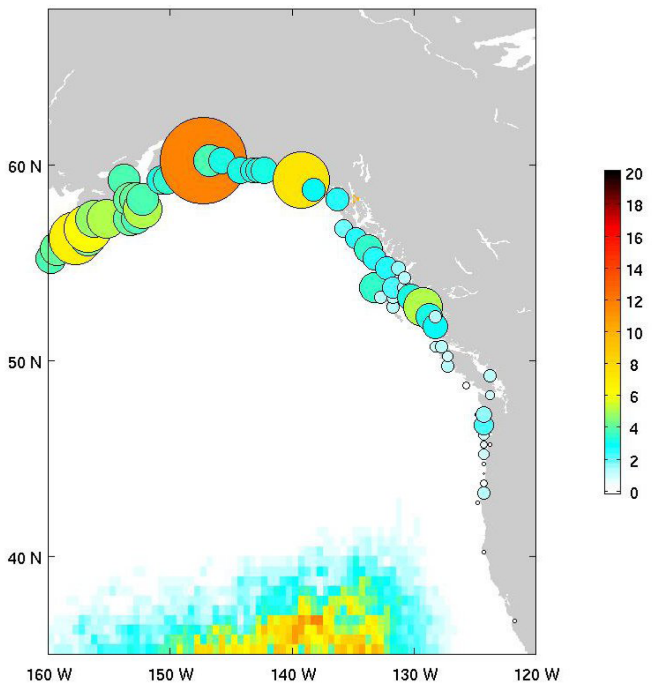

Figure 5. Relative concentration of beached drifters, in arbitrary units, after 10 years of from an initially uniform global distribution of floating drifters. Results were derived from the tracks of ~14,000 scientific satellite-tracked drifters. Colored pixels at lower part of figure are relative densities of floating debris over the same time frame (see Figure 2). Figure adapted from Lumpkin et al. (2012)

1979 to the present, it provides a time-averaged view of drifter transport. As has been documented (Ingraham et al., 1998), particular climate conditions may alter the average pattern dramatically and lead to different deposition patterns. Also, drifters are specifically designed to minimize windage and therefore may not effectively model the transport of some types of debris. On-shore wind probably plays a very important role in bringing debris to the coast of Washington, and the results of Lumpkin et al. (2012) may therefore underestimate the relative concentration of tsunami debris that can be expected on Washington's shoreline, especially debris with relatively high windage.

Other data on the spatial distribution of marine debris along the coast of the northeast Pacific Ocean is sparse. Keller et al. (2010) analyzed debris recovered from 1,347 bottom trawls conducted along the U.S. West Coast and found that debris accumulations were significantly higher south of 36° N than for the northern part of the study area (to 48° N). This study measured only non-floating debris found on the seafloor, however, and no effort was made to determine if the debris was from local sources or had drifted across the ocean. Doyle et al. (2011) analyzed very small plastic particles collected in plankton samples from stations in the Bering Sea, off northern Vancouver Island and off Southern California. They found the highest mass and concentration of plastic particles in the samples collected off Southern California. Nearly all plastic particles were found at the surface, and in most cases, concentrations of plastic particles were highest at stations nearer to shore. A seasonal difference (summer to winter) was found, with higher concentrations of plastic in winter samples off Southern California.

Again, it is unclear if the spatial or temporal patterns identified in this investigation are relevant to the floating debris associated with the Tōhoku tsunami. Finally, anecdotal observations suggest that there will be a great deal of spatial variability in the location of debris landfall over relatively short coastal lengths. Given variability in bathymetry and near-coastal currents, it is likely that certain beaches will accumulate more debris than others. Data that can help to hone estimates of accumulation at such a small scale is unavailable, though local expertise and observations may be valuable in response planning.

In summary, these empirical and model results suggest that over multiple years, the dominant portion of the debris that approaches the coast of the northeast Pacific may be deflected northward and make landfall in British Columbia and southeast Alaska. Based primarily on the work of Lumpkin et al. (2012), it seems reasonable to assume that that at least half of the debris that makes landfall on the coast of the northeast Pacific ocean will end up on the coast of Alaska, and that the actual ratio is likely to be much higher. Given the available data, though, it is impossible to exclude the possibility of a similar fraction of the debris washing up on more southerly beaches (British Columbia, Oregon and Washington). In particular, the influence of near coastal winds may promote debris landfall on the coast of Washington.

Fourth Revision: Debris Accumulation Patterns in Time

There is very little information on the temporal pattern of debris landings. Observations from southeast Alaska suggest that debris landings from a known point source can span decades (Ebbesmeyer et al., 1994; Ebbesmeyer, 2004; Ebbesmeyer et al., 2007). Ebbesmeyer et al. (2007) describe an interesting periodicity to landings of toys from the 1992 northeast Pacific spill, with peaks every two-to-three years in the number coming to shore near Sitka, Alaska. These peaks in the frequency of landings were attributed to the toys' entrainment in the Alaska Current (Figure 1) and then into the rotating Pacific Sub-Arctic Gyre in the Gulf of Alaska. Because the Pacific Sub-Arctic Gyre probably doesn't directly influence the frequency of landings in Washington, the duration or periodicity of landings in southeast Alaska may not be relevant to Washington's coast.

Assuming that debris landings in Washington aren't influenced by the Pacific Sub-Arctic Gyre, it seems reasonable to plan for the greater part of the debris associated with the Tōhoku tsunami to make landfall in Washington within four years after the event. This timeline assumes that most of the debris associated with the tsunami is entrained in the eastward flowing currents of the North Pacific (Figure 1) and travels at a mean speed of 0.1-0.5 miles/hour (Matsumura et al., 1989; Ebbesmeyer et al., 1992; Maximenko et al., 2012). Variability in the velocity of debris in the north Pacific is probably controlled in part by the windage factor of debris (Ebbesmeyer et al., 1994). Given the likelihood that the various pieces of debris have different windage factors, it is reasonable to assume that various pieces of debris will have variable velocities, and that their landings will be spread out through time.

Integration and Discussion

Available literature strongly suggests that the eventual fate of the majority (an estimate of 75 percent will be adopted here) of floating debris associated with the 2011 Tōhoku tsunami will be in the Subtropical Convergence Zone of the Pacific Ocean. There is also evidence suggesting that this estimate may be conservative. While approximately 2 percent of tracers released in the northeast Pacific Ocean in a given location and at a given time are likely to be recovered on the shores fringing the northeast Pacific, observations made of the trajectories of satellite-tracked drifters suggest the possibility that a larger fraction (up to 25 percent) may make landfall. We therefore suggest that between 2 and 25 percent (30,000-375,000 tons) of the floating debris associated with the Tōhoku tsunami may make landfall on the shores of the northeast Pacific Ocean. Spatial patterns of drifter accumulation along the shoreline suggest that the shorelines of Alaska will accumulate the greatest mass of tsunami debris. Based on the results of Lumpkin et al. (2012), who analyzed the loss of oceanographic drifters to the shoreline around the world, an assumption will be made that at least half of the debris associated with the Tōhoku tsunami expected to make landfall will recruit to the shorelines of Alaska. The remainder, 15,000-185,000 tons, may be available to make landfall along the shores of British Columbia, Washington and Oregon. Conflicting evidence and variability within the northeast Pacific Ocean make it difficult to refine this estimate further. In particular, on-shore directed winds in the near-coastal waters of Washington may promote the landfall of debris. Finally, it is unlikely that all of the debris will make landfall within one year, but an assumption is made that the largest fraction will be delivered within four years of the tsunami itself (March 2011), with the distribution in time perhaps controlled in part by the windage factor of the debris. For the purposes of this analysis, it is assumed that no more than 75 percent of the remaining debris (11,000 to 138,000 tons) will make landfall in any one year along the coasts of British Columbia, Oregon and Washington.

Assuming that this projected volume of tsunami debris distributes evenly around the full length of the tidal shoreline of British Columbia, Washington and Oregon (Table 1), debris accumulation over the course of a year would total about 0.5-6.7 tons/mile. Assuming instead that tsunami debris only impacts the shorter “general sea coast” of British Columbia, Oregon and Washington (Table 1), we would expect between 10.4 and 131.0 tons/mile of beach. This method of estimating the density of accumulated debris along the shoreline has clear shortcomings: The full tidal shoreline of Washington State, for example, includes embayments (i.e. Hood Canal and south Puget Sound) that will probably not be exposed to significant quantities of debris from the Tohoku tsunami. By contrast, the “general sea coast” length almost certainly underestimates the length of coastline that will actually receive debris. The accumulation densities therefore provide a range of possible scenarios. Additionally, the assumption of even distribution that is implied here will probably break down under the dynamic and variable movements of wind and water in the northeast Pacific Ocean. It is nearly certain that for the fraction of debris making landfall in Washington, Oregon and British Columbia, there will be “winners and losers” — beaches that accumulate more than others. Given the available information, it is impossible to hone these estimates further without additional research and/or locally-based knowledge and expertise.

Conclusion

The intent of this review was to provide a range of estimates of when and where, and in what quantities, debris associated with the Tōhoku tsunami will make landfall along the coast of the northeast Pacific Ocean and, in particular, Washington state. The evidence reviewed here suggests that a worst-case estimate of the amount of debris that could make landfall on the shores of Washington is approximately 131 tons/mile, or about 260 times the estimated baseline debris accumulation on the Pacific coast of Washington of 0.5 tons/mile/year. This high estimate is considered unlikely, given that it assumes that fully 25 percent of all of the debris associated with the tsunami will make landfall on the shores fringing the northeast Pacific Ocean (rather than entraining in the Sub-tropical Pacific Convergence Zone or exporting out of the Pacific Ocean), that at least half of that will make landfall along the relatively short shorelines of Washington, Oregon and British Columbia (rather than along the coast of Alaska), and that most of the debris will come ashore in one year (rather than spreading out over multiple years). Perhaps most importantly, this estimated debris concentration is derived using the relatively short general seacoast length (Table 1), which almost certainly underestimates the actual length of coast that will probably be exposed to debris from the Tōhoku tsunami. Assuming that less than 25 percent of the total debris makes landfall (likely), that the majority recruits to the shoreline in Alaska (also likely), that landfall is distributed evenly over multiple years, and that debris finds its way and spreads out along the embayments, around the islands and along the complex coasts of British Columbia, Oregon and Washington (likely), the total annual debris accumulation per mile of beach is likely to be less than this worst-case estimate and could be as low as 0.5 to 6.7 tons/mile. We note, however, that these estimates are spatially-averaged; particular beaches may accumulate considerably more than is suggested by the “even distribution” model used here. These rough estimates, while uncertain, are grounded in empirical observation and numerical models of the circulation of the north Pacific Ocean and provide a tool for scaling the potential impact of the debris from the Tōhoku tsunami.

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