Marine Pollution Bulletin 132 (2018) 26–32

Contents lists available at ScienceDirect

Marine Pollution Bulletin

journal homepage: www.elsevier.com/locate/marpolbul

The influx of marine debris from the Great Japan Tsunami of 2011 to North American shorelines[☆]

Cathryn Clarke Murray[a,b,*], Nikolai Maximenko[c], Sherry Lippiatt[d,e]

[a] North Pacific Marine Science Organization (PICES), 9860 West Saanich Road, Sidney, British Columbia V8L 4B2, Canada
[b] Fisheries and Oceans Canada, 9860 West Saanich Road, Sidney, British Columbia V8L 4B2, Canada
[c] International Pacific Research Center, School of Ocean and Earth Science and Technology, University of Hawaii at Manoa, 1680 East West Road, POST Bldg. #401, Honolulu, HI 96922, USA
[d] U.S. National Oceanic and Atmospheric Administration, Marine Debris Program, 1301 Clay St, Oakland, CA 94612, USA
[e] I.M. Systems Group, 3206 Tower Oaks Blvd, Rockville, MD 20852, USA

ARTICLE INFO

Keywords:
Marine debris
Japanese tsunami
Shoreline monitoring
Ocean drift model
North Pacific

ABSTRACT

Marine debris is one of the leading threats to the ocean and the Great East Japan Earthquake and tsunami on March 11, 2011 washed away an estimated 5 million tons of debris in a single, tragic event. Here we used shoreline surveys, disaster debris reports and ocean drift models to investigate the temporal and spatial trends in the arrival of tsunami marine debris. The increase in debris influx to surveyed North American and Hawaiian shorelines was substantial and significant, representing a 10 time increase over the baseline in northern Washington State where a long term dataset was available. The tsunami event brought different types of debris along the coast, with high-windage items dominant in Alaska and British Columbia and large, medium-windage items in Washington State and Oregon. Recorded cumulative debris landings to North America were close to 100,000 items in the four year study period. The temporal peaks in measured shoreline debris and debris reports match the ocean drift model solutions. Mitigation and monitoring activities, such as shoreline surveys, provide crucial data and monitoring for potential impacts should be continued in the future.

1. Introduction

Marine debris is an important threat to ocean diversity and health (Sutherland et al., 2010). It is a global problem that can have intense local impacts on wildlife, human health, aesthetic values, and the economy (Coe and Rogers, 1997; Criddle et al., 2009; Derraik, 2002; Gall and Thompson, 2015). The emergence and persistence of plastic as marine debris has increasing risks from entanglement, ingestion, provision of new surfaces for colonization, rafting, effects of microplastics and associated chemical contamination (Gregory, 2009; Gall and Thompson, 2015). The source of marine debris is generally difficult to trace making it challenging to mitigate and control (Ryan et al., 2009).

The Tohoku Earthquake in Japan and resulting tsunami washed an estimated 5 million tons of debris into the Pacific Ocean (Ministry of the Environment, Japan, 2012). This single event delivered an amount in the range of the global debris input to the ocean each year and more than any single country, other than China, was estimated to produce in a whole year (Jambeck et al., 2015). Marine debris associated with this unique natural history event differs from general marine debris because the source and date of dislodgment or entry into the ocean are both known and fixed. While general artificial marine debris is dominated by relatively small plastic items (fishing nets are an exception), tsunami debris included large items, such as lumber and other construction materials from broken homes as well as large objects, as ships and floating docks. Additionally, the predominant drift in the North Pacific is eastward toward the Pacific coast of North America and the Hawaiian Islands (Howell et al., 2012) and drift can be modeled to estimate the spatial and temporal trends in shoreline interception (Bagulayan et al., 2012). The first confirmed tsunami debris item to be found on shore, a soccer ball, landed in Alaska in March 2012 (NOAA Marine Debris Program, 2015). Anecdotal reports and documented sightings suggest that the influx of marine debris in the years after the tsunami was substantial and unprecedented but there have been no attempts to measure and analyze the amount of incoming debris. Large debris items (e.g. vessels, floating docks) present a hazard to navigation and may act as floating islands that carry fouling and hitchhiking organisms that

---

[☆] This is one of the papers from the special issue of Marine Pollution Bulletin on "The effect of marine debris caused by the Great Tsunami of 2011." The special issue was supported by funding provided by the Ministry of the Environment of Japan (MOE) through the North Pacific Marine Science Organization (PICES).

[*] Corresponding author at: Fisheries and Oceans Canada, 9860 West Saanich Road, Sidney, British Columbia V8L 4B2, Canada.
E-mail address: cathryn.murray@dfo-mpo.gc.ca (C.C. Murray).

https://doi.org/10.1016/j.marpolbul.2018.01.004
Received 20 April 2017; Received in revised form 5 December 2017; Accepted 2 January 2018

pose a risk to native ecosystems. Smaller debris items (e.g. lumber and building material) are more difficult to trace but the type of debris from the tsunami is generally different than baseline marine debris.

Monitoring and removal of shoreline debris in North America has been ongoing since the 1990s (Ribic et al., 2012; Morishige et al., 2007). After the tsunami occurred, sightings of debris were recorded and if possible, traced to the original owner and confirmed as lost during the tsunami. In the wake of the 2011 tsunami, this ongoing research provides an opportunity to analyze the landing and trends in amount of marine debris. Quantifying and categorizing the influx of tsunami-associated debris will assist in the prioritization of research on marine debris impacts, document impacts to wildlife and ecosystems, optimize clean ups and removal activities and investigate the potential for the introduction of invasive species.

Here we analyze available data on the landings of debris on North American and Hawaiian shorelines in order to 1) quantify the amount, distribution and timing of debris landfall, 2) estimate debris landfall attributable to the 2011 tsunami and 3) compare to oceanographic modeling predictions. In short, we ask whether we can we detect the signal of the tsunami debris against the background of ongoing marine debris and generalize sparse observational reports into a bigger picture of the event.

2. Materials and methods

2.1. Shoreline monitoring

The ongoing NOAA marine debris shoreline survey is a rapid, quantitative beach survey which uses trained community volunteer organizations to collect standardized and consistent data. NOAA's current shoreline Marine Debris Monitoring and Assessment Project (MDMAP) began in 2011 and continues through the present (Lippiatt et al., 2013). The MDMAP accumulation survey protocol measures the net accumulation of all types of marine debris items on a site's 100 m stretch of beach every 28 days. All debris items are recorded and removed from the shoreline. Surveys were conducted by citizen science groups or government staff and depending on weather and tides, the amount of beach and monthly schedule sometimes varied (Opfer et al., 2012). For each survey, the incidence of large items (> 30 cm) was specifically recorded and additional information and photos of the items were provided by surveyors. Between March 2012 and December 2015, over 1100 surveys have been conducted at > 120 sites in Alaska, British Columbia, Washington, Oregon, California and Hawaii. The NOAA dataset was analyzed for trends in distribution and abundance of debris influx and type over time and along the Pacific coast of North America and the islands of Hawaii.

Long-term spatially distributed marine debris monitoring datasets are rare so a dataset maintained by Olympic Coast National Marine Sanctuary (OCNMS) was used to establish a baseline of marine debris influx prior to the tsunami event. This survey protocol recorded marine debris indicator items at sites in northern Washington State from 2001 to 2011. All debris was removed from a 500 m stretch of beach at each site and the number of debris items in each of the 30 indicator categories was recorded (Supplementary Materials). Indicator items were chosen to represent different sources of debris (land, ocean and general source debris); the pre-2011 National Marine Debris Monitoring Program (NMDMP) protocol is described in more detail by Ribic et al. (2012).

In order to compare baseline debris influx with that after the tsunami event, we compared the two sets of debris categories and removed or combined categories and the data contained within as needed (see Supplementary Materials). The level of effort is consistent across both formal monitoring programs (MDMAP and NMDMP) as all items of interest from the survey area were recorded regardless of the number of surveyors. The NOAA MDMAP protocol records information on a more diverse set of debris items; only those fields that overlap with the NMDMP protocol were compared (Supplementary Table 1). We identified common sites between the two survey timelines, and then analyzed the spatial and temporal trends in marine debris influx. In total, 47 beaches were surveyed and 11 NMDMP sites continued to be surveyed with the new protocol (see Supplementary Materials). The mean number of debris items recorded per 100 m stretch of beach per day was analyzed and ANOVA with Tukey's b post-hoc statistical test used to test for differences between years and states or provinces. Spatial autocorrelation was investigated using Moran's I in ArcMap 10.1 (Environmental Systems Research Institute, Inc., Redlands, CA: 2010).

After the 2011 tsunami occurred, NOAA established a reporting system for public sightings of suspected tsunami debris items. Reports were received by email and maintained in a database, hereafter referred to as “disaster debris reports”. Records as of April 13, 2016 were analyzed for temporal and spatial trends and compared to the shoreline monitoring results. Confirmed tsunami debris items were those with identifying marks that could be traced to items known to be lost during the tsunami event, through diplomatic channels.

2.2. Modeling tsunami debris

Simulations with the Surface Currents from a Diagnostic (SCUD; Maximenko and Hafner, 2010) model were used to study particle and tracer motions after release on March 11, 2011 along the east coast of Honshu, Japan. SCUD is an empirical, diagnostic model, developed at the International Pacific Research Center, University of Hawaii and forced with data from satellite altimetry (sea level anomaly) and scatterometry (vector wind). The model is calibrated on a 1/4-degree global so that it reproduces trajectories of historical satellite-tracked drifting buoys. To include into consideration various types of debris a fraction of wind velocity, described by the windage parameter, was added representing the direct effect of the wind on items floating on the ocean surface. Model experiments used 61 values of windage ranging between 0 and 6%. In this paper we compare the monthly model predictions to observations of debris influx during the shoreline surveys and the sightings reported using Spearman's rank correlations.

3. Results

3.1. Debris monitoring

The debris landings after 2013 were significantly different than 2012 and prior (One-way ANOVA, F = 3.992, df = 12, $p < 0.001$) (Fig. 1). There was a sharp increase in the influx of indicator debris items, from mean 0.03 items per 100 m of shoreline per day between 2003 and 2012 to mean 0.29 debris items per 100 m per day from 2013 to 2015. This is an almost ten-fold increase in debris influx to sites in northern Washington State over that recorded in the nine year period prior to the tsunami event. Prior to the peak in indicator debris items (May 2012), monthly mean debris influx ranged from 0.01 to 0.08 indicator debris items per 100 m per day and after the peak indicator debris influx ranged from 0 to 0.78 debris items per 100 m per day (Fig. 2).

Across the West Coast of the US (Washington State, Oregon and California), there were peaks in all debris items (not just indicator items) in June 2012, March 2013, and smaller peaks in May 2014 and late 2014 (Fig. 2). Across all North American study sites, the recorded mean debris influx peaked in July 2012 at 13.8 debris items per 100 m per day. Mean monthly debris influx for all debris items (2012–2015) was 2.7 debris items per 100 m per day (ranged from 0.5 to 13.8 debris items per 100 m per day).

Across all the states and provinces of study, Hawaii, USA received the highest mean debris items over the post-tsunami study period (2012–2015) (Fig. 3). British Columbia, Canada has the second highest mean debris influx in this time period, driven by a few surveys in the islands of Haida Gwaii (northern BC) with high numbers of large

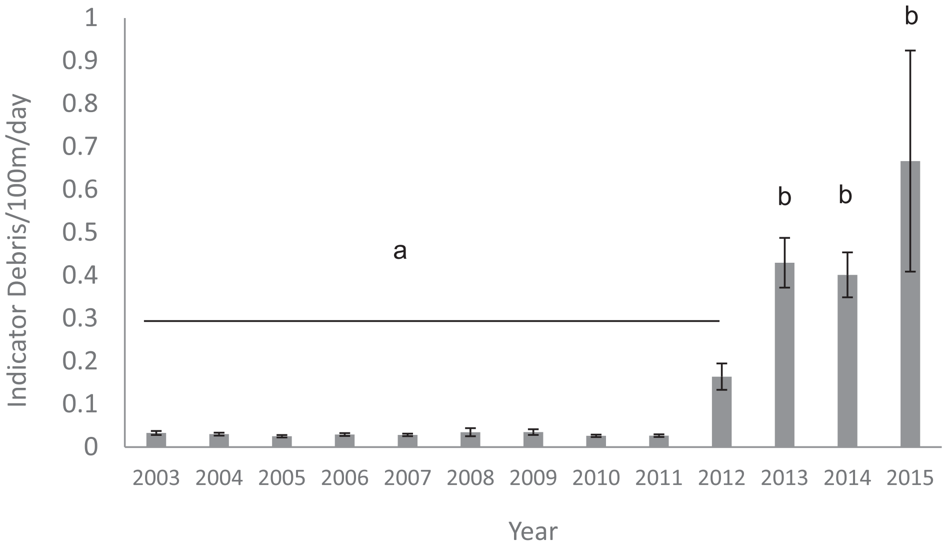

Fig. 1. Mean yearly debris influx of indicator items from 2003 to 2015 at sites in northern Washington State, USA. Letters denote significantly different groups using Tukeys HSD posthoc comparisons).

Styrofoam pieces. Alaska had few accumulation surveys to analyze and has not been included in the figures. The total amounts of debris arriving monthly to actively monitored North American coastlines in the post-tsunami months ranged from 150 to 1951 items (Fig. 4). The cumulative arrival of documented debris items to surveyed North American coastlines was > 93,000 items (Fig. 4).

3.2. Shoreline survey data: large items

The incidence of large debris items (larger than 30 cm) in MDMAP surveys was highest in Washington State (28 items/shoreline, 736 items total), followed by California (7.7 items/shoreline, 185 items total) and across regions, the highest arrival of large items occurred in 2013 and 2014 (Fig. 5). The prevalence of large items in California is not likely related to tsunami debris as the survey notes from California made no mention of possible tsunami debris items and many of the largest items were unable to be removed and were repeatedly noted in surveys. Large items sightings from monitoring surveys concentrated in Washington and very few large items were reported in Hawaii surveys (Fig. 5). This is a different pattern than that for debris smaller than 30 cm, where large numbers of debris items were found on surveys in Hawaii. The number of large items has significant spatial autocorrelation (Moran's $I = 0.0328$, $Z\text{-score} = 5.704$, $p < 0.00001$). Therefore neighboring sites have similar numbers of large items within a distance threshold of 24.5 km.

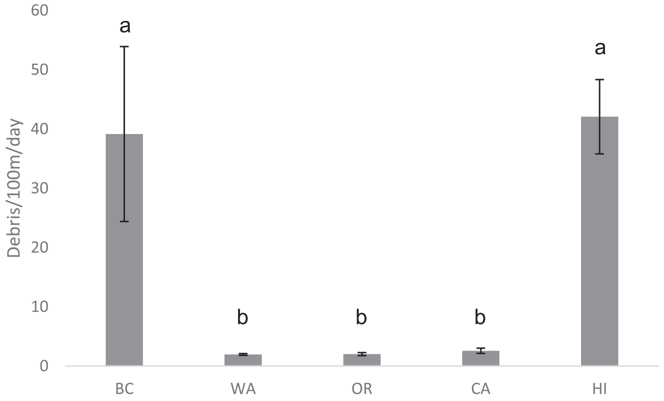

Fig. 3. Mean debris item arrival (debris/100 m/day) from 2012 to 2015 by province/state. BC = British Columbia, CA = California, OR = Oregon, WA = Washington State and HI = Hawaii. Letters denote statistically different subgroups.

3.3. Disaster debris reports

Reports of disaster debris peaked in June 2012, March 2013 and May 2014 with at least one confirmed 2011 Japan tsunami debris item in each of the temporal peaks (Fig. 6). The sightings are significantly spatially clustered at a mean distance of 16.268 km (nearest neighbour Euclidean distance: observed mean distance = 16.3 km, expected mean

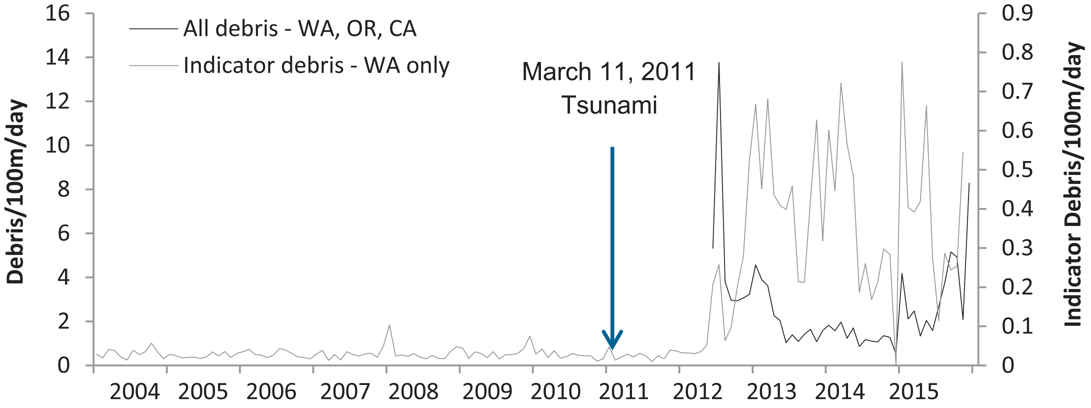

Fig. 2. Mean monthly debris influx of indicator items (indicator debris items/100 m/day) from 2004 to 2015 at sites in northern Washington State (grey line) and mean monthly mean influx of all debris items (debris items/100 m/day) for Washington State, Oregon and California from 2012 to 2015 (black line).

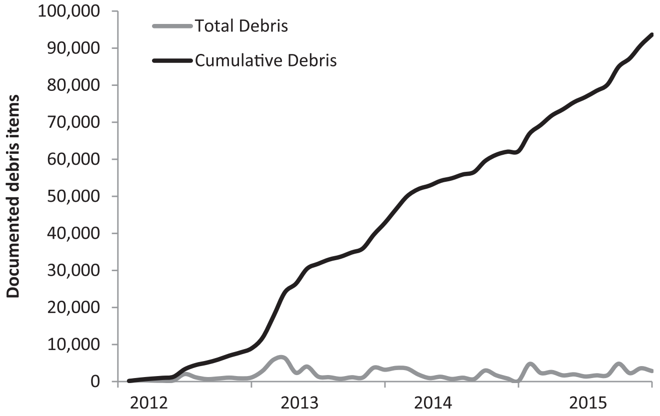

Fig. 4. Total (grey) and cumulative (black) number of documented debris items arriving to monitored shoreline sites (excluding Hawaii) over time (2012–2015).

distance = 137.205 km, nearest neighbour ration = 0.119, Z score = − 64.849, $p < 0.00001$). Miscellaneous or Mixed debris was the most commonly reported disaster debris, followed by Consumer debris (Table 1). Vessels were the most common type of debris that could be confirmed as lost during the 2011 tsunami. Many of these vessels had registration numbers or vessel names that could be more easily traced and officially confirmed as tsunami debris.

3.4. Modeling debris arrivals

The model solutions corresponded with observations by capturing all three main temporal peaks in the disaster debris reports and the shoreline debris arrival data, although disagree somewhat in the magnitude of the peaks (Fig. 6). Model solution indicates temporal peaks in June 2012, Jan 2013, and May 2014 (arrows in Fig. 6). The optimal windage for the disaster debris reports, identified with best fit, is 2.2% (red line in Fig. 6). The three peaks in MDMAP shoreline debris data after the tsunami (June 2012, March 2013, and March 2014) are similar to the peaks in disaster debris reported to NOAA (June 2012, March 2013, and May 2014) and these peaks are consistent with modeling predictions, although for 2013 the model solutions lead the observations by two months. There was a significant positive correlation between monthly model predictions (2.2% windage) and monthly total disaster debris reports (Spearman's $\rho = 0.699, p < 0.001, R^2 = 0.668$) and observed shoreline debris influx (Spearman's $\rho = 0.517, p = 0.001, R^2 = 0.441$).

High-windage tracer (black line in Fig. 6) arrives earlier than low windage (blue line) and high windage more readily lands on shore while low windage tends to remain in the ocean for longer durations. As a consequence, the magnitude of high-windage peaks decays faster with time while low-windage arrivals can continue over many years. The changing composition of JTMD landing over time may cause changes in the optimal windage, leading to mismatch between model solutions and observations.

4. Discussion

4.1. Unprecedented influx of marine debris

The Great Japan Tsunami of 2011 caused a significant and substantial influx of debris to North American shorelines and the evidence presented here is in agreement with anecdotal reports of high abundances and unusual debris types outside the normal range of cultural memory. In the locations where long term data exists, an increase of > 10 times (from 0.02 to 0.29 indicator items) over the baseline level was recorded. This increase is likely a conservative estimate as it is based on only a subset of debris, indicator items. Debris types unique to the tsunami event, such as lumber, were not recorded in the original NMDMP protocol. The concordance between the different data sources and modeling predictions suggests that the influx is a result of the tsunami event and is outside the baseline influx of marine debris experienced in North America and Hawaii.

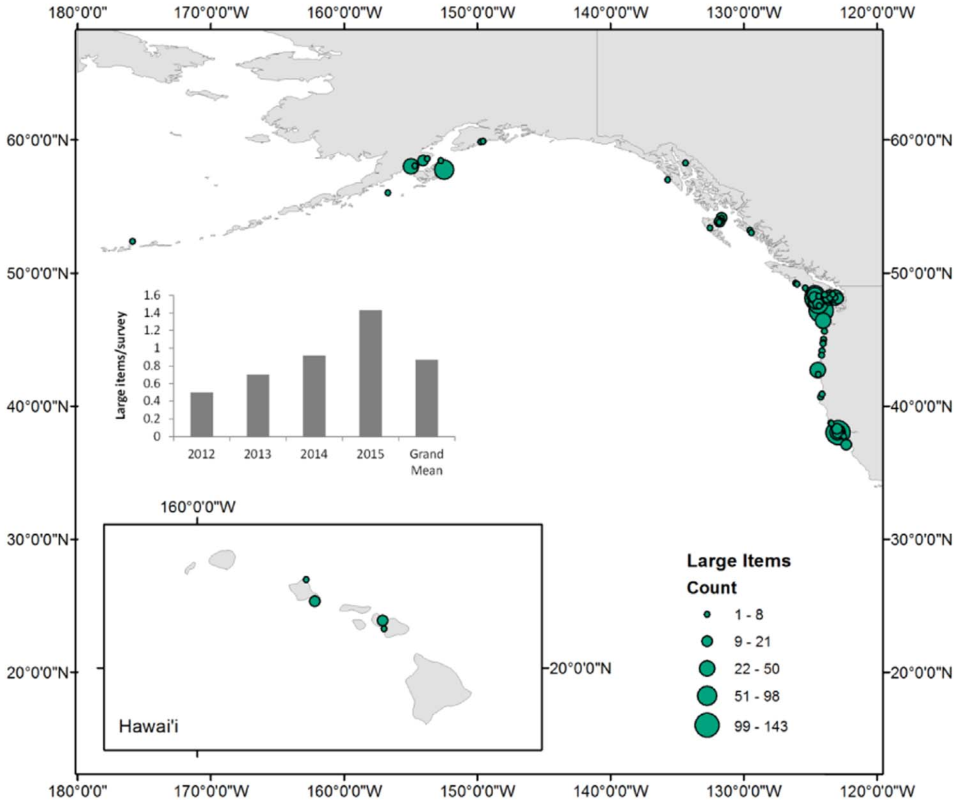

Fig. 5. Map of large item reports per survey, circles of increasing size represent increasing numbers of large items recorded. Inset shows large items per survey between 2012 and 2015.

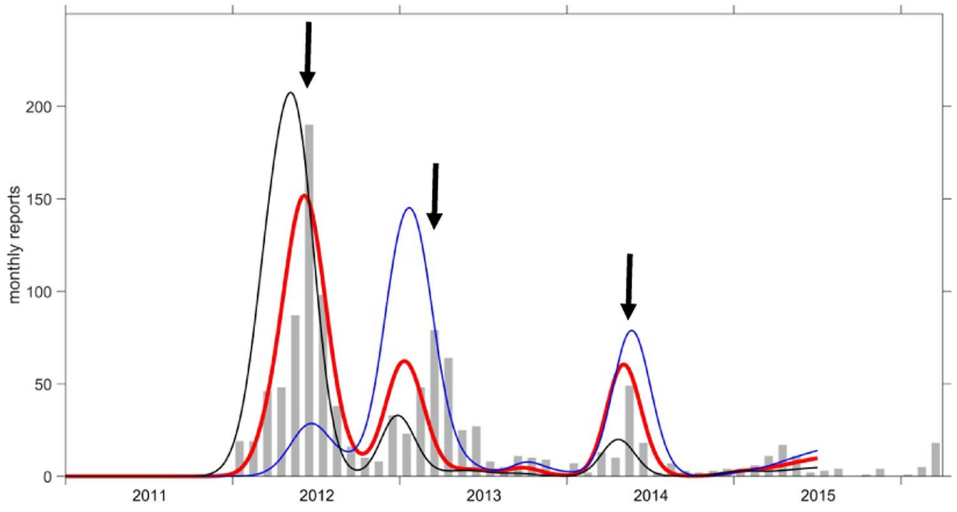

Fig. 6. Timeline of monthly disaster debris reports for North American landfall (grey bars), as of April 13, 2016, and simulated monthly debris arrival from SCUD model. Lines represent model solutions for differing model windage values: 1.5% (blue), 2.2% (red), and 3.0% (black), arrows mark peaks in disaster debris reports. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Disaster debris reports by type to the NOAA Marine Debris hotline and their status as confirmed or not confirmed 2011 tsunami debris, as of April 13, 2016.

Debris type	Not confirmed	Confirmed	Total
Construction debris	76	2	78
Consumer debris	421	6	427
Fishing gear	257	4	257
Misc. or mixed debris	644	15	659
Vessel	169	33	202
Total	1567	60	1627

Prior to the peak in indicator debris items attributed to the tsunami (June 2012), debris influx was in the range previously reported for the North Pacific coast. Ribic et al. (2012) reported a mean of 0.2 marine debris indicator items per 100 m per day for the North Pacific Coast from 1998 to 2007. After the tsunami, indicator items averaged 0.29 items per 100 per day, and reached as high as 4.1 debris items per 100 m per day. After tsunami debris began to arrive, indicator debris at sites in northern Washington increased 10-fold. The cumulative arrival of debris to the North Pacific coast was recorded only at those sites undergoing shoreline monitoring and removal. Even at this small subset of available shoreline, almost 100,000 debris items were recorded. Those shorelines remotely located or inaccessible to cleanup groups may be the most affected by remaining debris loads and experience greater impacts from debris accumulation (Gall and Thompson, 2015). Additionally, debris remaining at these sites have the potential to become re-suspended and make landfall elsewhere in the North Pacific (Kako et al., 2010), acting as secondary sources of debris.

Therefore, although a significant background level of marine debris existed prior to the tsunami, this one event increased the debris load across the entire region. North Pacific ecosystems are believed to be under pressure from the substantial influx of marine debris, microplastic and fishing gear causing entanglement of marine mammals and birds, toxicity issues and the possibility of introduction of rafting species (Gregory, 2009; Gall and Thompson, 2015). This substantial increase in debris agrees with the anecdotal evidence that there was a large increase and different diversity of debris landing after the tsunami event; increased building materials, vessels, and large pieces of Styrofoam in particular.

There was large spatial and temporal variation in debris influx after the first peak of tsunami debris was recorded. In keeping with general marine debris trends in this region (Ribic et al., 2012), across the MDMAP monitoring sites, overall debris influx post-tsunami was highest in Hawaii. This is likely a result of its proximity to the Central Pacific Gyre with temporal variation attributed to the ENSO cycle (Ribic et al., 2012). The influx of large items and disaster debris reports was higher than expected for Washington State. Disaster debris reports vary with public interest in the issue and shoreline visitation, but are an indication of increased debris. Large items with medium windage parameters were expected to make landfall in Washington and Oregon. Model solutions suggest that windage of landed debris increases with latitude so that high windage items are more common in Alaska (e.g. large Styrofoam pieces) and low windage items more common in Washington, Oregon and California. The oceanography models predicted that items of similar windage values, such as small skiffs, would be expected to concentrate in Washington and Oregon, and > 150 of these have been documented landing in these areas (see Maximenko et al. this issue). Note that there were few surveys in Alaska and northern BC due to the remote nature of these coastlines and therefore it is difficult to document trends for these regions.

Variation in storm season duration and strength and the timing of the spring transition are responsible for the observed temporal trends in debris arrival to North America (see Kako et al. this issue). The composition of JTMD landings changed over time, with high-windage items arriving earlier than low windage. High windage items (styrofoam and buoys) are blown onshore while low windage items (low-lying vessels and lumber) tend to remain in the ocean for longer durations. As a consequence, the magnitude of high-windage peaks decayed faster with time while low-windage arrivals can continue over many years. Temporal trends in Hawaii were more variable and the peaks from the 2011 tsunami were undetectable against the background variation of marine debris influx. Hawaii receives more ocean-based debris than other regions within the North Pacific (Ribic et al., 2012; Blickley et al., 2016) because of its proximity to the Pacific gyre and the so-called garbage patch. Therefore, the signal from the tsunami may be harder to detect against this high baseline influx.

There is a detectable signal of large debris items (larger than 30 cm) in the beach surveys and in the disaster debris reports, a portion of which were confirmed lost during the 2011 Tsunami. These peaks match the modeling predictions, suggesting that they were real temporal waves of debris from the tsunami. An increase in large debris items was one of the major impacts from the tsunami, which distinguishes this event from background marine debris trends. Washington State was the most affected by large items, followed by California while Oregon and Hawaii were the least affected by large items, as recorded in the beach surveys. There is some anecdotal evidence that suspected tsunami debris items may not have been as well reported to the disaster debris reporting system in Hawaii as in other states and impacts from large items may be underestimated in Hawaii (Maximenko unpublished data).

While previous surveys documented declining or stable debris influx across the west coast of North America and Hawaii (Ribic et al., 2012), the 2011 tsunami increased the debris loads to unprecedented levels for three years. Large debris items continued to make landfall in spring 2015 and many more remaining debris items have likely become entrained in the Central Pacific Gyre and will persist in the North Pacific for decades (Maximenko et al. this issue).

4.2. Potential ecological impact of debris

A substantial increase in marine debris influx increases the risk of impacts similar to marine debris in general – entanglement and ingestion, provision of new habitat, dispersal via rafting and assemblage-level effects (Gall and Thompson, 2015). In contrast to general marine debris, debris resulting from the 2011 tsunami had a specific start position and time and differing debris types. The tsunami debris field contained similar household debris but also coastal floating infrastructure such as aquaculture equipment, docks and wharves, large and small vessels as well as construction materials and vegetation (NOAA Marine Debris Program, 2015). Plastic debris has a suite of impacts such as entanglement, ingestion, addition of habitat, smothering, and chemical contamination (Gall and Thompson, 2015; Rochman et al., 2016).

The directional drift from Japan to North America combined with an unknown residency in coastal Japanese waters has increased the biodiversity and fitness of attached sessile fouling organisms and hitchhiking organisms. Those species native to the western Pacific are at risk of arriving, establishing and spreading in the eastern Pacific, potentially becoming invasive species. Debris items that were in the coastal waters may have had established fouling communities that were taken with the debris item during the tsunami. Terrestrial origin debris items (logs, lumber, household items and small vessels) may have spent weeks in the coastal Japanese waters where marine species settled and became attached. Hundreds of Japanese species from a diverse set of taxa arrived in North America and Hawaii associated with tsunami debris (Calder et al., 2014; Carlton et al., 2017). Mussels arrived alive and in reproductive condition (Miller et al., in press). The risk of these species to the eastern Pacific is under investigation and surveys have been conducted to monitor for new introductions (Hansen et al. in review this issue; Therriault et al., in review this issue; G Ruiz. Smithsonian Environmental Research Center, unpublished data).

The arrival of high numbers of large marine debris items brings another set of potential impacts. Large items may carry higher numbers of individuals and higher diversity of species which could pose a greater risk of species introductions (Lockwood et al., 2005). Large items could also have physical impacts on the receiving coastal ecosystem, scouring soft substrate and sessile organisms, shading marine plants and algae, and dislodgement, dismemberment and mortality of coastal organisms are possible but have not been documented specifically from this event (Gall and Thompson, 2015). Long-term monitoring is required in order to fully investigate the physical and ecological impacts of this event (Ryan et al., 2009).

4.3. Uncertainty and assumptions

The shoreline monitoring site locations were opportunistic, chosen by partner organizations and volunteers interested in joining the MDMAP and dependent on access, proximity and other desirable traits. Therefore, sampling sites are not evenly distributed across the area of interest and may not accurately represent the debris influx in more remote and sparsely populated areas. Some shorelines known to accumulate debris in British Columbia and Alaska are too remote to survey regularly or to participate in the accumulation surveys which require complete removal of debris items. Additionally, some locations could not be accurately surveyed during the peak of tsunami debris arrival. Survey notes from Haida Gwaii in northern British Columbia recorded that the high amounts of large Styrofoam pieces were not fully enumerated as the focus became removal rather than an accurate accounting of the number of items.

The number of reported debris items confirmed as lost during the tsunami is certainly an underestimate. Not all debris items had identifying marks that could be used to trace their origin. The uncertainty surrounding additional items means that the true amount of tsunami debris washed up on North American and Hawaiian shorelines is unknown and difficult to quantify. The frequency of disaster debris reports varied with public and media interest. Although a significant amount of public outreach occurred, it is highly likely that items were found and never reported to NOAA or were never found at all. Sampling error is introduced because of untraceable debris items, debris that washes up and back out again before it can be sampled, and the household items similar to those regularly found in marine debris samples were also washed away in the tsunami. Additionally, there is an unknown quantity of debris items likely still floating in the open ocean and entrained in the Central Pacific gyre. For example, of the four floating docks known to be lost from Misawa during the tsunami, two washed ashore, one was sighted at sea but not recovered and the fourth has never been seen and is presumed to have sunk.

The model demonstrated an impressive correspondence with observations by capturing all three main peaks, although disagree somewhat with the magnitude of the peaks. They also systematically lead the observations by 2 to −3 months. These differences may reflect the complexity of the near-surface ocean dynamics and its representation in numerical models. This complexity was exemplified by Potemra (2012), who demonstrated significant differences between mean surface streamlines calculated in the eastern North Pacific using outputs of the four most advanced ocean general circulation models. SCUD is a specialized model built on the drift data of real buoys, however, differences between the dynamics of a standard drifter and real debris may be more complex than assumed in this study. At the same time, lags in observations may reflect the influence of storms in bringing coastal debris onshore or delays in item identification and reporting resulting from the delay in developing public concern and awareness.

5. Summary

There was a significant increase in debris from baseline levels, representing at least 10 times more debris than baseline levels. The spatial and temporal trends in disaster debris reports, shoreline debris surveys and oceanographic modeling were in alignment. From this body of evidence we conclude that the Great Japan Tsunami of 2011 produced a significant and substantial increase in debris influx to the shorelines of North America and Hawaii. Mitigation and monitoring activities, such as the shoreline surveys through the MDMAP program provided crucial data in the wake of this unprecedented event and monitoring for potential impacts, including those from potential invasive species, should be continued in the future.

Acknowledgements

The authors would like to acknowledge the assistance and advice of Nancy Wallace, Peter Murphy, Liam Antrim, Lexter Tapawan, Carlie Herring, and other NOAA Marine Debris Program staff that supported and contributed to the MDMAP. Jan Hafner (University of Hawaii) helped acquire model solutions. Funding for this research was provided by the Ministry of Environment of Japan through the North Pacific Marine Science Organization (PICES) and NOAA's Marine Debris Program funding supported data collection in the MDMAP. NM was supported in part by NASA through membership in the Ocean Surface Topography Science Team. We would also like to thank the many organizations and citizens that contributed to the NOAA disaster debris reporting system. The MDMAP relies on numerous organizations and citizen groups to conduct shoreline surveys; for this research in particular we wish to thank 4H Tsunami Surfers, BC Ministry of Environment, BC Parks, Blue Fox Bay Lodge, Boy Scouts of America, California Coast National Monument Task Force, Coastal Footprint, CoastWatch and CoastWatch partners, Greater Farallones National Marine Sanctuary, Hawai'i Wildlife Fund, Hawaiian Islands Humpback Whale NMS, Hawppon, Humboldt State Marine Debris Program, Kenai Peninsula Borough School District, Kupu, National Park Service, Natural Resource Crews Community Services Consortium, Olympic Coast National Marine Sanctuary, Oregon Coast Aquarium, Oregon Marine Debris Team, Pacific Whale Foundation, Redfish Rocks, Save Our Shores, Sonoma Coast Surfrider, Surfrider Foundation Monterey, Surfrider Foundation Siuslaw Chapter, Surfrider Vancouver Island, Sustainable Coastlines Hawaii, and The Santa Barbara Beach Angels. NOAA, Robert Medeiros, and Kirsten Moy provided photographs of debris items. The manuscript was improved by comments from C. Herring and the efforts of anonymous reviewers. The scientific results and conclusions, as well as any views or opinions expressed herein, are those of the author(s) and do not necessarily reflect the views of NOAA or the Department of Commerce. This publication is IPRC/SOEST Publication 1292/10262.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpolbul.2018.01.004.

References

Bagulayan, A., Bartlett-Roa, J.N., Carter, A.L., Inman, B.G., Keen, E.M., Orenstein, E.C., Patin, N.V., Sato, K.N., Sibert, E.C., Simonis, A.E., Van Cise, A.M., 2012. Journey to the center of the gyre: the fate of the Tohoku tsunami debris field. Oceanography 25 (2), 200–207.

Blickley, L.C., Currie, J.J., Kaufman, G.D., 2016. Trends and drivers of debris accumulation on Maui shorelines: implications for local mitigation strategies. Mar. Pollut. Bull. 105 (1), 292–298.

Calder, D.R., Choong, H.H., Carlton, J.T., Chapman, J.W., Miller, J.A., Geller, J., 2014. Hydroids (Cnidaria: Hydrozoa) from Japanese tsunami marine debris washing ashore in the northwestern United States. Aquat. Invasions 9 (4), 425–440.

Carlton, J.T., Chapman, J.W., Geller, J.B., Miller, J.A., Carlton, D.A., ... Treneman, N.C., Steves, B.P., Ruiz, G.M., 2017. Tsunami-driven rafting: Transoceanic species dispersal and implications for marine biogeography. Science 357 (6358), 1402–1406.

Coe, J.M., Rogers, D.B. (Eds.), 1997. Marine debris. Springer-Verlag, New York.

Criddle, K.R., Amos, A.F., Carroll, P., Coe, J.M., Donohue, M.J., Harris, J.H., Kim, K., MacDonald, A., Metcalf, K., Rieser, A., Young, N.M., 2009. Tackling Marine Debris in the 21st Century. The National Academies Press, Washington, DC.

Derraik, J.G.B., 2002. The pollution of the marine environment by plastic debris: a review. Mar. Pollut. Bull. 44, 842–852.

Gall, S.C., Thompson, R.C., 2015. The impact of debris on marine life. Mar. Pollut. Bull. 92 (1), 170–179.

Gregory, M.R., 2009. Environmental implications of plastic debris in marine settings – entanglement, ingestion, smothering, hangers-on, hitch-hiking and alien invasions. Philos. Trans. R. Soc. B 364, 2013–2025.

Howell, E.A., Bograd, S.J., Morishige, C., Seki, M.P., Polovina, J.J., 2012. On North Pacific circulation and associated marine debris concentration. Mar. Pollut. Bull. 65 (1), 16–22.

Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. Science 347 (6223), 768–771.

Kako, S.I., Isobe, A., Magome, S., 2010. Sequential monitoring of beach litter using webcams. Mar. Pollut. Bull. 60 (5), 775–779.

Lippiatt, S., Opfer, S., Arthur, C., 2013. Marine debris monitoring and assessment. In: NOAA Technical Memorandum NOS-OR&R-46.

Lockwood, J.L., Cassey, P., Blackburn, T., 2005. The role of propagule pressure in explaining species invasions. Trends Ecol. Evol. 20 (5), 223–228.

Maximenko, N.A., Hafner, J., 2010. SCUD: surface currents from diagnostic model. IPRC Tech. Note 5 (17pp). http://apdrc.soest.hawaii.edu/projects/SCUD/SCUD_manual_02_17.pdf.

Miller, J.A., Carlton, J.T., Chapman, J.W., Geller, J.B., Ruiz, G.M., 2017. Transoceanic dispersal of the mussel Mytilus galloprovincialis on Japanese tsunami marine debris: An approach for evaluating rafting of a coastal species at sea. Mar. Pollut. Bull (In Press Online).

Ministry of the Environment, Japanese Agency, 2012. Estimated Total Amount of Debris Washed Out by the Great East Japan Earthquake. http://www.env.go.jp/en/focus/docs/files/20120901-57.pdf, Accessed date: 5 May 2014.

Morishige, C., Donohue, M.J., Flint, E., Swenson, C., Woolaway, C., 2007. Factors affecting marine debris deposition at French frigate shoals, northwestern Hawaiian islands marine national monument, 1990–2006. Mar. Pollut. Bull. 54 (8), 1162–1169.

NOAA Marine Debris Program, January 2015. Detecting Japan Tsunami Marine Debris at Sea: A Synthesis of Efforts and Lessons Learned. Technical Memorandum NOS-OR&R-51 (34 pp). https://marinedebris.noaa.gov/sites/default/files/JTMD_Detection_Report.pdf.

Opfer, S., Arthur, C., Lippiatt, S., 2012. NOAA marine debris shoreline survey field guide. In: US National Oceanic and Atmospheric Administration Marine Debris Program, . http://marinedebris.noaa.gov/sites/default/files/ShorelineFieldGuide2012.pdf (19 pp).

Potemra, J.T., 2012. Numerical modeling with application to tracking marine debris. Mar. Polut. Bull. 65 (1–3), 42–50. http://dx.doi.org/10.1016/j.marpolbul.2011.06.026.

Ribic, C.A., Sheavly, S.B., Rugg, D.J., Erdmann, E.S., 2012. Trends in marine debris along the US Pacific Coast and Hawai'i 1998–2007. Mar. Pollut. Bull. 64 (5), 994–1004.

Rochman, C.M., Browne, M.A., Underwood, A.J., Franeker, J.A., Thompson, R.C., Amaral-Zettler, L.A., 2016. The ecological impacts of marine debris: unraveling the demonstrated evidence from what is perceived. Ecology 97 (2), 302–312.

Ryan, P.G., Moore, C.J., van Franeker, J.A., Moloney, C.L., 2009. Monitoring the abundance of plastic debris in the marine environment. Philos. Trans. R. Soc. Lond. Ser. B Biol. Sci. 364 (1526), 1999–2012.

Sutherland, W.J., Clout, M., Côté, I.M., Daszak, P., Depledge, M.H., Fellman, L., Fleishman, E., Garthwaite, R., Gibbons, D.W., De Lurio, J., Impey, A.J., Lickorish, F., Lindenmayer, D., Madgwick, J., Margerison, C., Maynard, T., Peck, L.S., Pretty, J., Prior, S., Redford, K.H., Scharlemann, J.P.W., Spalding, M., Watkinson, A.R., 2010. A horizon scan of global conservation issues for 2010. Trends Ecol. Evol. 25, 1–7.