PICES-MoE project on "*Effects of marine debris caused by the Great Tsunami of 2011*"

Year 3 Final Scientific Report

1. PROJECT INFORMATION

Title	Modeling studies in support of research on impact of alien species transported by marine debris from the 2011 Great Tohoku Tsunami in Japan
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2. YEAR 3 PROGRESS SUMMARY

In Year 3 modeling team continued providing support to the ADRIFT project team. Work on the project included further improvements of model experiments, investigation of sensitivity of results to poorly known parameters and to the model used, verification of model solutions using available observations, understanding interactions between tsunami debris and species from various eco-regions.

Model improvements included source functions of Japan tsunami marine debris (JTMD) on the east coast of Japan, enhancement of the SCUD model resolution by blending it in coastal regions with modified HYCOM model velocities, and extension of the analysis to Hawaiian Islands and the open ocean. We used the data of houses broken by the 2011 tsunami available from municipal reports and from Asahi Shimbun (obtained through personal communication with Dr. Maki) (Fig. 1a) to produce an index of the coastal source of model tracers (Fig. 1c) that would provide more realistic model simulations than the source uniformly distributed along the shoreline that was used in model experiments in previous years. Importance of this improvement was demonstrated through a set of 'sensitivity' experiments that revealed significant differences between model fluxes on the shorelines of North America (Fig. 11) and Hawaii (Fig. 14), originating from the northern, central and southern segments of the eastern Honshu.

To study the robustness of conclusions derived from model studies, all major experiments performed with the SCUD model (University of Hawaii, Fig. 5) have been repeated using the MOVE/K-7/SEA-GEARN model (Japanese team, Fig. 6) and GNOME model (NOAA, Fig. 7). To enhance the detail of JTMD drift in coastal areas and its accumulation on the shore, SCUD model has been blended with HYCOM data. This way, the original ¼-degree grid of SCUD dictated by the satellite altimetry and wind products has been enhanced to 10 km. The blending was limited to 100 km coastal bins and additional 100 km zone has been added for a seamless transition between the two model velocities. Also the latter zone was used to calculate and eliminate (before blending) the biases existing between the two models.

As a result, the high-resolution patterns of model "landings" have been calculated on the US/Canada west coast (Fig. 18) and Hawaii (Fig. 19) and compared with the patterns of observational reports from these regions. Refinement of the model was particularly important for simulations around Hawaii as the fine grid had better "opened" straights between the islands allowing more realistic regional circulation. We have also compared model fluxes on Hawaiian shoreline with reports of JTMD boats, identified matching peaks and discussed influence of beach morphology and pattern of monitored sites on the revealed differences.

Original methodology developed for comparison between model tracer concentration with sparse and random at-sea reports has been further developed for the GNOME model runs based on large number of particles (Fig. 17). Calculations confirmed that definition of the optimal windage values, determined from these comparisons, differ significantly between different models.

Modeling team has also contributed to the vector risk assessment working group. As a part of this contribution we calculated the statistics of satellite sea surface temperature (SST) at individual locations in the North Pacific (Fig. 25) and produced the maps showing the basin-wide SST range match (Fig. 27) that can be used to assess the probability of survival of species travelling between different eco-regions. We found that because of the strong seasonal cycle, the SST range is the largest in the source area of JTMD (Fig. 26). As a result, Japanese coastal species, pre-colonizing JTMD items could survive under a range of climate conditions from California to Alaska. (Note that 'survival' of the travel is not sufficient for 'invasion'. The latter requires 'establishment' of alien species and their 'reproduction' that pose more severe, often poorly known, constraints. Also survival is a function of oceanographic conditions along the trajectory, not only a match between that start and end locations. For each item, documented in the 'biofouling' dataset, we calculated its probable path and probable exposure to various ocean conditions. These data have been submitted to the vector risk assessment team for implementation in the eco-model.

Particular case are warm water species that are absent from the areas, affected by tsunami, but have been found on at least some JTMD items, for example, on the Misawa dock found and sampled in Oregon. We demonstrated (Fig. 24) that JTMD from the north, having a relatively high windage, had in March 2011 a tendency to drift southward and could partly cross the Kuroshio Extension front into the subtropical waters. At the same time, larvae of coastal species living along the southern Honshu, Shikoku and Kyushu could be quickly advected by the Kuroshio Extension (which was flowing near the shore during that period) hundreds of miles east of Japan to meet with the JTMD items.

Overall work on the project was well planned and technical problems and scientific complexities did not prevent us from achieving main goals of Year 3. The main difficulties were associated with the complexity of the ocean dynamics, its interaction with JTMD in drift models and limitations of observational data, whose number and quality could not allow us to find answers even on basic questions. Amounts and composition of debris floating into the ocean are still not known. For example, it is not clear how accurately the number of broken houses characterizes the amount of lumber that washed away from those towns. Even more difficult question is if there is correspondence between different types of JTMD, e.g., that more broken homes correspond to more lost boats. The situation with observations is not much better in North America and Hawaii. We do not know what fraction of JTMD items has been reported and included into the datasets. Several existing datasets often use anecdotal information and have very different formats. Quality control, including identification of duplicates and errors, is very difficult and we had to work with a limited-quality data. According to isolated reports degradation and decay were significant for such types of JTMD as wood. Degradation and biofouling could result in changes of JTMD windage with time and decay could significantly affect the quantity of JTMD reaching North America and Hawaii. Because of the lack of data, these important effects were completely neglected in our model experiments.

Regarding the simulations of JTMD drift, most difficult problems were unknown windage (a parameter that describes the hydrodynamics of a floating item under the influence of wind and wind waves) as well as the coastal and the island ocean dynamics. Existing models and existing satellite observations do not capture the full dynamics of ocean motions close to the coast (hundreds of meters to several kilometers). As a rule these motions are not consistent but rectify from high-frequency processes such as tides and the Stokes drift. Our models were not able to prove or disprove a southward long-shore drift of JTMD down to the Boso peninsula. However, they did demonstrate significant motion of model tracers and particles toward southwest (Fig.3) that could have nearly same effect on JTMD distribution, paths and interaction with warm water species as a pure southward drift.

The dynamics of JTMD near Hawaiian Islands is much more complex than (e.g.) its dynamics near the North America west coast. In the latter case, "waves of JTMD" are controlled by the large-scale dynamics of ocean and atmosphere (Fig.8b), so that the items arriving on shores that can't accept the debris (such as cliffs) will likely drift along the shore and end on beaches in the neighborhood. In the case of an island, debris approaching from the cliffy side will likely float around the island and back into the ocean. Figure 12d demonstrates the patchiness of JTMD boat reports from Hawaiian Islands that also largely disagrees with the model results shown in Figure 19. Presently, it is not clear how the model biases, coastal dynamics, shoreline morphology and activity of observers interplay to distort the agreement between the models and observations.

In Year 3, we also continued extensive educational and outreach activity that strengthened the visibility of the ADRIFT project. List of specific actions, lectures and publications in included below into the final project report. We paid particular attention to finalizing the three-year study, creating a coherent archive of model simulations and publishing main results in the special issue of Marine Pollution Bulletin magazine.

3. ABSTRACT

Our team provides modeling support to the ADRIFT project. The team includes scientists from the University of Hawaii, Japan, and US NOAA. We work in close collaboration with biologists and ecologists, helping to quantify potential impacts on North American and Hawaiian ecosystems of marine debris generated during the 2011 tsunami in Japan.

The project uses three numerical models: SCUD model operated at IPRC, GNOME model based on the Navy's HYCOM OGCM operated by NOAA, and MOVE/K-7/SEA-GEARN system operated by the MRI/JAMSTEC/JAXA group. Model solutions are validated and scaled using available observational data, and new methods are developed to facilitate the interdisciplinary research.

During the three years of the project, numerous tasks have been solved or advanced, addressing all stages of the JTMD (Japan tsunami marine debris) drift.

Sensitivity of JTMD fluxes on the North American and Hawaiian shorelines to the distribution of sources along the east coast of Japan, affected by the tsunami, was demonstrated in numerical experiments. Source distribution has been optimized using the data from municipal sources and from Asahi Shimbun that show the number of houses destroyed by the tsunami.

Streamlines of surface currents have been carefully analyzed to understand locations and strengths of along-shore currents, near-shore eddies, meanders of the Kuroshio Extension and their influence on the off-shore (eastward) JTMD transport and interaction with warm-water species.

Model experiments, providing the overall description of the paths and fates of different types of JTMD, demonstrated that, consistent with observational reports, regions in the US and Canada most affected by JTMD extend from California to Alaska and also include Hawaii. Majority of high-windage items were directed by the wind to northern areas while many low-windage items recirculated into the Subtropical Gyre. A significant fraction of the latter is still wandering in the ocean. The particular case of JTMD small fishing boats demonstrated excellent correspondence between reports from North America and model solutions, allowing the estimate that originally about 1000 boats were washed into the ocean by the tsunami, of which 300-500 may still be floating.

Statistics of satellite temperature observations were used to demonstrate that conditions along the US/Canada West Coast and in Hawaii are within the range of that along the eastern shores of Japan.

New methods and approaches developed by the project's modeling team allowed us to derive trajectories of the most significant JTMD items and to contribute to the vector risk assessment of Japanese coastal species arriving in North America and in Hawaii on JTMD. The methods are based on a probabilistic approach, interpreting tracer concentration as a probability density function of a single particle. This allows useful assessments even in cases where important information about the source, destination, or windage of items is missing or inaccurate. This technique has been used to calculate probable trajectories of individual JTMD items as well as probable oceanographic conditions (temperature, salinity, sea state, chlorophyll, etc.) along the JTMD trajectories that will facilitate assessment of possible survival of coastal species during their trans-Pacific travel.

4. PROJECT DESCRIPTION

a) Research Purpose

The power of numerical modeling is in its capability of generalizing previous experience and applying it to new tasks. Over recent decades, ocean general circulation models (OGCMs) and ocean observing system went through critical enhancements, so that many applications have been developed (e.g.) for oil spill response and for search and rescue. However, the Great Tohoku tsunami of 2011 generated an unprecedented amount of debris, whose paths, fate and impacts became a challenge for oceanography and for society.

The purpose of the modeling component of the ADRIFT project included the following:

- Use numerical models to improve our understanding of the paths, patterns, timelines and fate of JTMD.
- Calibrate models against observations and help to convert patchy observations into a coherent picture.
- Whenever possible, help to obtain integral estimates of JTMD impacts.
- Support interdisciplinary research, such as vector risk assessment.

b) Objectives

The following objectives were included in the modeling plan.

- Develop models that adequately simulate motion of JTMD.
- Develop techniques that allow to validate/calibrate the models and derive integral characteristics of JTMD.
- Support biological studies by providing model assessments on the feasibility of trans-Pacific travel of coastal species from various eco-regions in Japan.

c) Methods

To address the questions formulated in the ADRIFT project, the modeling team has developed a set of new methods and enhanced existing techniques. The accuracy on the modeling results has been verified through their comparison with available observations and in sensitivity studies, conducted using three different models and different setups for numerical experiments.

The *SCUD model* (Surface CUrrents from Diagnostic) was developed at the IPRC, University of Hawaii to obtain high-resolution maps of ocean surface currents, consistent with trajectories of the sparse array of satellite-tracked drifting buoys, drogued at 15 meter depth. The model utilizes two satellite data sets: sea level anomaly from altimetry, processed by the AVISO and surface wind from QuickSCAT (1999-2009) and ASCAT (since 2007) satellites. The model currents are calculated as a combination of mean flow, geostrophic anomalies, and locally-induced Ekman currents. The model coefficients are calibrated using collocated (in time and space velocities of nearly 18,000 drifting buoys of the Global Drifter Program and satellite observations. The SCUD model produces daily, near-real time, nearly global maps on a ¼-degree grid, distributed through the IPRC servers (Maximenko and Hafner, 2010). The effect of the direct wind force, applied to the part of marine debris object, sticking out of water is described by adding a corresponding fraction of the local wind vector (windage) to the advection by ocean currents. SCUD was successfully used to describe global distribution of microplastic (Maximenko, 2009; Maximenko et al., 2012). Model solutions helped to explain historical data (Law et al., 2010; van Sebille et al., 2016) and verify empirically new garbage patches (Eriksen et al., 2013).

The MOVE/K-7/SEA-GEARN drift/dispersion model has been created by a team of scientists in Japan from JAMSTEC, JAEA, MRI, and JAXA in order to examine the positions in the North Pacific, landing positions, and landing dates on the coast after the Great East Japan Earthquake having occurred on March 11, 2011. Model simulation that provided velocity product and particle data, used in this project, included:

- Calculation of ocean currents from March 2011 to August 2013 using a data assimilation model with an eddy-resolving general ocean circulation model (MOVE system by JMA/MRI).
- Forecasting current and wind fields from September 2013 to May 2016 by an atmosphere-ocean-land coupled data assimilation system (K-7 system by JAMSTEC)
- Calculation of dispersion of marine debris, using the above-mentioned current and wind fields with a dispersion model (SEA-GEARN by JAEA).

Analysis of the model experiments and its verification using available observations has been published by Kawamura et al. (2014).

Modeling efforts of the NOAA team have been focused on producing a "hindcast" model run, which simulates the movement of tsunami debris from March 11, 2011 through the present. The debris is modeled as particles initialized at 8 sites along the Japan coast spanning a distance of approximately 700 km. Trajectories were run within the NOAA model GNOME (General NOAA Operational Model Environment). GNOME is a particle tracking model that was initially developed for predicting trajectories of marine pollutants (primarily floating oil). However, GNOME allows user specified parameterization of the "windage" drift, making it applicable for predicting trajectories of different types of floating or neutrally buoyant material. GNOME utilizes ocean currents from the Global 1/12° operational HYCOM from Naval

Research Laboratory[1] and 0.25° global NOAA Blended Sea Winds[2]. Unlike other models, GNOME also allows to account for such coastal processes as a re-floatation of debris, temporarily washed ashore.

Modeling studies on this project combined such very different approaches as particle and tracer simulations. Lagrangian particles provide a natural analogy to individual JTMD items drifting across the ocean. At the same time, particles tend to converge in some areas and run away from others that creates large gaps on basin-wide maps. Also an extremely large number of particles is required to include effects of stochastic processes or parameters that are not known inaccurately.

Tracer concentration, on the other hand, provides coherent description of the motion of a large ensemble of JTMD items. It reflects the fact that, while trajectories of individual floating objects are subject to various uncertainties, the motion of "cloud" is highly deterministic.

During the project, we further developed this idea into a new probabilistic technique that utilizes model tracer to study pathways of individual JTMD items. This approach interprets the concentration of the tracer as a probability density function for a discrete particle and, combined with all information available from observations it allows to derive most probable paths of individual JTMD items.

Whenever possible, we used observational data to verify and scale our models. New methods were developed to compare fragmentary JTMD reports with model fluxes to the US/Canada west coast and to Hawaii and with model tracer concentration in the open ocean.

Probabilistic methods combining information about JTMD drift with oceanographic (climatological and real-time) data have been also developed to help evaluate the possibility of travel of Japanese coastal species colonizing JTMD to eco-regions in North America and Hawaii.

d) Results

This section describes numerous results of the project. It is organized according to the chronology of JTMD generation and movement rather than the chronology of the efforts on the project.

- *Source optimization*

The tragic Great Tohoku tsunami of 2011 was a major disaster that devastated many towns and villages and changed appearance of a significant stretch of the coastline of the eastern Honshu. With the main effort being on mitigation and recovery of the area affected by the tsunami, data on the amounts, composition and geographical distribution of JTMD sources are largely unavailable. Japan Ministry of Environment estimated that as much as 5 million tons of debris could be created of which about 1.5 million tons could become a floating JTMD. Generation of JTMD is a complex multi-phase process: it starts with an inundation of coastal areas with tsunami waves, damage to the structures and later washing into ocean with retreating waters. Exchange between the ocean and land is very complex and depends not only on the tsunami waves height but also on the ocean and land topography, resilience of buildings and structures, etc., etc. While much of debris was brought in the ocean, there were also many reports on boats, ships and marine structures brought by the same waves on the land. We used recent data on the number of homes destroyed by the tsunami, collected by municipal services and by Asahi Shimbun, which we received through a personal communication with Dr. Maki. Figure 1a shows the distribution of reports along the shoreline and

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[1] http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html
[2] http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html

reveals that the highest numbers are located between 37.5N and 39.8N. Our analysis of the overlaps between the two sources of the data confirmed a good agreement between them, so for towns where two estimates were available we used an average number. In other region, municipal and Asahi data were complementing each other. To convert discrete data of Fig. 1b into a continuous function, shown in Fig. 1c, a set of parameters has been tried for a Gaussian filter. Finally, we selected the source distribution function (black line in Fig. 1c) because it contains a single peak without excessive smoothing. Simulations with this source function replaced the early model experiments using homogeneous or discrete sources. Although this adjustment has not change main conclusions of our study, Figures 11 and 14 show that some details of model fluxes on the North American and Hawaiian coastlines are sensitive to the choice of sources.

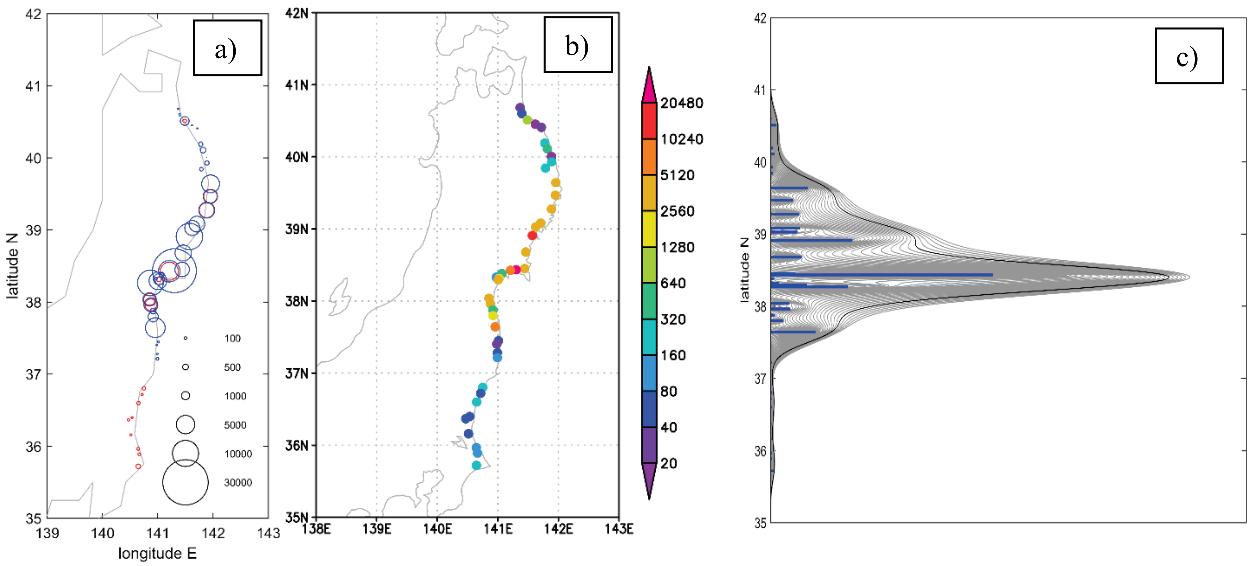


Figure 1. (a) Number of broken homes, reported by municipal sources (blue) and Asahi Shimbun (red). (b) Composite data distribution. (c) 'Source function' of JTMD calculated with a variety of filter and used to initiate model simulations.

- *Initial drift from Japan*

Structure of ocean currents east of Japan is very complex and characterized by several very strong jets and energetic meanders and eddies that determine the initial evolution of JTMD field before it enters the open ocean. Our analysis of model currents on the day of the tsunami confirmed that most important features are adequately represented in all three models (Fig. 2) and include: the Kuroshio taking an offshore path south of Honshu, Kuroshio Extension with a well-developed first meander around 143E, subpolar front around 40N, and a very strong anticyclonic eddy centered approximately at 39N, 143.5E. The latter eddy may have played a very important role in the JTMD drift in March 2011. While most time, there is a branch of Oyashio Current that flows southward along the east coast of Honshu, the eddy interrupted this current and was pulling JTMD offshore. This process is clearly visible in model simulations, illustrated by Figure 3.

Particularly good correspondence is obtained between the SCUD and MOVE/K-7/SEA-GEARN simulations. The northern portion of JTMD is swirling around the eddy center while the southern flank of the JTMD is quickly picked by the Kuroshio Extension and advected east. This structure corresponds well with the Japan Coast Guard who reported March 20-21, 2011 smaller off-shore extent of the debris field between 37 and 38N than north and south of these latitudes. Particle simulations with GNOME are hard to compare with tracers in other models. A model source from eight point locations produces artificial "blobs" that persist for at least a month. Also the GNOME particles demonstrate stronger dispersion in the north-south direction than SCUD or MOVE/K-7/SEA-GEARN.

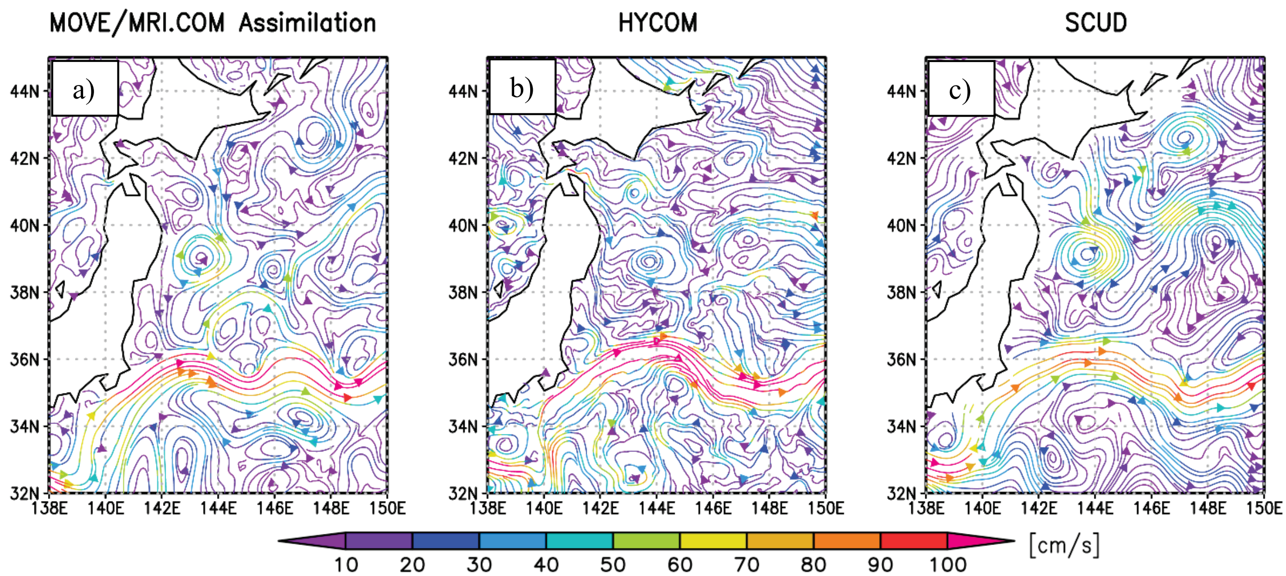


Figure 2. Streamlines of surface currents in (a) MOVE/K-7/SEA-GEARN, (b) HYCOM, and (c) SCUD (right) models for March 11, 2011. Colors represent current speed and units are cm/s.

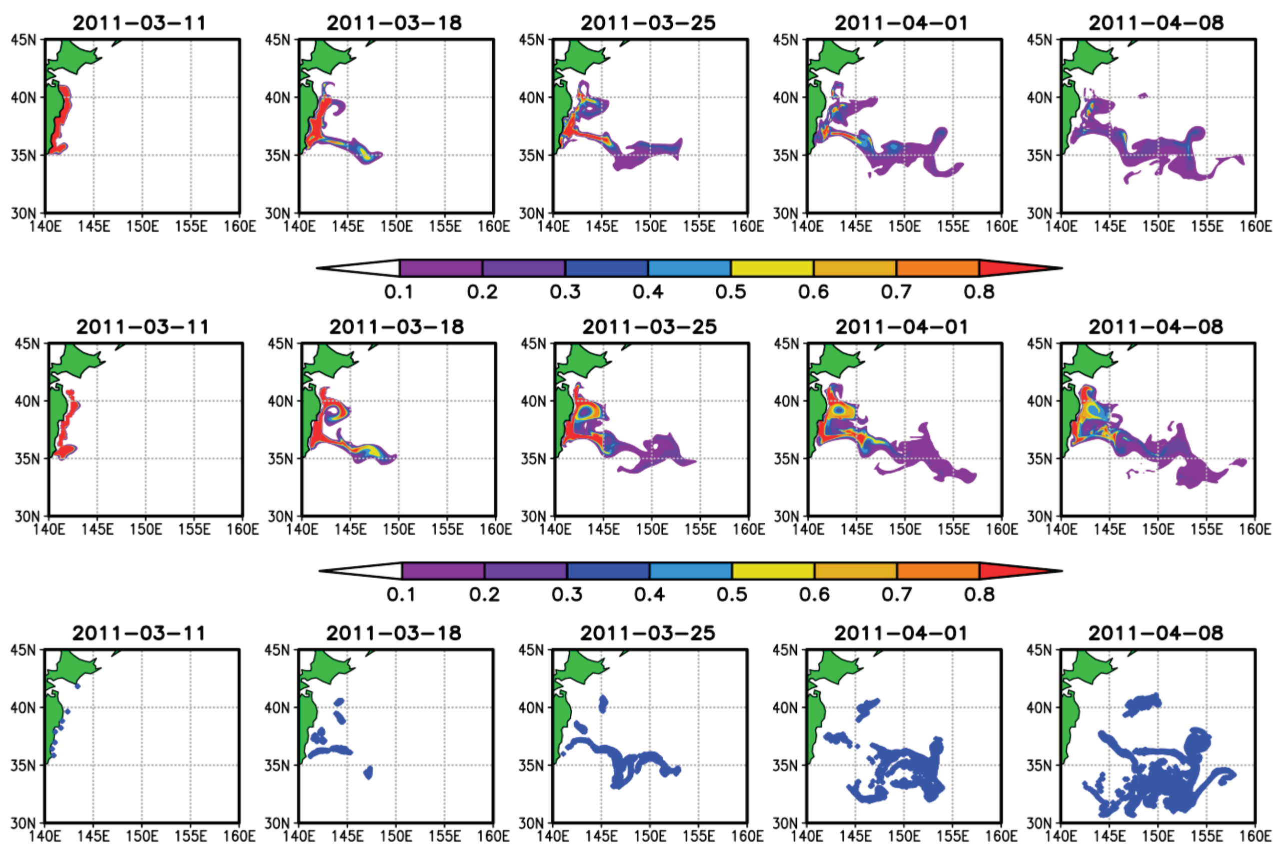


Figure 3. Tracer concentration for (top row) SCUD and (middle row) MOVE/K-7/SEA-GEARN and particle locations in (bottom row) GNOME models for windage parameter 1.5% on March 11, 2011 and 1, 2, 3, and 4 weeks later.

- *High-resolution in coastal areas.*

High model resolution is important for adequate simulations of debris drift in coastal areas, where dynamical scales are commonly smaller than in the open ocean. It is particularly critical for numerical experiments around the Hawaiian Islands. The original model grid of SCUD was ¼-degree, corresponding to resolution of satellite altimetry and wind data. This grid (Fig. 1a) didn't resolve the straights between most of the islands and converting the chain of islands into a 600-km-long barrier. Model solution in this configuration had a strong tracer gradient between the windward (northeastern) and leeward (southwestern) regions. Originally, to mitigate this problem we interpolated current data over the land. In this configuration (Fig. 4b), debris flux on the islands was calculated from the density of the tracer, velocity of the current and geometry of individual islands. Finally, we improved the model by blending SCUD in the coastal areas with the 10-km HYCOM model data. The latter were unbiased using offshore model inter-comparison and blended as follows: (i) the new model grid is a 10-km HYCOM grid, (ii) data > 200 km from shore are interpolated SCUD data, (iii) data < 100 km from shore are unbiased HYCOM data, and (iv) 100-200km is a transition zone between the models. The new model (Fig. 4c) has fully open straights and allows the full complexity of JTMD motion around the islands. (Unfortunately, this does not guaranty that the full complexity of the coastal dynamics is actually captured by the modern model.)

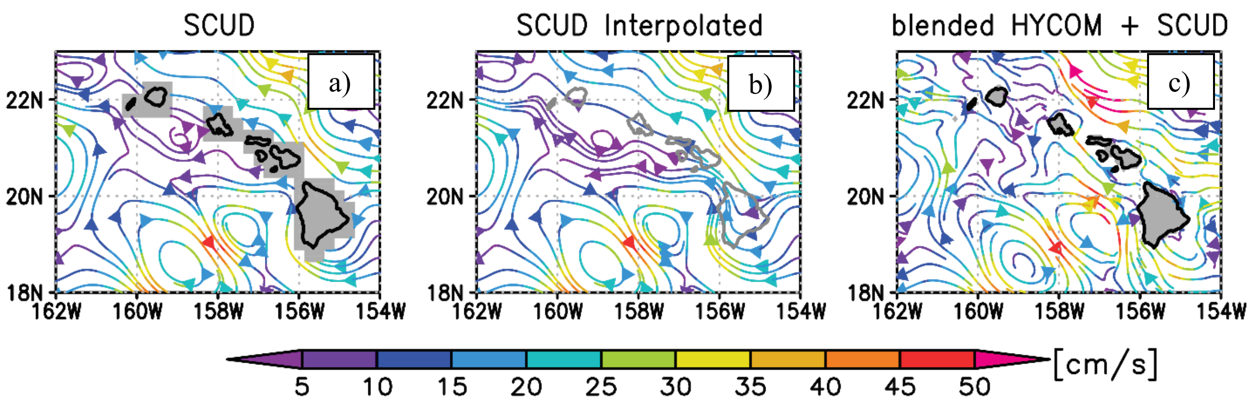


Figure 4. Streamlines of surface currents around Hawaii for March 11, 2011 in (a) the original ¼-degree SCUD model (gray shows model land mask), (b) same as (a) but interpolated over Hawaiian Islands, and (c) SCUD model blended with HYCOM data on a 10km grid. Colors represent current speed and units are cm/s.

- *Multi-windage modeling based on particle/tracer simulations*

Ocean models describe motion of water parcels. 'Windage' is a parameter that characterizes drift of an object relative to the water. Usually, this drift is due to the direct force of the wind and is assumed to be in the direction of the wind and at speed proportional to the wind speed. (Note that because wind-driven surface currents have most complex dynamics and their estimates vary significantly between different models, the latter may need to use different windage values to simulate the drift of the same object.) Figures 5-7 show the results of full-scale JTMD modeling with the three project models. To address the wide range of JTMD types, all models are ran with windages ranging from 0% to 5%. The SCUD (Fig. 5) and MOVE/K-7/SEA-GEARN (Fig. 6) models in this example are used to calculate tracer density evolution and GNOME (Fig. 7) operates with a large number of particles.

Even without further analysis, Figure 5-7 provide important conceptual description of the drift of JTMD, its pattern, pathways, and sometimes its fate. All models agree that in the first months after the tsunami, JTMD gets sorted according to its windage. High windage tracer and particles move faster and reach in less than 12 months the US/Canada west coast where a big fraction of it washes ashore. In 2012, medium-windage debris recirculates into the subtropical gyre and some ends on the Hawaiian Islands. By 2014, most of the tracer is concentrated in the gyre.

Comparison also reveals significant differences between the models. For examples, SCUD suggests that the primary residence site of low-windage JTMD is in the eastern subtropical gyre, known as a Garbage Patch where concentration of microplastics is maximum (e.g., van Sebille et al., 2016). At the same time, MOVE/K-7/SEA-GEARN and GNOME models suggest a broader east-west extension of JTMD. This discrepancy can be partly explained by the fact effective windages in the SCUD are higher than in the two other models. Also, after August 31, 2013 MOVE/K-7/SEA-GEARN model switches into a forecast mode that results into some loss of accuracy, especially in the eastern North Pacific, where model resolution is degraded to ½-degree.

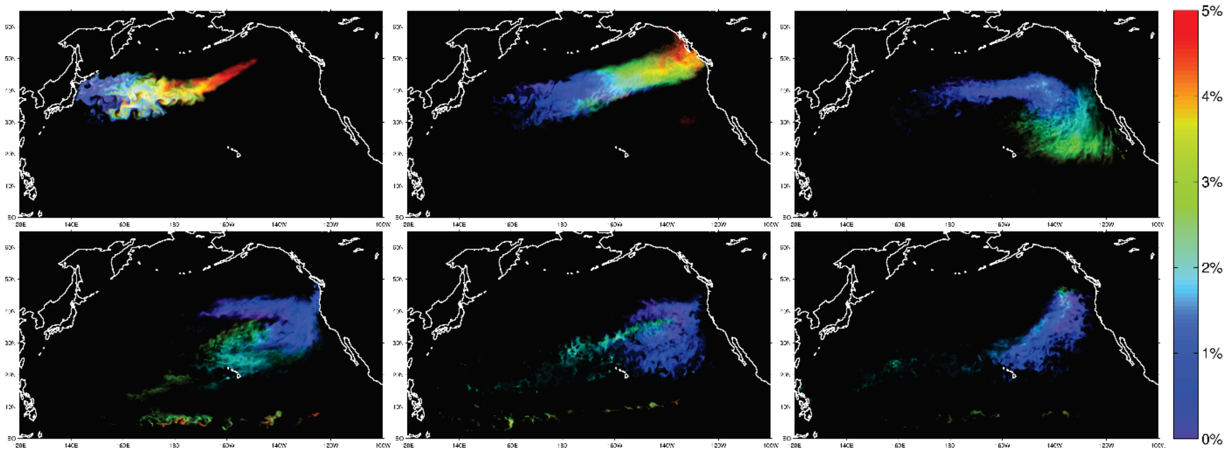


Figure 5. Evolution of JTMD tracer in the SCUD model simulations. Colors indicate windage of the debris. Shown are maps, corresponding to September 1, 2011, March 1, 2012, September 1, 2012, March 1, 2013, September 1, 2013, and March 1, 2014.

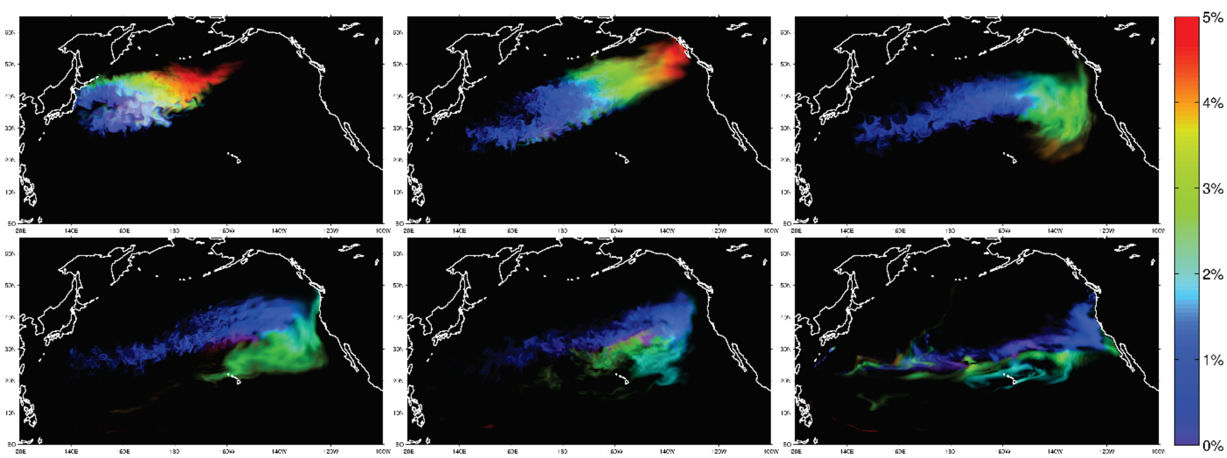


Figure 6. Same as in Figure 5 but for but for MOVE/K-7/SEA-GEARN model simulations.

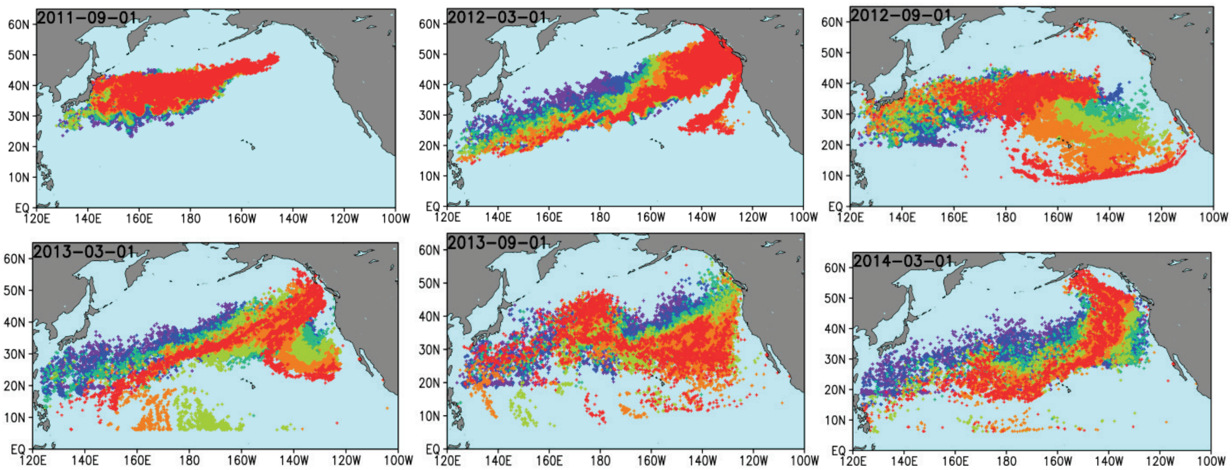


Figure 7. Same as in Figures 5 and 6 but for particle locations in the GNOME model simulations. Colors indicate particle windages according to the color scales of Figs. 5 and 6. High windages are plotted on a top of lower windages.

- *Model comparison with observational reports from North America*

Overall, observations of marine debris are very sparse and do not allow quantitative comparison with the models. In the case of JTMD study, most items are hard to discriminate from the general debris, not associated with the tsunami. We found that reports of boats from the US/Canada west coast are unique in a sense that (i) there was a high probability of them being noticed and reported and (ii) many of them could be traced back to the disaster area and often to the owner in Japan. Geographical distribution of reports is shown in Figure 8a and by 2015 they can be grouped in three "waves" (Fig. 8d). Remarkably, during each wave, reports were coming almost synchronously from the full stretch of the shoreline, indicating that the "flux" of the JTMD boats was controlled by relatively large-scale dynamics of the ocean and atmosphere that made the investigation insensitive to many poorly known factors.

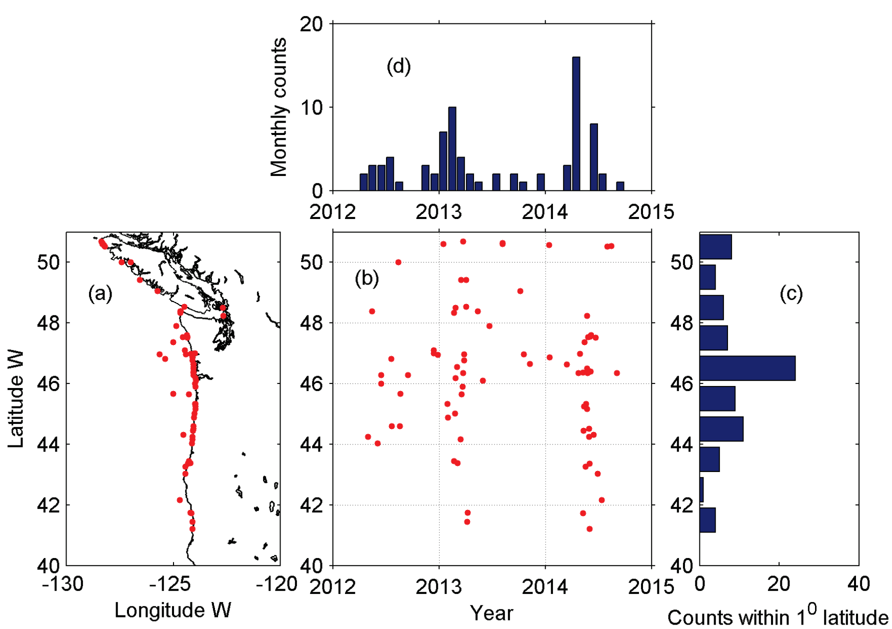
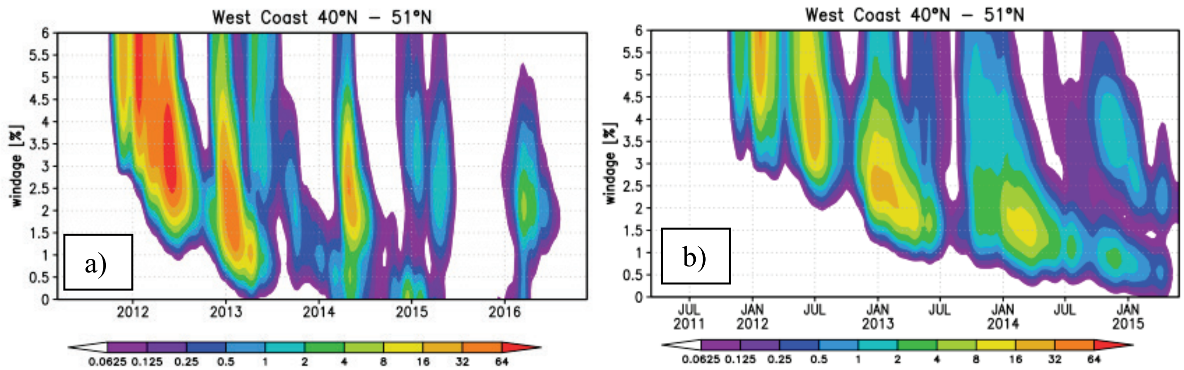


Figure 8. Reports of JTMD boats from the US/Canada coastline between 40 and 51N. (a) Location of reports relative to the shoreline. (b) Latitude-time diagram. (c) Number of reports in 1-degree latitude bins. (d) Monthly number of reports.



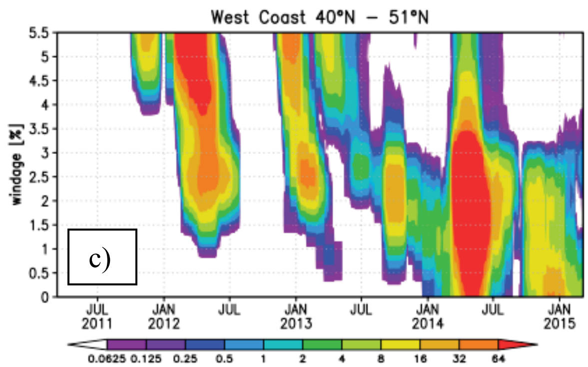


Figure 9. Model fluxes timelines on the North America west coast for different windages, calculated from (a) SCUD, (b) MOVE/K-7/SEA-GEARN, and (c) GNOME. Units are conventional and differ between the panels.

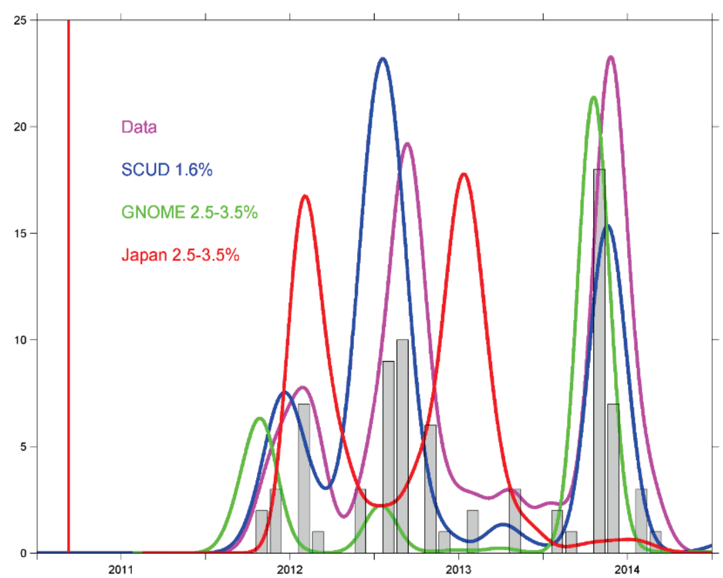
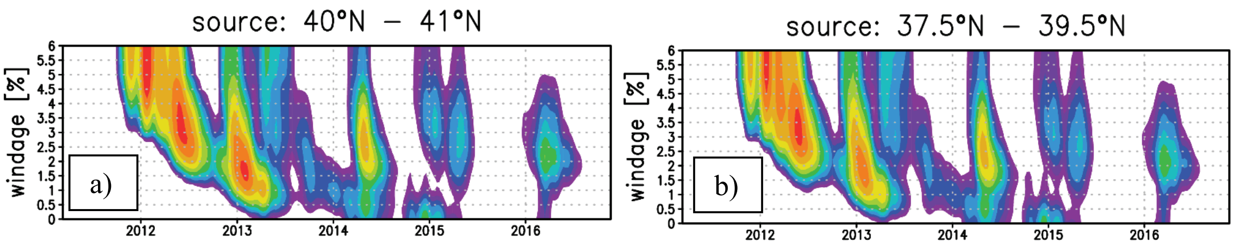


Figure 10. *Monthly counts of boats on the U.S./Canada west coast (gray bars) and low-pass filtered timelines of boat fluxes in observations (magenta) and model experiments with different windages: 1.6% for SCUD (blue) and 2.5–3.5% averages for GNOME (green) and SEA-GEARN/MOVE-K7 (red). Vertical red line marks March 11, 2011. Units on y-axis are boat counts for monthly reports and conventional for other timelines.*

As described by Maximenko et al. (2015), comparison with the models included several steps. First, model fluxes on the chosen part of the shoreline have been calculated (Figure 9). Then observational reports have been filtered to produce a continuous timeline (magenta in Fig. 10) and the same filter was applied to the model fluxes. Finally, windages (or combinations of windages) were identified, for which model-observation comparison provided the best correspondence. SCUD solution for 1.6% windage (blue line in Fig. 10) contains three main peaks and one secondary peak with time and amplitudes close to the observed timeline. Optimal windages for SEA-GEARN/MOVE-K7 and GNOME are somewhat higher – between 2.5 and 3.5%. The former model (red line) correctly simulates the first but misses the second one and loses the accuracy after switching to the 'forecast' mode. The GNOME solution (green line) contains three main peaks but the first peak leads observations by 3-4 months and the magnitude of the second peak is severely underestimated. Low magnitude of the 2nd peak in SEA-GEARN/MOVE-K7 and GNOME may be due to the ‘westward’ bias in their solutions seen in Figures 6 and 7. A big part of the model tracer seems circulating in 2013-2014 around the large gyre before returning to the eastern Pacific. On contrary, majority of tracer in the SCUD model resides after year 2013 in the eastern convergence, close to North America.

Scaled and projected back to the start point, the SCUD model gives 1000 as an estimate of the initial number of floating boats in March 2011. This does not contradict to other estimates. On November 16, 2011, the Japan Coast Guard detected 506 skiffs/vessels, drifting off the devastated shoreline. The Ministry of Agriculture, Forestry and Fisheries (MAFF) of Japan estimated the total number of fishing skiffs/vessels that were lost or crushed by the tsunami as 18,936 but how many of these vessels drifted away remains unknown. The Ministry of the Environment (MoE) of Japan estimated that the total amount of skiffs and vessels that became JTMD was about 102,000 tons but the total tonnage of skiffs/vessels that floated away was only 1,000 tons. Scaled SCUD solution estimates that less than 10% of the tracer washes ashore annually and suggests that more than 70% of JTMD with windage close to 1.6% (equivalent to 400–700 boats) was still floating at the end of 2014. By 2017 this number reduced to 300-500 boats that continued coming to various shores in 2015 and 2016.



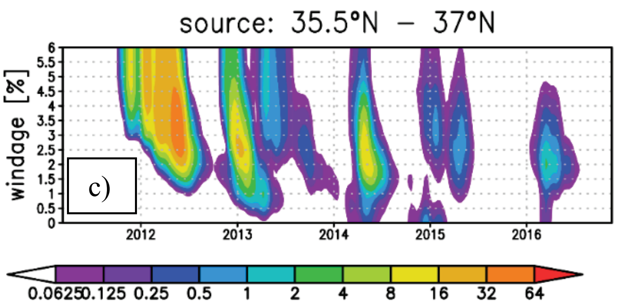
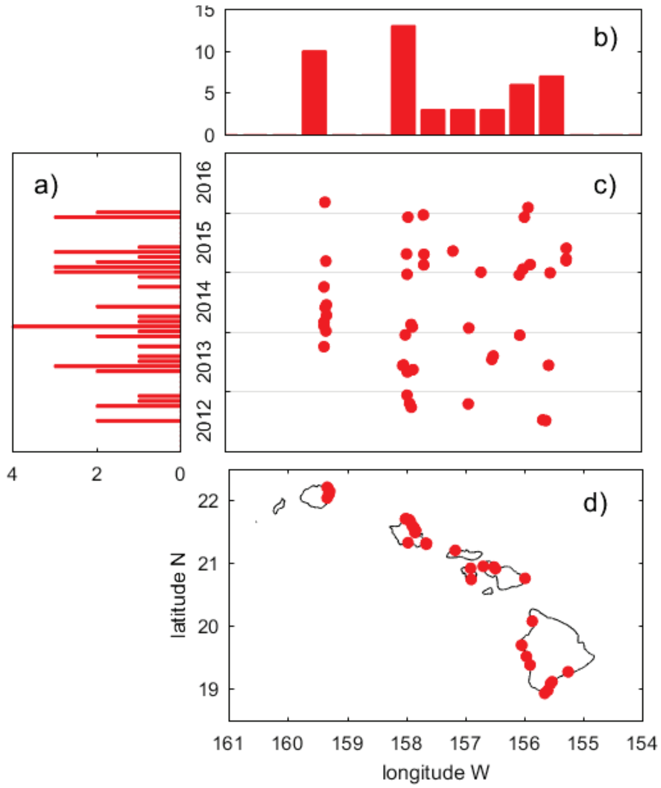


Figure 11. Sensitivity of fluxes to the latitude of source. Fluxes on the US/Canada coastline in the SCUD simulations with sources of various windages located in the (a) northern, (b) central and (c) southern sector of the east coast of Honshu, affected by the 2011 tsunami. Units are conventional.

In addition to large-scale biases, fluxes in Figure 10 can be different in different models due to somewhat different distribution of sources. A simple illustration can be found in Figure 11 that compares the JTMD fluxes in the SCUD model, coming to on the US/Canada west coast from sources, located in three different regions on the east coast of Japan. Although main peaks are present in all model runs, amount of tracer coming from the northern and central areas of Japan is markedly higher than from the southern segment. According to Figure 1, the ‘central’ region of Figure 11b corresponds to the area with the most broken homes, however, it’s not clear whether the correlation between the homes and JTMD boats is high or not.

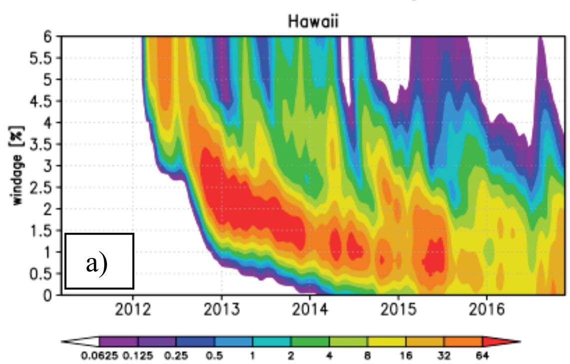
- *Model comparison with observational reports from Hawaii*

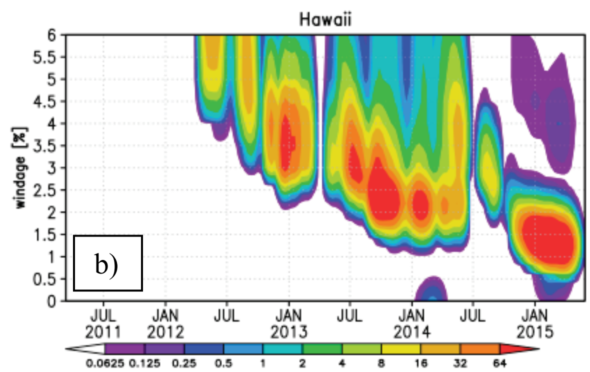
Other area where JTMD is relatively well documented is the Hawaiian Islands. Located in the central subtropical gyre, it receives lower-windage marine debris than typical for the US/Canada west coast. With a relatively short shoreline and relatively high density of population (say, compared to Alaska), many site in Hawaiian Islands have very complex terrain and are hard to reach. With a few rare exceptions, “hot spots” or “dirty beaches”, collecting large amounts of litter are very localized and driven by a strong local dynamics of waves, currents and wind. Unlike the North America west coast, where waves of debris have seasonal time scales and high probability to find a beach accepting marine litter, in Hawaii there is high probability for floating debris to “miss” the land, float around and between islands back in the open ocean.



In addition, the site in Hawaii monitored by experience cleanup groups cover only selected parts of the islands, so that some phases of debris flux are observed better than others. For example, almost all JTMD boat reports from Kauai came from the eastern sector (Fig. 12d), actively monitored by the Surfrider Foundation Chapter led by Dr. Carl Berg. It is not clear whether other shores were not accepting boats or if the boats were not reported. The timeline of monthly number of boat reports contains hints on several peaks but they are much less pronounced than in Fig. 8. Some peaks appear synchronously on several islands but some others do not.

Figure 12. (same as Fig. 8 but for Hawaii) Reports of 45 JTMD boats from the US/Canada coastline between 40 and 51N. (a) Monthly number of reports. (b) Number of reports in 1/2-degree longitude bins. (c) Longitude-time diagram. (d) Location of reports relative to the shoreline.





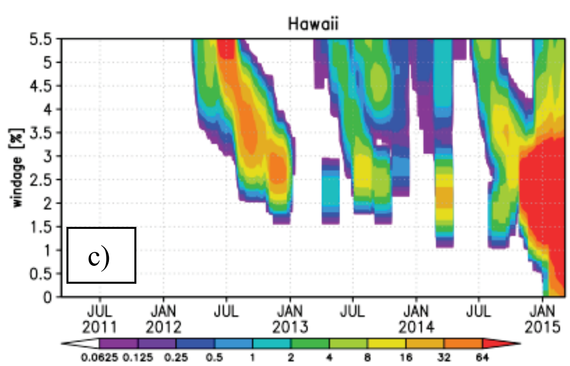


Figure 13. (same as Fig. 9 but for Hawaii) Model fluxes timelines on Hawaiian coast for different windages, calculated from (a) SCUD, (b) MOVE/K-7/SEA-GEARN, and (c) GNOME. Units are conventional and differ between the panels.

The complexity of the island dynamics is illustrated in Figure 13 by the significant differences between the fluxes in the three project models. By the time of this report, no satisfactory correspondence has been found between observations and models. Each of the models produces peaks, coinciding with some peaks in the observational timeline, but they strongly disagree with observations during other periods.

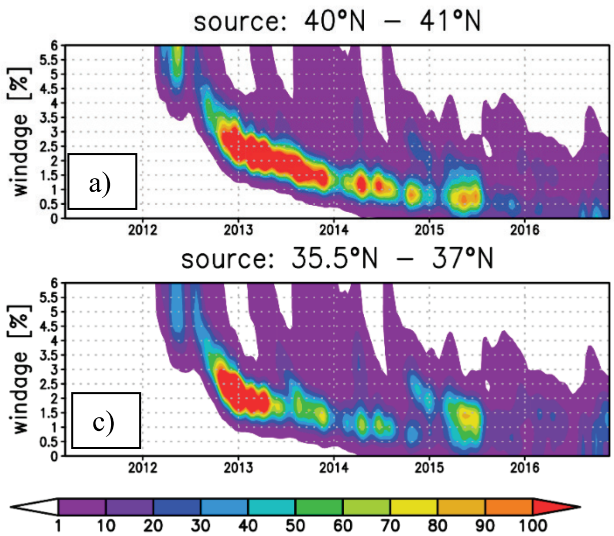


Figure 14. (same as Fig. 11 but for Hawaii) Sensitivity of fluxes to the latitude of source. Fluxes on the Hawaii coastline in the SCUD simulations with sources of various windages located in the northern (a), central (b) and southern (c) sector of the east coast of Honshu, affected by the 2011 tsunami. Units are conventional.

Similarly to Figure 11, fluxes in Hawaii demonstrate dependence on the source location in the north, center or south of the area affected by the tsunami (Fig. 14). Especially peculiar is the conclusion, supported by Fig. 14a, that Hawaii is more connected to (i.e. receives more tracer from) the north of Honshu. The explanation of this fact can be found by considering the pathways of JTMD, shown in Figures 5-7. One can see that model does not move from Japan to Hawaii directly but recirculates from the northeast. This recirculation is more feasible for tracer coming from northern sources, while tracer prom the southern regions gets more easily trapped in the subtropical convergence.

- *Model comparison with at-sea observational reports*

In addition to reports from the shoreline, large number of data has been collected at the sea. This valuable information is not readily available for model validation because it is tremendously sparse and biased towards observing ships. Figure 15 illustrates distribution of boat reports in space (dots) and time (colors). Careful analysis reveals that the pattern of the dots does reflects the pattern of ship lanes and search campaigns rather than the pattern of drifting JTMD boats. Also, there are no reports from the areas where JTMD were not present. Such negative reports would be tremendously helpful in outlining the pattern of JTMD clusters but, unfortunately, they are not practiced. However, we noticed that even this limited dataset reflects systematic drift of the JTMD boats from west to east (change in color from purple and blue in the west to green, yellow and red in the east) a developed a new technique allowing to evaluate model performance by subsampling model solution at locations and times of the JTMD boat reports.

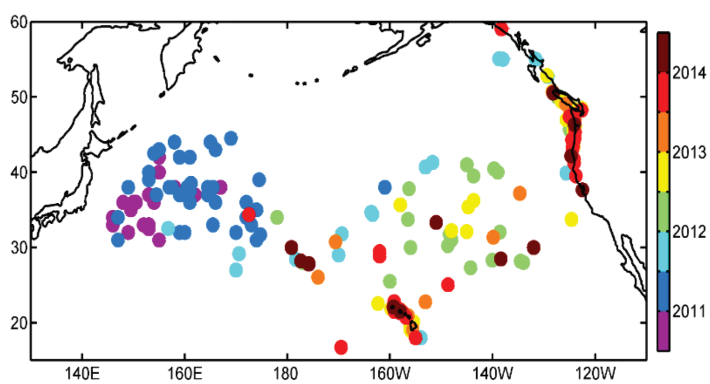


Figure 15. Reported locations of boats/skiffs/ships and (colors) times of the reports. Color bar spans January 2011–December 2014 and labeled ticks mark central moments of the years.

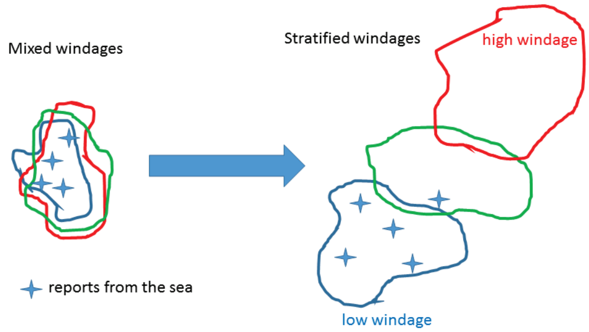


Figure 16. Illustration to the method of optimal windage estimate by subsampling model solution at locations/time of marine debris reports.

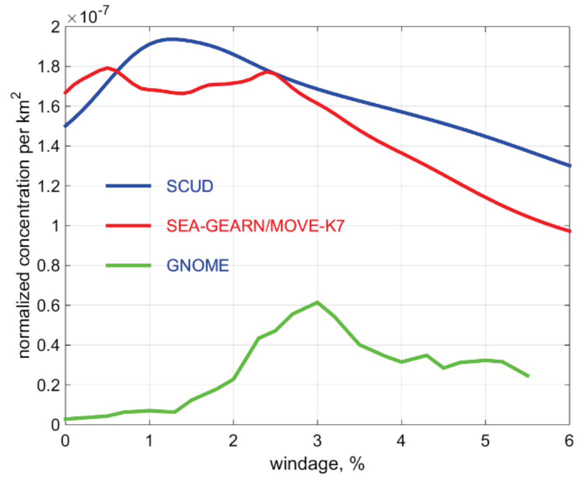


Figure 17. Mean tracer concentrations for SCUD (blue), SEA-GEARN/MOVE-K7 (red) and GNOME (green) for different windage values averaged over locations and times of boat reports shown in Figure 15 and model solutions shown in Figures 5-7.

The idea of the method, illustrated by the sketch in Figure 16 is that the greater the overlap between the "clouds" of the model tracer and reported JTMD items, the higher value of the model tracer concentration is retrieved at the JTMD item location. This technique can be used to compare performance of different models or performance of the same model under different settings (for example, windage of the tracer).

To produce Figure 17, evolution of tracer cloud in the SCUD and SEA-GEARN/MOVE-K7 models after release east of Japan was simulated for 61 values of windage parameter ranging between 0 and 6% and concentration was then normalized by the volume of the source. The GNOME model was used to release about 40,000 particles for each of 23 windage values ranging between 0 and 5.5%. Distance to the nearest model particle was calculated from each boat report and concentration was estimated as one particle per an area of the circle of radius twice the distance. Particle concentration was then normalized by the number of released particles.

Figure 17 suggests that two models (SCUD and SEA-GEARN/MOVE-K7) perform equally well while their comparison with the particle-based GNOME model is difficult. Optimal windage values are estimated at 1.4% for SCUD and 3% for GNOME and are in an excellent agreement with similar estimates in Figure 10. At the same time, SEA-GEARN/MOVE-K7 performs best at 0.5-2.5% windages that is somewhat lower than in Figure 10 – the reason for such discrepancy is currently not known.

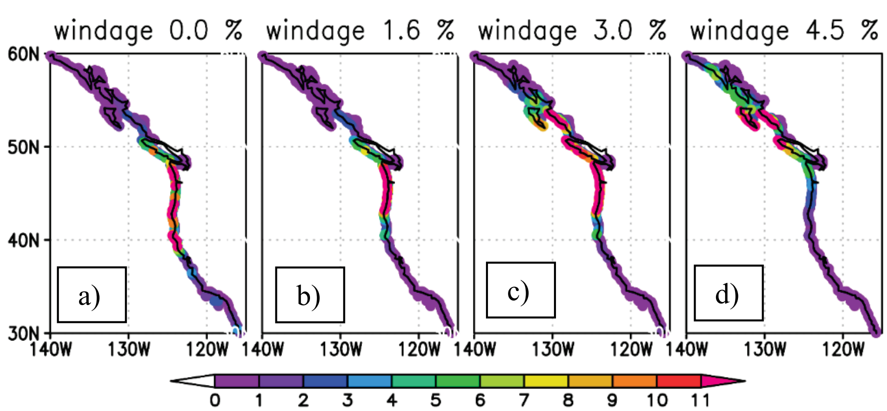


Figure 18. Relative amount of model tracer that washed on North America west coast in the SCUD runs between March 11, 2011 and March 10, 2016. Units are conventional. Windage values are (a) 0%, (b) 1.6%, (c) 3%, and (d) 4.5%. Units are conventional.

- *Patterns on shore*

One of most challenging questions to the models is whether they can adequately reproduce coastal "hot spots", i.e., locations that collect more debris than other areas. The answer on this question is not easy because observational data that could help are not available on the model scale. Comparison between models and available JTMD reports is difficult because information on the coastline accessibility to the JTMD floating near the shore (as a sandy beach versus a vertical cliff) as well as availability of observers who would notice and properly report the JTMD, is largely unknown and not included into the models. In some cases (such as our Fig. 10) averaging over a larger domain helps to reduce effects of unaccounted factors. Distribution of the model tracer at 1.6% windage shown in Figure 18b has a maximum between 43 and 48N that is in good agreement with the distribution of JTMD boat reports shown in Figure 8c. However, the model does not capture a spike near 46N (a latitude of Portland, the biggest city in the region), indicating that ocean dynamics (such as possible bifurcation of the North Pacific current) is not relevant. The peak is likely due to a larger (than in other areas) number of visitors to the shoreline.

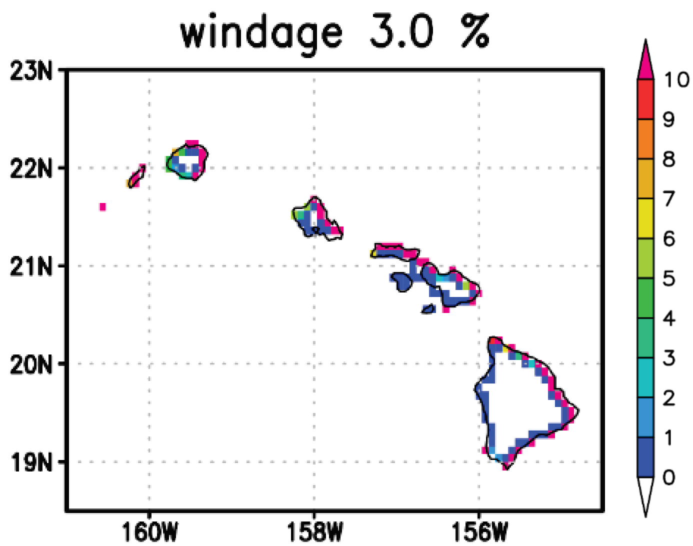


Figure 19. Relative amount of model tracer (with 3% windage) that washed on the Hawaiian coastline in the SCUD runs between March 11, 2011 and March 10, 2016. Units are conventional.

In Hawaii, the distribution of reports (Fig. 12d) is even more complex and agreement with the models varies between islands and windages. For example, at 3% windage model tracer ends on the eastern side of Kauai island more frequently than on the western side. This is in a good agreement with boat reports as well as the case of the windward (northeast-facing) shore of Oahu. At the same time, many reports from Big Island (Island of Hawaii) came from the western side -- area of Kailua-Kona – where model does not produce much flux.

These examples suggest that more studies are required in future to help understand the effects of the coastal dynamics and pattern on observations and to scale it for comparison with ocean model simulations.

- *Using model tracer for probabilistic study of motion of JTMD items*

Objects, floating on the ocean surface, are moved by many processes, some of which are stochastic by their nature. Errors and unknowns also add to the stochasticity of the debris path. To take these factors into account, model experiments operating with particles introduce a "random walk" and launch an ensemble rather than a single particle. In this project we developed a new technique that proved to be very useful in such practical tasks as determination of a probable path of observed JTMD item. The method is based on experiments with the model tracer launched at a single point or from a distributed source, in which tracer concentration is interpreted as a probability density function (PDF) for a single particle to be found at a given location at a given time.

It is illustrated by Figure 20a on the example of a particle that started from the northern Honshu March 11, 2011 (point A). The map of the model tracer concentration calculated for January 1, 2012 outlines probable locations of a particle at that moment. Any additional information about particular JTMD item can be incorporated in this probabilistic technique to produce more sophisticated assessments. For example, for a JTMD item found August15, 2012 on shores of Washington State in the US (point B), Figure 20b calculated using reverse equations shows its probable locations on January 1, 2012. The two PDFs can be combined and their product (logical operation "AND") shown in Figure 20c illustrates probable intermediate location of a particle traveling from point A to point B. Figure 21 shows probable trajectories and visited locations, calculated using this techniques applied to the three Misawa docks that all started from the same harbor in the northern Honshu and were later reported from Oregon, Washington and Hawaii.

Our new techniques allows addition practically any weak or strong constraints for various applications. For example, if the exact start point is not known, a probable distributed source can be implemented in calculations. Or the fate of JTMD can be assessed even if it's not confirmed by observations. For example, our method suggests that Misawa dock reported in 2012 north of Molokai, ended (with 90% probability) in the South China Sea (Fig. 21d).

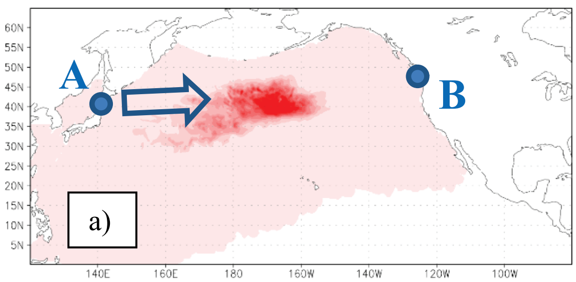
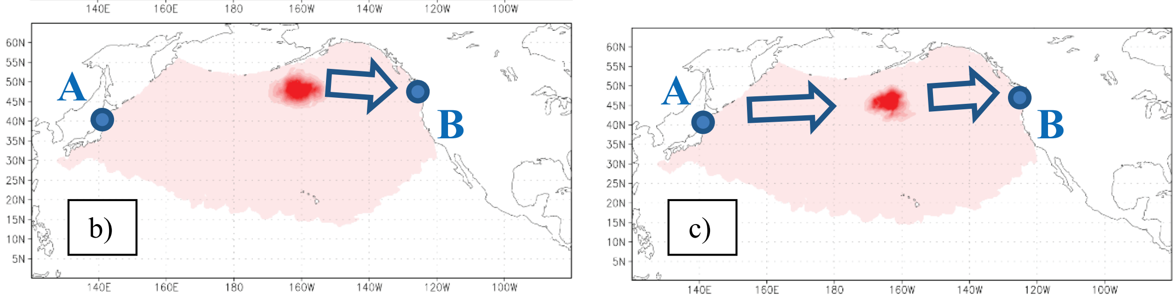


Figure 20. PDFs of model particle locations on January 1, 2012 for the particles that: (a) started from Japan on Mar 11, 2011 (point A), (b) ended in Washington state on Aug 15, 2012 (point B), and (c) started at point A and ended at point B.



Similarly, other information can be included in our method. For example, Figure 22 shows PDF and probable timelines of the sea surface temperature (SST), estimated using AMSR satellite data along the probable trajectory of the three Misawa docks. These timelines can be used to evaluate the chances of survival of species colonizing particular debris items and can be validated against actual samples. Probable paths and oceanographic conditions along the paths have been calculated for all reports, collected in the ADRIFT 'biofouling' dataset and submitted to the Vector Risk Assessment team to be used in its tasks (personal communication with Drs. Therriault, Murray and Drake. By their nature, accuracy of probabilistic methods is small for a single object but increases with the size of an ensemble or if additional information is available. For example, in future studies, information about species found on JTMD items can be added to improve estimates of probable paths. In the course of the project, our technique demonstrated its power in many difficult applications. It was able to provide an "educated guess" in the cases when answers were not obvious. For example, it successfully identified the likely routes of a JTMD boat found near Kami town in the end of 2011 (Fig. 23a) and a similar boat (Fig. 23b) that was found in Okinawa in 2016 (i.e. five years later).

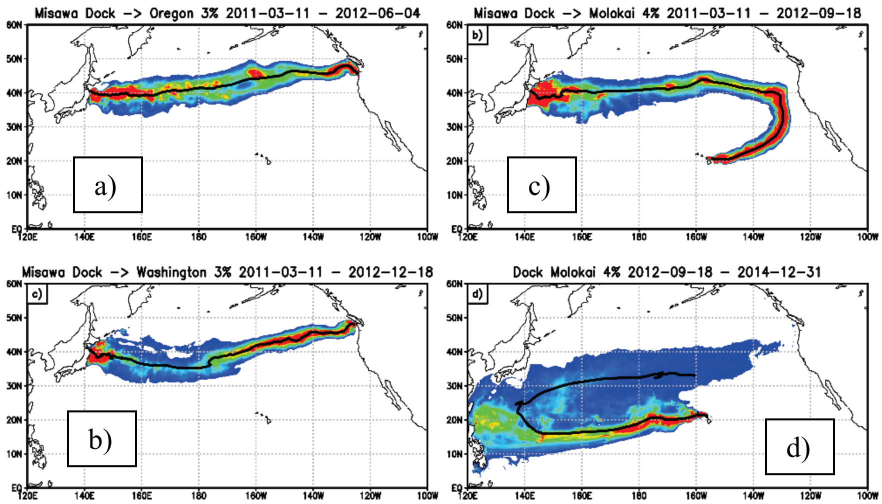


Figure 21. Probable visited locations (colors) and trajectories (lines) for Misawa docks, reported from (a) Oregon, (b) Washington, and (c) Hawaii. (d) Probable trajectory of the Molokai dock after drifting between Hawaiian Islands.

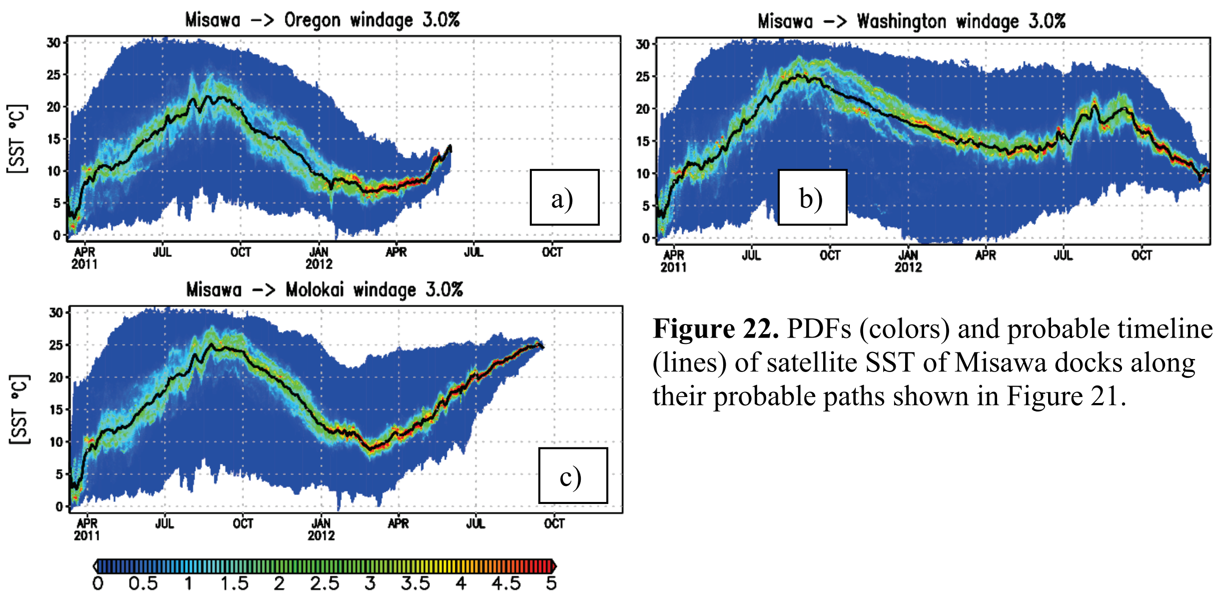


Figure 22. PDFs (colors) and probable timeline (lines) of satellite SST of Misawa docks along their probable paths shown in Figure 21.

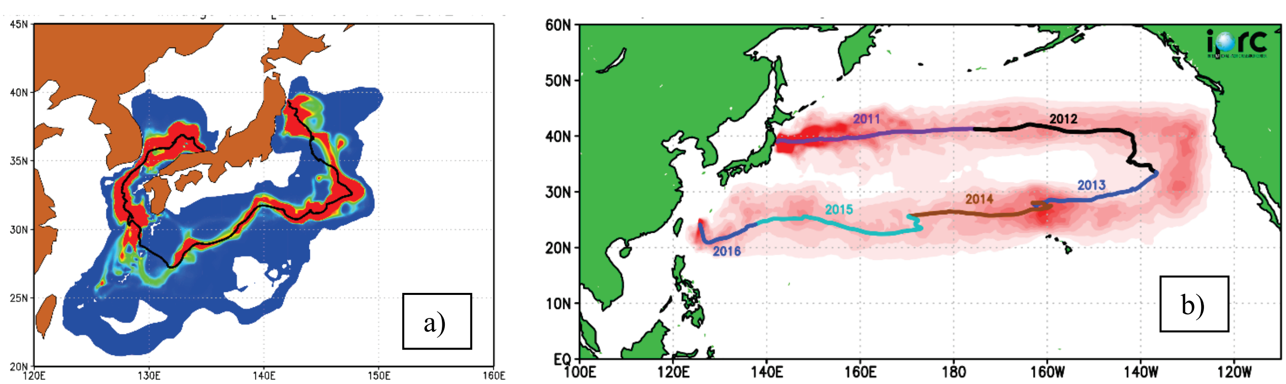
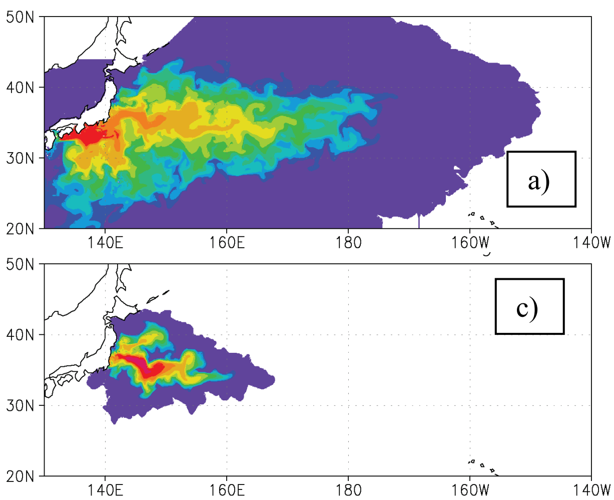


Figure 23. Probable visited locations (colors) and trajectories (lines) for the JTMD boats found (a) December 31, 2011 near Kami on the west coast of Japan and (b) May 12, 2016 in Okinawa.

- *Simulations of biological tracer interaction with JTMD*

While the original focus of our modeling team was on the ocean dynamics and JTMD drift, gradually we have become involved in collaboration with biological and ecological tasks. Biological samples collected from JTMD items formulated many difficult questions. For example, Misawa dock found in Oregon hosted not only cold-water species characteristic for the northern Honshu but also subtropical species, suggesting that during its drift the dock spent some time in warm water (personal communication with Prof. Carlton). To study the interaction between JTMD and subtropical species we simulated advection of larvae from the southern coast of Japan by setting up continuous tracer source (at 0% windage) along the southern Honshu, Shikoku, and Kyushu. Despite a short lifetime span of the larvae (7-day e-folding decay), it was advected hundreds of kilometers eastward by the fast Kuroshio Extension (Fig. 24a). JTMD tracer released north of the Kuroshio Extension has also mainly drifted eastward but effect of the higher windage was also pushing it southward (Fig. 24b). As a result, as demonstrated by the product of the model JTMD and larvae concentrations in Figure 24c, strong interaction was taking place along the Kuroshio Extension axis between 140 and 160E. Once attached to a JTMD item, larvae could develop into an adult species and continue journey toward North America and Hawaii.



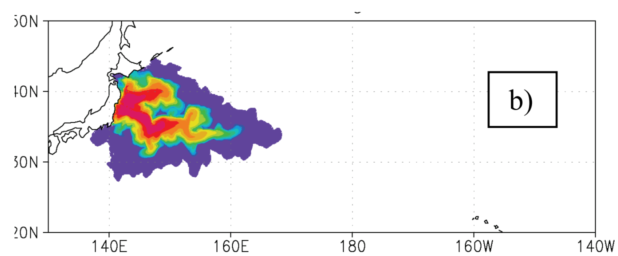


Figure 24. Interaction between tsunami debris and subtropical coastal species in SCUD simulations: (a) March 31, 2011 concentration of model larvae, continuously released from the south coast of Japan and having 7-day e-folding life span; (b) concentration of JTMD tracer with 2% windage; and (c) strength of debris-larvae interaction.

- *Temperature match between eco-regions along the east coast of Japan and west coast of North America and Hawaii*

As a contribution to the Vector Risk Assessment team we calculated climatologies of temperature in the North Pacific and their correspondence to the temperature statistics in the areas in Japan affected by the 2011 tsunami. Temperature is a critical parameter that has almost immediate effect on the survival of species. Several datasets and formalisms have been tried. Figure 25 shows how temperatures, observed by the AMSR satellite mission, change with the latitude and differ on the western and eastern sides of the North Pacific. Importantly, the area in Japan located between 38 and 40N and corresponding to maximum JTMD generation (Fig. 1) also has the broadest SST range, reaching 20 degrees Celsius. This is explained with a very strong seasonal cycle with temperatures below 5C in winter and above 25C in summer. Figure 26 confirms that the SST range east of Japan exceeds the one in North America by as much as two times. Generally speaking, this means that coastal species that are able to survive in the eco-region of the northeastern Honshu, may be resilient to temperature conditions practically anywhere in the North Pacific north of 30N. This suggestion is further confirmed by Figures 27a and b that shows that nearshore SST conditions between Baja California and Alaska all fit in the temperature range of the east coast of Japan between 39 and 41N.

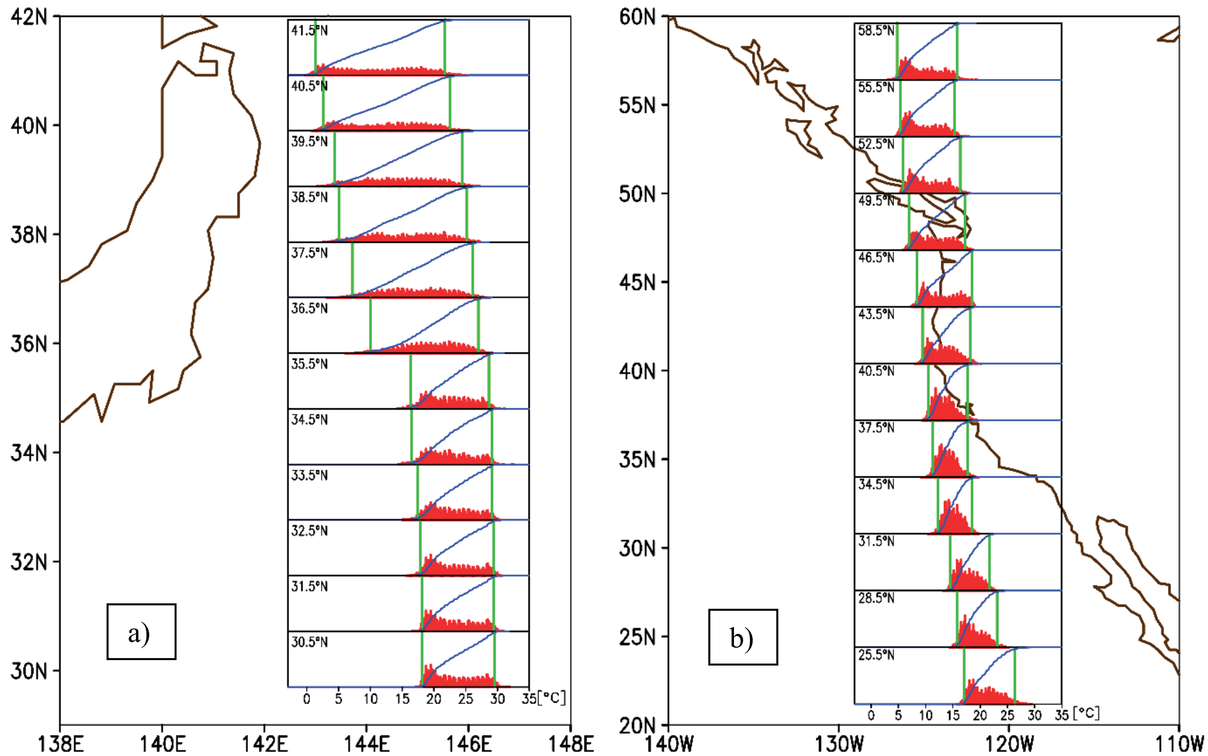


Figure 25. PDF (red bars) of sea surface temperature at different locations along (a) the east coast of Japan and (b) the west coast of North America, calculated from the AMSR satellite data. Blue lines are cumulative PDFs and green bars indicate SST limits after removing outliers.

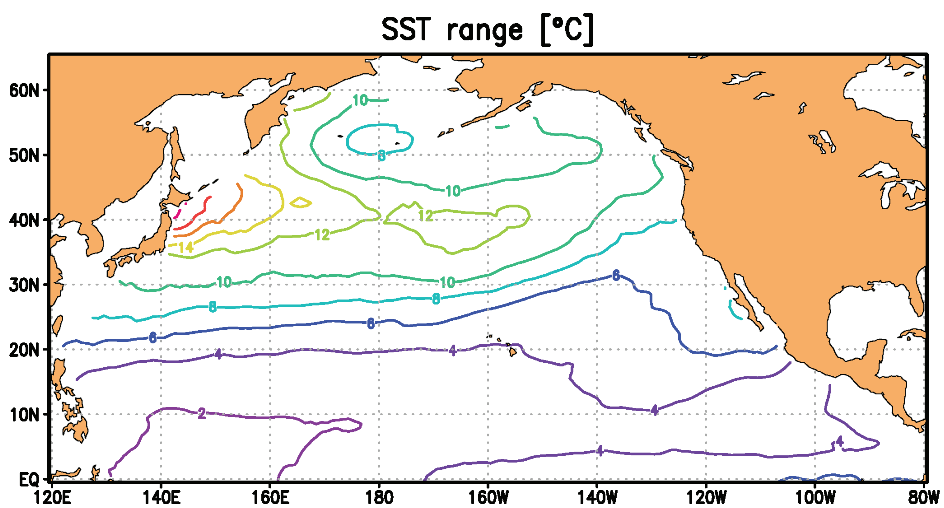


Figure 26. SST range in AMSR satellite data.

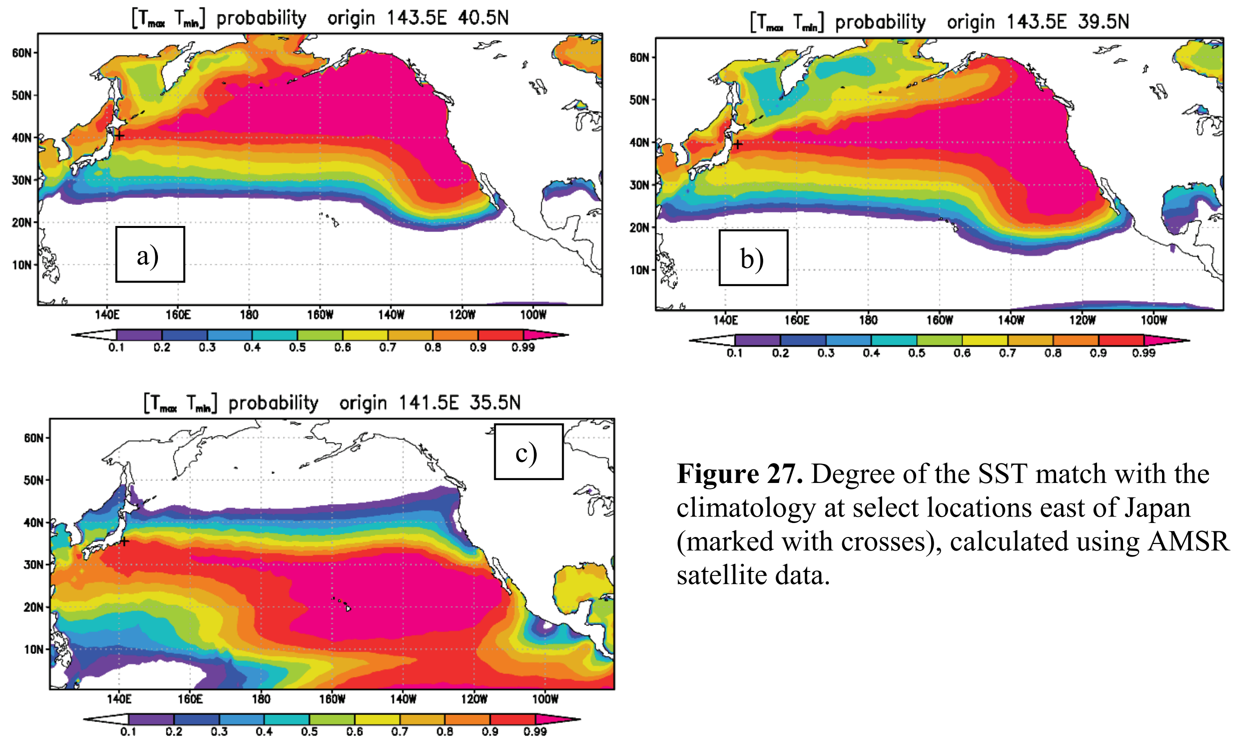


Figure 27. Degree of the SST match with the climatology at select locations east of Japan (marked with crosses), calculated using AMSR satellite data.

This pattern does not include Hawaii, where tropical temperatures are significantly higher, suggesting that Japanese species from the north of Japan are not a threat there. However, subtropical species (Fig, 27c) that could be picked by the northern JTMD in the Kuroshio Extension (Fig. 24) would find water temperature in Hawaii quite comfortable. Open-ocean patterns of high-match areas is consistent with the JTMD paths in first years after the tsunami (Figs. 5-7). However, on a longer run, JTMD remaining in the Garbage Patch or in the larger Subtropical Gyre is exposed to conditions that may or may not fit into the SST ranges in the eco-regions east and south of Honshu. Long-term survival of coastal species in the open ocean is an interesting and difficult task that requires future investigation and, importantly, sample collection from marine debris in the open ocean.

- **Discussion**

During the three years of the ADRIFT project, our modeling study progressed from qualitative illustrations of the propagation and fate of JTMD to specialized model schemes and settings as well as model data analysis techniques, providing quantitative answers on specific practical questions. New technique now allows verification and scaling using observational data and is available for investigation of patterns and timelines of large categories of JTMD as well as oceanographic conditions along probable paths of individual items. By combining ocean circulation with such parameters as sea surface temperature, salinity and chlorophyll, we facilitated vector risk assessments.

- **Achievements**

Achievements of the modeling team during the ADRIFT project include the following.

By careful comparison with available observational information we identified important factors that affect the accuracy of JTMD drift simulations and tuned them for the best performance of the models.

Model solutions were validates and calibrated using new methodologies developed for on-shore and at-sea observational data. Synthesis of the model and data from the US/Canada west coast allowed to estimate the total number of JTMD boats and predict their fate.

Blending of the SCUD and HYCOM resulted in the model that is free from Lagrangian biases in the open ocean and addresses the coastal dynamics using the best presently available approaches.

New original methodology based on a probabilistic approach has been developed in the project that allows to combine heterogeneous information and fill gaps with an "educated" guess. This technique now allows estimates of probable trajectories of JTMD items and oceanographic conditions along these trajectories.

JTMD field evolution in the first weeks after the tsunami has been studied and important roles of jets and eddies have been described. The Kuroshio Extension is identified as a region where JTMD items originating from the north of Honshu have likely acquired larvae of coastal warm water species characteristic for the eco-regions south of Japan.

Climatology of sea surface temperature has been calculated in the North Pacific and suggests that large seasonal cycle along the east coast of Japan makes temperatures almost along the entire stretch of the North America west coast acceptable for Asia species arriving on JTMD. This excludes Hawaii, where temperature conditions are comfortable for subtropical eco-system from the south coast of Japan.

Project achievement helped to improve ocean circulation models and their applications, including biological-physical interactions.

- **Challenges**

The tragic 2011 tsunami resulted into an unprecedentedly large amount of marine debris and associated reports and other data. However, in the absence of the well-developed observing system most of JTMD was not documented. Fragmentary information from selected shorelines requires careful quality control and severe filtering that allows only very general comparison with the models, based on the large-scale dynamics. The situation is much worse with observations at sea and with biological samples.

Presently available models, used to simulate drift of marine debris, suffer multiple gaps in our understanding of the ocean dynamics and in the modern observing system. Near-shore currents remain the biggest challenge as they are commonly a result of rectification of high-frequency small scale processes that are beyond the capabilities of our models. The question of the southward drift of JTMD (including Misawa docks) along the east coast of Honshu remains open.

The hydrodynamics of marine debris under various wind/wave conditions as well as degradation and biofouling processes (that change windage with time) require further careful investigation and parameterization in the drift models.

In our research we tried to make sure that models capture most important dynamics of JTMD. When possible, we used available data to improve model parameters. When it was not possible, we ran our models under a range of settings to investigate sensitivity of our conclusions to unknown parameters.

We believe that our effort provided most complete and accurate results that were possible on the current level of the knowledge. We hope that future projects will produce next iterations that will validate and enhance our conclusions.

- **Literature Cited**

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5. OUTPUTS

Outputs of the modeling team include the following.

In the 1st year of the ADRIFT project the IPRC team compiled and made available to other members the online database of JTMD reports from Hawaii[3]. It is still available but was not updated since 2015.

To help planning on-shore and at-sea sample collection we also established an automated webpage with a short-term JTMD forecast, based on simulations with the SCUD model[4]. (Last updated Nov 17, 2015.)

JTMD reports from Hawaii, received by the IPRC team, are updated on the “Tsunami Debris Sightings” webpage[5]. Recently this webpage has been expanded to include reports on peculiar non-JTMD items.

The IPRC webpage also includes “Tsunami Debris Model”[6] with daily updated tracer maps and “Marine Debris News“[7], on which news

Japanese partners developed FORA (Four-dimensional Ocean Data Reanalysis), a new product of ocean current velocities that will be used in future studies. Access to the product can be obtained by contacting fora_req@jamstec.go.jp

Data of the ADRIFT modeling study are archived and available from the PI on request.

[3] http://iprc.soest.hawaii.edu/PICES-MoE-database/
[4] http://iprc.soest.hawaii.edu/users/hafner/NIKOLAI/SCUD/TSUNAMI/DEBRIS/PICES/Tsunam_diagnostic_and_forecast.html
[5] http://iprc.soest.hawaii.edu/news/marine_and_tsunami_debris/sightings.php
[6] http://iprc.soest.hawaii.edu/news/marine_and_tsunami_debris/IPRC_tsunami_debris_models.php
[7] http://iprc.soest.hawaii.edu/news/marine_and_tsunami_debris/debris_news.php

a. Completed and planned publications

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- Murray, C. C., S. Lippiatt, N. Maximenko, and N. Wallace, 2017. The influx of marine debris from the 2011 Great Japan Tsunami to North American shorelines. Marine Pollution Bulletin special issue. 17 pp.
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b. Poster and oral presentations at scientific conferences or seminars

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- Maximenko, N., A. MacFadyen, M. Kamachi, and J. Hafner, Modeling the drift of marine debris generated by the 2011 tsunami in Japan and synthesis with observations, ASLO Meeting, Honolulu, USA, February 26 – March 3, 2017.
- Maximenko, N., Ocean surface currents and applications to marine debris, Oceanography Seminar, University of Hawaii, February 16, 2017.
- Maximenko, N., Ocean surface circulation: dynamical challenges, impacts and applications, Symposium "Past, Present, Future of Predicting Ocean and Climate Variability", APL/University of Tokyo, January 26, 2017.
- Maximenko, N., Presentation at the Vector Risk Assessment workshop, Burlington, Canada, January 10-12, 2017.
- Maximenko, N., The IPRC Marine Debris Project, Marine Litter Workshop, Barcelona, Spain, October 27-28, 2017.
- Maximenko, N., J. Hafner, A. MacFadyen, M. Kamachi, C. C. Murray, J. T. Carlton, Y. Chao, D. Moller and Calibration, validation and advanced applications of ocean drift models, forced with ocean satellite data, using marine debris reports from natural disasters, Ocean Surface Tomography Science Team Meeting, La Rochelle, France, October 31 - November 4, 2016.
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- Kamachi, M., Y. Ishikawa, H. Kawamura, N. Maximenko, J. Hafner, & A. MacFadyne (2016): Ocean Modeling the Drift Simulation of Japan Tsunami Marine Debris (JTMD), in the Special Lecture Series for Graduate Students about Moe-PICES JTMD Project, at Tohoku University, May 19, 2017.

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c. Education and outreach

The PIs of the modeling team conducted extensive educational and outreach activity to popularize outcomes of the ADRIFT project. Kamachi and Maximenko spoke at several public meetings, included in the meeting list in the previus section of this report.

On June 2, 2016 Masafumi Kamachi participated in the press release by the Miyagi Prefectural Government regarding the research boat Kaisyou (Fig. 23b) that was lost during the 2011 tsunami and five years later was found in Okinawa. May 18, 2016 he also gave interview to Sanriku-Shinpou newspaper about this boat “Drifting 5 years in the Pacific”.

Outreach activity was particularly high in the IPRC team. Students from Morioka Daisan High School and their teachers visited the IPRC in March 2015 (Fig. 28). Morioka, the capital of Iwate Prefecture, suffered much devastation in the March 2011 tsunami. The students listened attentively to Jan Hafner’s powerpoint presentation about how the IPRC Drift Model was able to simulate the travels of the debris across the ocean to the North Pacific Coast, into the Great Garbage Patch, and to the north-east facing shores of Hawaii.

Jan Hafner helped groups of students prepare for the FIRST® LEGO League Challenge, Tracking Trash Robotics Competition. Seeing pictures, real objects and model simulations from the 2011 tsunami, as well

Figure 28. Students from Morioka Daisan High School learn about JTMD in Hawaii.

Figure 29. Local students learn about JTMD in preparation for *Tracking Trash* Robotics Competition.

as handling microplastics helped the students become ware of the huge ocean debris problem (Fig. 29). One of the groups Hafner worked with won the District Challenge first place for the Robot Mission and Project Presentation. Their winning design was a solar-powered Nurdle Turtle, inspired in part by Hafner's description of floating and sinking debris. About 5-ft. long and 4-ft. tall, the turtle scoops up sand that is deposited into a compartment filled with water. The sand sinks while the microplastic floats to the top, where it is collected by a robotic arm and dropped into a second compartment where it stays until emptied. A trap door opens to release the sand.

Hafner also worked with a group of public-school fifth-grade students, who are studying marine debris. He showed them how ocean currents and winds push floating marine debris along pathways in the large ocean gyres and how the Great Pacific Garbage Patch formed. The students inspected with fascination the pieces of wood and the refrigerator door stemming from the 2011 tsunami and floating all the way to Hawaii. The students were amazed at how larger pieces of plastic get ground down into microplastics.

We participated in the biennial Open House of the School of Ocean and Earth Science in October 2015. Every other year thousands of students from Hawaii private, public, and home schools come with teachers and parents to the two-day event to see demonstrations and hand-on science activities. The 2015 IPRC program featured Tsunami Debris, Marine Debris, and the Garbage Patch by Jan Hafner, who provided an intriguing look at the movement of debris around the Pacific Ocean basin.

We have hosted two Brazilian marine debris interns, recipients of the scholarship of the Brazilian government program called "Ciências sem Fronteiras." In Summer 2015 Melanie Vianna Alencar, an undergraduate oceanography student, worked with Nikolai Maximenko, Jan Hafner, and Kin Lik Wang. Part of her work dealt with the IPRC Japan tsunami marine debris database and monitoring marine debris on Oahu windward beaches. Our second intern was Joao Pedro Cardoso, an undergraduate oceanography student from Rio de Janeiro State University. As part of his internship, he did coastline marine debris surveys of several windward beaches on Oahu under the supervision of Nikolai Maximenko and Jan Hafner.

The book 438 Days, published in 2015 by Simon & Schuster and authored by Jonathan Franklin, tells the story of the fisherman Jose Salvador Alvarenga's over 14-month-long drift from Mexico westward across the Pacific to Ebon Atoll in the Marshall Islands. To verify his unlikely story, Nikolai Maximenko and Jan Hafner had run the IPRC Drift model. The simulations confirmed the fisherman's story and their work was acknowledged in the book.

Maps showing the path of tsunami debris generated with the IPRC Drift Model were a central part of the poster "Effect of Marine Debris Caused by the Great Tsunami of 2011," presented in Barcelona by Alexander Bychkov, PICES Executive Secretary in November 2014 at the 2nd International Ocean Research Conference. Bychkov also coordinates the study on the impact of invasive species arriving along the US West Coast in the 2011 tsunami debris. Of 400 entries, his poster was one of 10 chosen for posting on sailboats taking part in the Barcelona World Race.

We applied the IPRC Debris Drift Model to the search for Flight MH370. The flow paths of the various objects simulated by the model from the crash site were consistent with the locations the objects were found. Thus, maps to guide on-shore search for Flight MH370 Debris were published on our website and generated interaction with the public.

In September 2014, Jan Hafner was invited by Howard Wiig, the host of Code Green on ThinkTech Hawaii TV show, to speak on "Plastic, Plastic Everywhere!" The show focused on plastic in marine environment, its transport and impacts, especially its impact on Hawaii. Hafner showed how large pieces of different types of plastic pieces gathered by our team break down into tiny sand-like pieces that are then eaten by fish, thereby leading to the chemicals in the plastic entering the food chain.

In November 2014, Hafner was interviewed by Amber Liggett for an episode about the Great Pacific Patch that was posted on Millersville University Weather Watch TV. Hafner described how wind and currents push marine debris into the Great Pacific Garbage Patch and how the occasional storms and strong winds push the debris out of the patch again. The video can be viewed YouTube Video: https://www.youtube.com/watch?v=_04GC4BTk_I&feature=youtu.be&t=2m. Liggett's story goes from 2:00 to 4:15 minutes, with Hafner's interview starting at 2:35.

Several times we were contacted by reporters who wished to find out more about the paths of boats that had been lost in the tsunami and had been found. When tiny Daini Katsu washed up on Oahu shores in April 2015, more than 4 years after the tsunami sucked it into the ocean in Ogatsu-town, the IPRC Drift Model was used to simulate the 30-foot fishing boat's likely journey. Nikolai Maximenko was interviewed by Hawaii Department of Land and Natural Resources (DLNR) and by Hawaii News Now TV station. The boat returned home to be displayed at a cultural center to commemorate the earthquake and tsunami. https://vimeo.com/156482512.

The Research Vessel Kaisyou of the Kesennuma Local Fisheries Laboratory in Miyagi_Prefecture, lost in the tsunami, was spotted on May 12, 2016, about 4 miles offshore from Miyako-jima, Okinawa Prefecture. The IPRC Drift Model was used to simulate the likely route the Kaisyou drifted during its astonishing 5-year-2-month-long journey, floating eastward across the Pacific during 2011 and 2012 and then circulating back westward during 2013 to 2016.

In June 2016, Maximenko and Hafner received a visit from Norimasa Tahara, the Los Angeles Bureau Chief of the Yomiuri Shimbun, a leading Japanese daily newspaper, and Sam Hecht, a reporter for the newspaper. Tahara wanted to gather the most recent information on the driftage from the 2011 tsunami for a follow-up article on the disaster.

The Oceans & Law of the Sea of the United Nations published in 2016 its "First Global Integrated Marine Assessment." Chapter 25, Marine Debris, opens with reference to the article Tracking Marine Debris, which appeared in the 2008 IPRC Climate and shows the map of the 5 garbage patches in the World Ocean as simulated in the IPRC Drift Model. These simulations, according to the UN publication, confirm that debris will be subject to transport by ocean currents and will tend to accumulate in a limited number of sub-tropical convergence zones.

Maximenko, Hafner and Speidel were invited to speak at the 2015 Hilo Symposium on Marine Debris & Tsunami Driftage held on December 3 and 4, 2015. Hafner spoke on Transport of JTMD in IPRC model simulations & observations, Maximenko presented Model calibration using reports of JTMD boats, and Gisela Speidel spoke at the evening public forum on 'The science behind Japanese Tsunami Debris'. The over 50 conference participants were mostly organizers and volunteers of beach-cleanup groups that included participants from Japan, the West Coast and Alaska.

We were invited in September 2016 by the US Department of States Office of Foreign Missions (OFM) to join the International Coastal Cleanup (ICC) effort in Kahuku, Oahu, on its 30th Anniversary (Fig. 30). Under its new initiative, Greening Diplomacy, the OFM had also invited Hawaii Consular Corps, and members from Japan, Korea, Taiwan, and Switzerland also participated in the cleanup, held at the Campbell Wild Life Refuge. Together we removed between 1,000 to 2,000 pounds of plastic debris and fishing lines from 150 feet of shoreline. Among the debris collected were items that stemmed from the 2011 tsunami: a dock with a concrete shell over styrofoam, a refrigerator door, and crates and a sign from Fisheries in Iwate Prefecture.

Our Workshop on Mission Concepts for Marine Debris, held in Honolulu in January 2016, was featured in October in the print-edition of EOS, the Earth and Space Science Newsletter of the American Geophysical Union. Workshop participants discussed how to adapt and apply existing technologies to remotely track marine debris to monitor trends and help answer these and other questions.

Ongoing outreach of the IPRC marine debris project is its maintenance of its Marine and Tsunami Debris News webpage and the Sightings webpage, which has featured likely tsunami debris washing up on Hawaii beaches and which is now expanded to include peculiar items even if they are not relevant to the tsunami.

Figure 30. Participants of the Sep 2016 beach cleanup, organized by the US Department of State.

6. RESEARCH STATUS AND FUTURE STEPS/PLANS

This project gave our team a unique opportunity to apply our experience of physical oceanographers to biological and ecological tasks. These applications required development of new methods, which will also advance general studies of the ocean drift from various sources. Unique JTMD data collected as a part of the ADRIFT project and in other programs, allowed us to greatly improve our models and increase confidence in our numerical experiments. Results of the project will contribute to future initiatives (such as development of remote sensors of marine debris and construction of the marine debris observing system) and may result in multidisciplinary proposals to be submitted to funding agencies in the US and in Japan.