

Modeling floating debris generated by the 11 March 2011 Tohoku tsunami

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Abstract

A global ocean circulation model is coupled to a particle-tracking model to simulate the transport of floating debris washed into the North Pacific Ocean by the Tohoku tsunami. A release scenario for the tsunami debris is based on coastal population and measured tsunami runup. Archived 2011/2012 hindcast current data is used to model the transport of debris since the tsunami, while data from 2008 to 2012 is used to investigate the distribution of debris on timescales up to 4 years. The vast amount of debris pushed into ocean likely represents thousands of years worth of 'normal' litter flux from Japan's urbanized coastline. This is important since a significant fraction of the debris will be comprised of plastics, some of which will degrade into tiny particles and be consumed by marine organisms, thereby allowing adsorbed organic pollutants to enter our food supply in quantities much higher than present.

1. Introduction

The great Tohoku tsunami of 11 March 2011, generated runup of over 40 m (Mori et al., 2011), devastated the east coast of Japan, resulted in nearly 20,000 casualties (IOC/UNESCO Japan Tsunami Bulletin No. 29, 30 September, 2011) and caused damage throughout the Pacific Ocean (Borrero et al. 2012; Lynett et al. 2012; Reymond et al. 2012). One aspect of this event not usually associated with a tsunami disaster was the massive influx of debris washed from the coastline and into the ocean. The popular media has reported extensively on the story of the 'tsunami debris' while international research efforts are underway to study the transport and distribution of the debris field as well as its potential effects on the environment and maritime transport. Groups such as The Ocean Conservancy and the National Oceanic and Atmospheric Administration (NOAA) host internet sites devoted to the debris while researchers at the University of Hawai'i International Pacific Research Center (<http://iprc.soest.hawaii.edu>) host a website providing real time updates of the debris field based on numerical model results.

Since the tsunami, there have been several reports of tsunami debris encountered in the Pacific Ocean. Detailed reports of debris sightings with positions and descriptions have been made available by the Japanese government: (http://www.kantei.go.jp/jp/singi/kaiyou/hyouryuu/senpaku_eng.html). In September 2011 the Russian training vessel *Pallada*, encountered tsunami debris – including a fishing boat from the Fukushima prefecture – approximately 300 miles northwest of Midway Atoll. In December 2011 a multi-institution team of researchers visited the waters around Midway Island to collect debris samples and deploy additional drifters to track the progress of the debris field (<http://www.oceanrecov.org/tsunami-debris/about.html>). In late March 2012, a so called 'ghost ship' from Japan was spotted off of the west coast of British Columbia and subsequently sunk by the US Coast Guard. Throughout 2012, there have been numerous reports of tsunami related debris, particularly floats and other objects that sit higher above the waterline reaching the coast of North America.

2. Studies of marine debris transport and accumulation

Nautical lore has long romanticized the notion of the 'message in a bottle', tossed into the sea and washed up on a distant shoreline; modern oceanography has also benefitted from the messages carried by debris dropped into the ocean. Examples include the work of by Ebbesmeyer and Ingraham (1992, 1994) and Ebbesmeyer et al. (2007) who studied the fate of shoes and children's toys lost from transoceanic container ships to refine and calibrate numerical models of oceanic circulation. Debris entering the ocean as a result of a natural disasters has also been studied by Doong et al. (2011) who looked at typhoon debris and Prasetya et al. (2011) who investigated the transport of debris in the vicinity of Banda Aceh following the 2004 Boxing Day tsunami.

On a larger scale, the identification and description of oceanic accumulation zones, 'garbage patches' or gyres, characterized by high concentrations of plastic debris (Moore et al., 2001), has attracted worldwide media and scientific attention. The formation of these accumulation zones at subtropical latitudes is related to overlying wind systems and there is a considerable body of existing literature describing the extent and concentration of debris contained within them (Carpenter and Smith, 1972; Law et al., 2010). Recently, Lebreton et al. (2012) proposed a methodology to quantify and track, floating debris from coastal input sources to oceanic accumulation zones. The debris field caused by the 2011 Tohoku tsunami presents an opportunity to combine data describing likely debris sources with oceanic circulation models.

3. Model and Method

Our particle tracking model uses a two-stage process; first a hydrodynamic model solves the equations of motion to describe water movements throughout the model domain. In the second stage, virtual particles are introduced into the flow field and allowed to move freely through hydrodynamic forcing. For this study, sea surface currents are extracted from the oceanic circulation modeling system HYCOM/NCODA (Cummings, 2005). The HYCOM model is forced by the US Navy's Operational Global Atmospheric Prediction System (NOGAPS) and includes wind stress, wind speed, heat flux, and precipitation. The model provides systematic archiving of daily ocean circulation on a global scale with output data archived back to mid-2003. The HYCOM model is computed on a Mercator grid between 78°S and 47°N at 1/12° resolution. The tsunami debris model grid covers the North Pacific from the Equator through 48°N and from 130°E to 105°W and comprises 1551 701 grid nodes with an average grid spacing of 7 km. While the full HYCOM model contains 32 vertical layers, we only consider velocities in the surface layer as the principal driver of floating particles.

The velocity data extracted from HYCOM are then coupled to the Lagrangian particle tracking model Pol3DD and used to drive the dispersion of floating material across the ocean surface. The model Pol3DD tracks virtual particles to simulate waterborne dispersion of material including neutrally buoyant anthropogenic material, larvae, oil spills, outfall discharges and estuarine or beach sediment transport. Pol3DD tracks and stores the origin, age, and trajectory information of individual particles. The particle tracking model uses a second-order accurate advection

scheme (Black and Gay, 1990) and is described in detail in Lebreton et al. (2012). Since wind driven currents are already expressed in the HYCOM hydrodynamic data, no additional wind stress terms are applied to the motion of particles. This model assumes that debris particles are mostly submerged in the water and extra forcing on potentially emerged parts of the debris is neglected. Using this approach leads to the underprediction of the transport of debris particles that sit high above the water line and are subject to additional wind stress. Indeed, at the time of writing of this article, several pieces of larger debris have reached the north American west coast. However, in this study, the simulation applies only to objects that have essentially zero windage, which represents an unknown but probably large fraction of the total debris field.

4. Debris Input

For our simulations, a total of 50,000 tracer particles were released into the model domain. We used two methods to simulate the input of debris from the tsunami; the first considered a uniform distribution of material released along the Japanese coast ('uniform release'), while the second approach used a weighting method ('weighted release') combining measured tsunami runup heights (Mori et al., 2011) with data describing coastal population density (Halpern et al., 2008). The relationship between tsunami height and population is an important consideration, since plastics, which exist in higher amounts in populated or urbanized areas, would be the most buoyant and longest lasting of the debris washed into the ocean. Along sparsely populated sections of the coast, the majority of the debris would consist of plant material, which would eventually break down in the ocean environment. Inspection of Fig. 1 shows that some of the highest measured tsunami runup heights occurred on areas of the coast with relatively low populations.

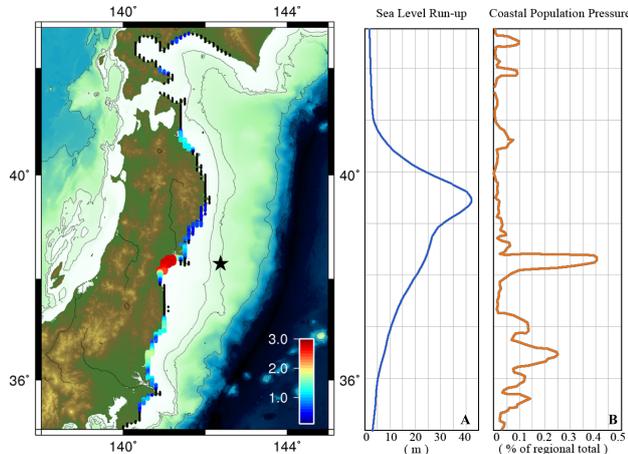


Figure 1. Northern Tohoku and southern Hokkaido Japan (left), dots along the coastline are scaled in size and color according to the logarithm of the number of particles released from that location for the distributed release scenario. Tsunami runup (panel A) is schematized from the data published by Mori et al. (2011), coastal population pressure (Panel B) is taken from data provided by Halpern et al. 2008. The black star indicates the epicenter of the 11 March, 2011 earthquake.

Based on these inputs, we then devised two modeling experiments. The first experiment used only 1 year of oceanic current data (11 March 2011–11 March 2012) and compared the distribution of tsunami debris as a function of the particle release scenario. The second experiment used only the weighted release scenario. Initialising the model on 11 March of each year from 2008 through 2011, we ran the simulation through 11 March 2012. This experiment was designed as means of assessing the potential inter-annual

variability of the debris transport as well as forecasting the progress of the debris field by using historical data, assuming that overall oceanic surface currents do not vary significantly from year to year.

5. Results and Analysis

Fig. 2 illustrates the difference in the predicted distribution of tsunami debris as a function of the input scheme. In Fig. 3 we compare the outer limit of the predicted debris field from both input scenarios at 1-month intervals to reported sightings of tsunami debris from coincident time intervals. These plots suggest that different release scenarios result in differences in the distribution of the particle concentrations, but that the outer limit of the debris field predicted by the model for both releases is virtually identical. While the modeled extent of the debris field compares well to observations, there are discrepancies, particularly in the north, where tsunami debris has been identified outside of the zone predicted by our model. We attribute this to additional wind stress acting on pieces of floating debris, an effect not included in our assessment. This effect would be more pronounced on larger pieces of debris that sit higher above the water level such as boats or shipping containers. Indeed, most of these outlying examples were fishing boats or partially submerged shipping containers. This effect would also explain reports of boats and other objects that sit above the waterline reaching the west coast of North America in early 2012 since these objects are subject to increased wind stress.

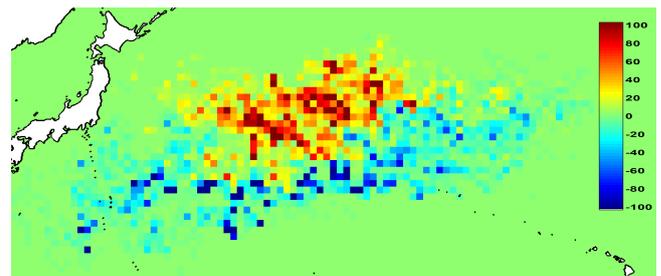


Figure 2. The absolute difference in the number of particles after 1-year of circulation between the uniform release and weighted release scenarios. Individual model cells are binned in to 10x10 regions to calculate the difference. The warmer colors represent the presence of more particles due to the weighted release scenario.

The results of the second modeling study are depicted in Figs. 4 and 5 which show the integrated number of particle visits per cell and the number of particles existing in a cell (expressed as a percentage of the total number of particles released) at particular times. While the overall patterns are similar, there are noticeable differences in the year-to-year details. Ultimately however, the results suggest that the bulk of the tsunami debris will accumulate in the eastern North Pacific Ocean between Hawai'i and California. This finding is in line with results from studies by other researchers (for example see:

http://iprc.soest.hawaii.edu/news/marine_and_tsunami_debris/IPRC_tsunami_debris_models.php). The results show that after 6 months, the debris field extends eastward to the international dateline and that subsequent eastward transport is much slower, requiring another 2.5 years is required for the debris to reach 130°W. Once east of the dateline, the speed of progression of the debris field is approximately 5 cm/s (50° longitude at 40°N = 4250 km over 2.5 years) which is consistent with the speed of the eastward geostrophic flow of the North Pacific Current (Cummins and Freeland, 2007).

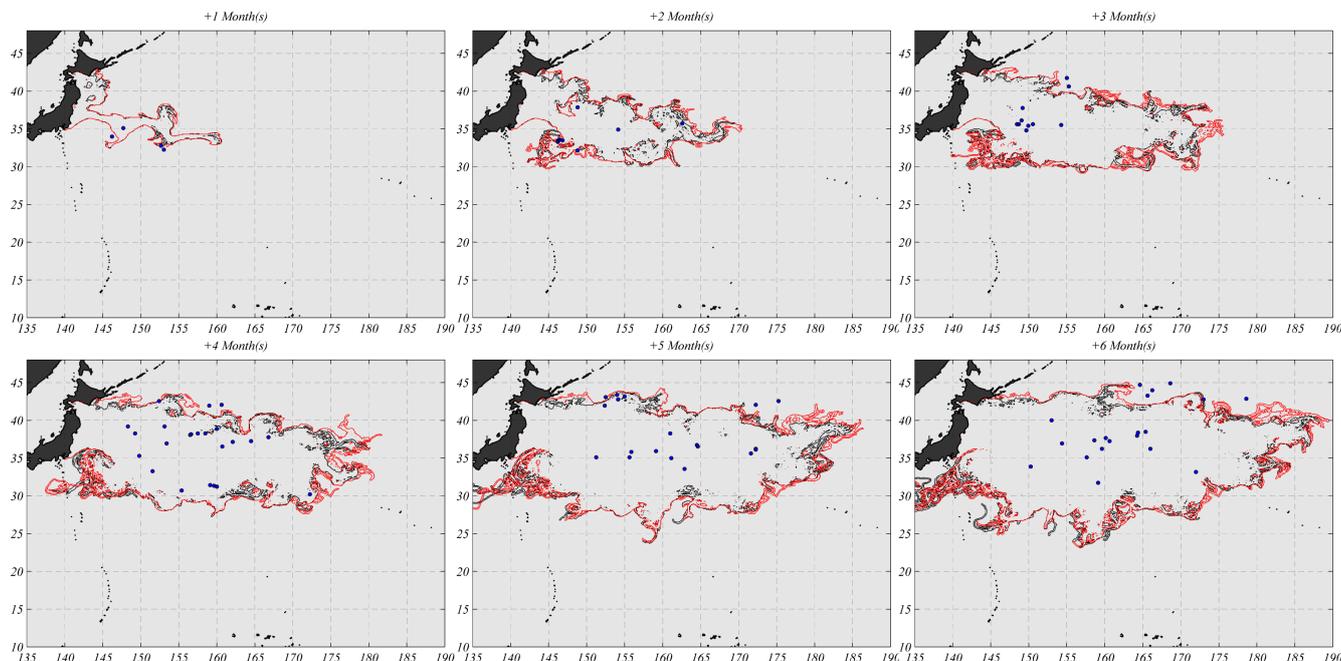


Figure 3. Model predictions compared to sightings of tsunami debris as reported by the Japanese Government for the first six months after the tsunami. The red contour represents the outer edge of model cells visited by particles from the weighted release scenario, whereas the black contour corresponds to the outer limits of the uniform release scenario. Blue dots are debris sightings.

Finally, in Fig. 6, we show the rate of progress of the debris field across the North Pacific Ocean by plotting the outer limit of the predicted particle positions at different time intervals. The results indicate that progress of the debris field is relatively quick over the first year, but then slows considerably, taking an additional 3 years for the eastern edge of the debris field to approach the North American coastline. Indeed, as indicated in Fig. 5, most of the material is predicted to stay in circulation in the Pacific. Our results suggest that no large scale beaching of tsunami debris will occur, but rather, isolated items of debris will be shed from the clockwise rotating North Pacific gyre/accumulation zone and pushed towards land either on the west coast of North America or on the windward shores of the Hawai'ian Islands. While this may not be the mass deposition of huge amounts of material alluded to in press accounts of the phenomenon, it is by no means insignificant. Rough order calculation suggest that even if only 1% of the total tsunami debris were to be beached, this would equate to about 1 kg of material per meter of coastline – assuming 15,000 km of coastline along western North America and Hawaii.

The most interesting part to this story however will be the ultimate effect of the Japan tsunami debris on the total mass of material, particularly plastics, contained in the so-called 'Great Pacific Garbage Patch'. While it is virtually impossible to quantify the amount of material input into the Pacific Ocean from the Japanese coast on a typical day, it is readily apparent that the debris released on 11 March 2011 exceeded the norm by orders of magnitude. Lebreton et al. (2012) calculated that Japan contributes between 10% and 27% of the floating material contained in the North Pacific subtropical gyre. Given the amount of debris generated by the Tohoku tsunami, this fraction should increase significantly. That the majority of the tsunami debris eventually ends up in the North Pacific subtropical gyre should not be a complete surprise given recent studies on oceanic accumulation zones (Martinez et al., 2009; Law et al., 2010; Maximenko et al. 2011). The study by Lebreton et al. (2012) defined inner and outer regions of the North Pacific accumulation zone based on thresholds of debris concentration after 30 years of oceanic circulation. Using these boundaries, our modeling indicates that within 4

years, nearly 90% and 76% of the debris will end up in the outer and inner accumulation zones respectively.

To put the Tohoku tsunami debris into perspective, we first consider the work of Yoon et al. (2010) who, in a study of floating debris in the Japan Sea, estimated that one piece of litter is released into the ocean each day for every 100,000 persons living in a coastal city. Extrapolating these numbers to the city of Sendai (pop. 1 million) yields approximately 10 pieces of floating litter per day. Simply looking at the aerial images taken of the tsunami debris reinforces the fact that 'normal' daily litter inputs were exceeded by many orders of magnitude. Taking the population of the five prefectures most affected by the tsunami (Iwate, Miyagi, Fukushima, Ibaraki and Chiba) at 14.9 million, this would suggest 149 pieces of litter released per day under normal conditions. If we assume each bit of litter weighs 100 g and that there is still 1.5 million tons (1.5×10^9 kg) of material floating in the ocean that originated from the tsunami, as reported by the Government of Japan and repeated on the NOAA's Marine Debris Program website:

(<http://marinedebris.noaa.gov/info/japanfaqs.html>), this would equate to 276,000 years worth of 'normal' debris input. A more conservative approach considers the entire population of Japan (128 million), assuming 1 kg of litter per day per 100,000 persons, this still equates to 3200 years worth of debris input in this one event.

Alternately, we can consider the work of Moore et al. (2001), who quantified the mass concentration of floating plastic in the central part of North Pacific subtropical gyre at an average of roughly 5 kg/km² with a range of 0.06–30 kg/km². If one considers the area of the North Pacific Ocean (north of 20°N) to be 35 million square kilometers, distributing the remaining floating debris over that area yields an average mass concentration of 43 kg/km² – higher than the maximum and more than 8 times the average concentration of the most severely impacted portion of the North Pacific. And finally, we can also consider the analysis of Law et al. (2010), who estimated that the surface waters of the north Atlantic contained a total of 1100 tons of floating plastic particles. Given the estimate above of 1.5 million tons of tsunami debris still afloat and assuming that just 1% of this amount is plastic

that will remain floating on the surface, this still implies that the Tohoku tsunami released more than 13 times the total plastic contained in the Atlantic Ocean into the

Pacific Ocean in one event. This will undoubtedly lead to a measurable and significant increase in plastic concentration in the North Pacific subtropical gyre in coming years.

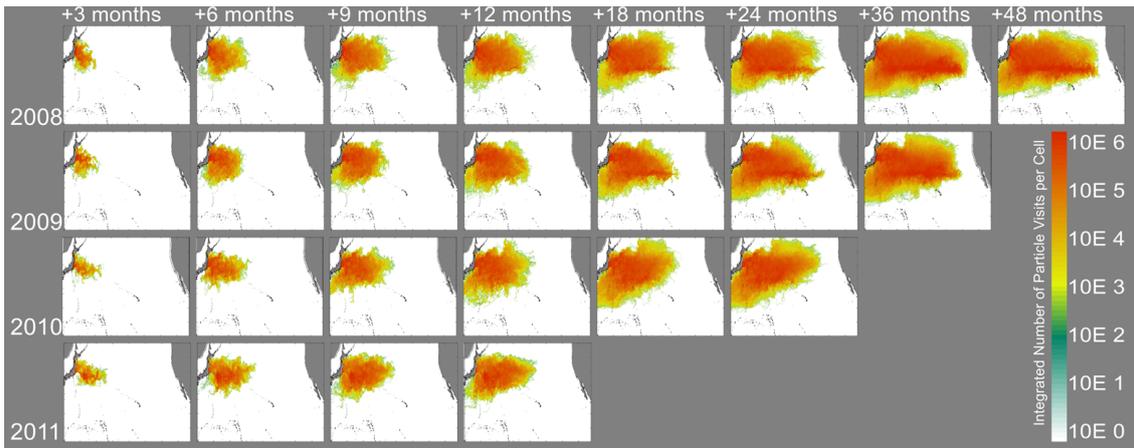


Figure 4. The number of particle visits per cell using the weighted release scenario. The simulation is started on March 11th of each year.

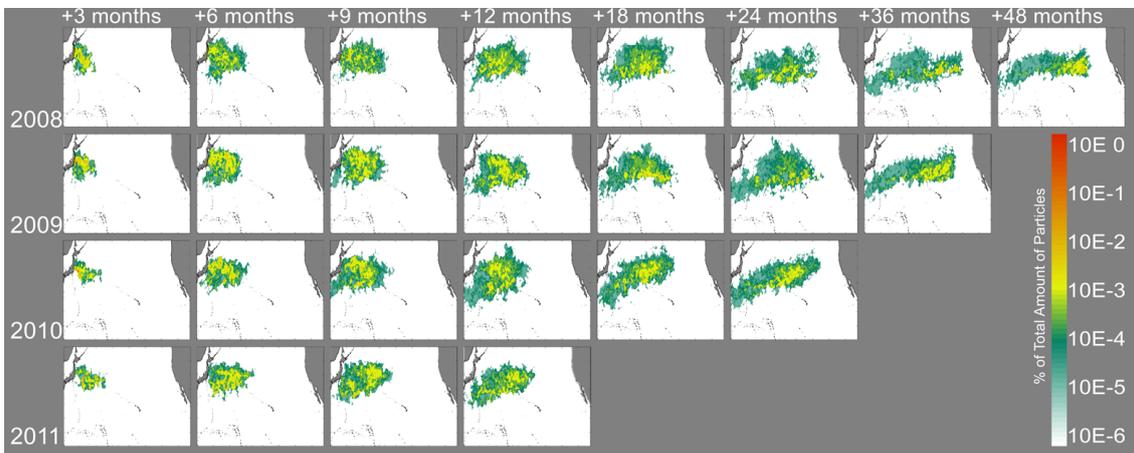


Figure 5. Modelled particle concentration expressed in percentage of the total number of particles released in to the model (weighted release scenario). The simulation is started on March 11th of each year. Particle concentration is computed over 10x10 cell bins.

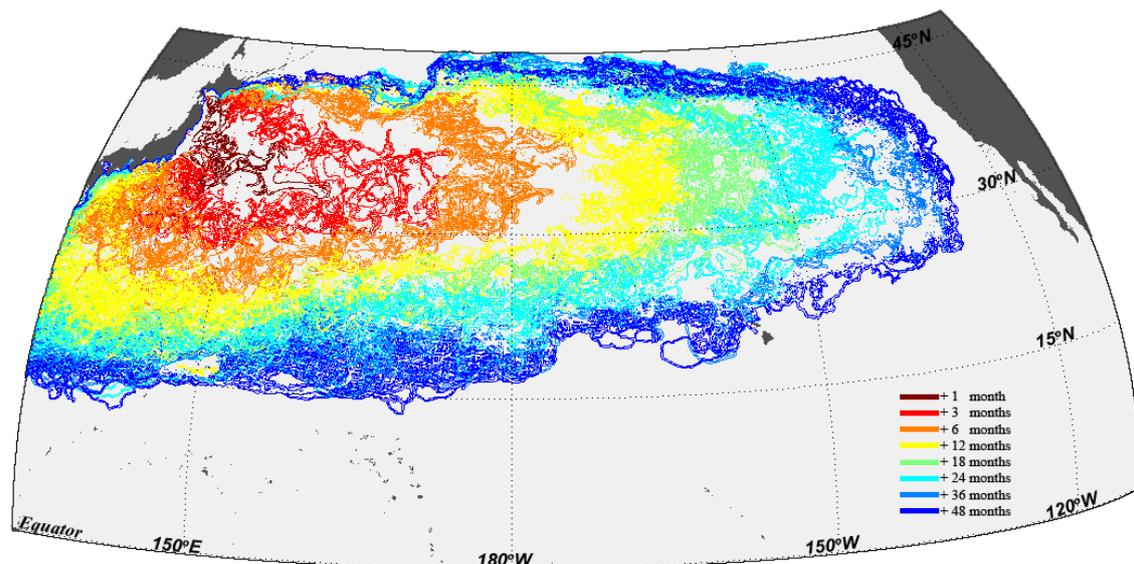


Figure 6. Tsunami debris travel time map. Colored contours represent the furthest extent reached by tsunami debris for a particular time interval. Model results for months 1, 3, 6 and 12 contain results from the four model runs starting on March 11 of 2008, 2009, 2010 and 2011. The month 18 and 24 contours show only results from the 2008, 2009 and 2010 years, month 36 shows the result from the 2008 and 2009 model runs while the 48 month contour comes from the 2008 model run.

6. Conclusion

The March 11, 2011 Tohoku tsunami washed an unprecedented amount of debris into the Pacific Ocean. We have modeled the transport of this material using hindcast current data from a global circulation model. Our model does not show any gross inconsistencies between the results and the limited available observations of the progress of the tsunami debris field, and suggests that the bulk of the tsunami debris will eventually accumulate in the North Pacific Ocean subtropical gyre, increasing the concentration of debris in the so-called 'Great Pacific Garbage Patch'. International research efforts into this phenomenon should continue to track the progress of the debris field and collect reports of debris sightings both at sea and on land to monitor and mitigate any potential adverse environmental impacts or disruptions to maritime activities. Furthermore, research efforts should focus on quantifying the inevitable increase in plastics in the North Pacific subtropical gyre, as this material is known to adsorb organic pollutants, which then enter our food supply through the ingestion of plastic fragments by marine organisms and subsequent bio-magnification up the food chain. Only consistent monitoring of both the surface water and organisms of the North Pacific Ocean will alert us of any potentially dangerous levels of such toxins and allow appropriate action to be taken.

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