Modeling the drift of marine debris generated by the 2011 tsunami in Japan

by Nikolai Maximenko, Amy MacFadyen, and Masafumi Kamachi

Role of modeling in addressing problems of marine debris

The tragic event of the March 11, 2011 tsunami in Japan has taken the lives of more than 15,000 people and generated an estimated 1.5 million tons of debris floating off eastern Honshu (Japan Ministry of Environment, 2014), an amount comparable to the annual budget of plastic marine debris of the entire North Pacific (Jambeck *et al*., 2015). This Japan tsunami marine debris (JTMD) was originally seen in photographs (Fig. 1), taken during rescue operations, as thick mats of very heterogeneous composition and sometimes reaching many kilometers in size. Several weeks later, after JTMD drifted off shore and dispersed, its monitoring became very difficult. Sparse reports from the sea were not able to provide a coherent description of the pattern and motion of JTMD and this task was adopted by numerical modelers. Even after the JTMD moved across the North Pacific and started arriving on the US/Canada west coast and, later, in Hawaii, reports from the shoreline provided very fragmentary information distorted by many biases. Questions like 'Where is the JTMD now? How much of it is still floating? When is the next "wave" coming?' can currently be answered only by models, utilizing the full strength of the Global Ocean Observing System (GOOS).

Since 2014, when PICES started a new project "Assessing the Debris Related Impact From Tsunami" (ADRIFT) on the North America and Hawaii coasts (Clarke Murray *et al*., 2015), funded by the Japan Ministry of Environment, scientists at the International Pacific Research Center (IPRC) of the University of Hawaii (UH), the U.S. NOAA Emergency Response Division (ERD), and the Japan modeling group, including members from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA), and Japan Atomic Energy Agency (JAEA), work together to provide modeling support to biological studies, focusing on identification of alien species colonizing JTMD and assessment of their potential impacts on the North American ecosystem.

Models used in the project

A suite of models, developed independently in the three participating groups, produced diversified outputs that were used to characterize the drift of JTMD and to assess the robustness of the conclusions under different model setups.

SCUD (Surface Currents from Diagnostics) is an empirical model, developed at IPRC/UH, forced with the data from satellite altimetry and scatterometry, and calibrated on a 1/4° global grid using trajectories of satellite-tracked drifting buoys (Maximenko and Hafner, 2010). The model calculates particle trajectories and evolution of tracer density, released on March 11, 2011 along the eastern coast of Honshu, Japan (Fig. 2).

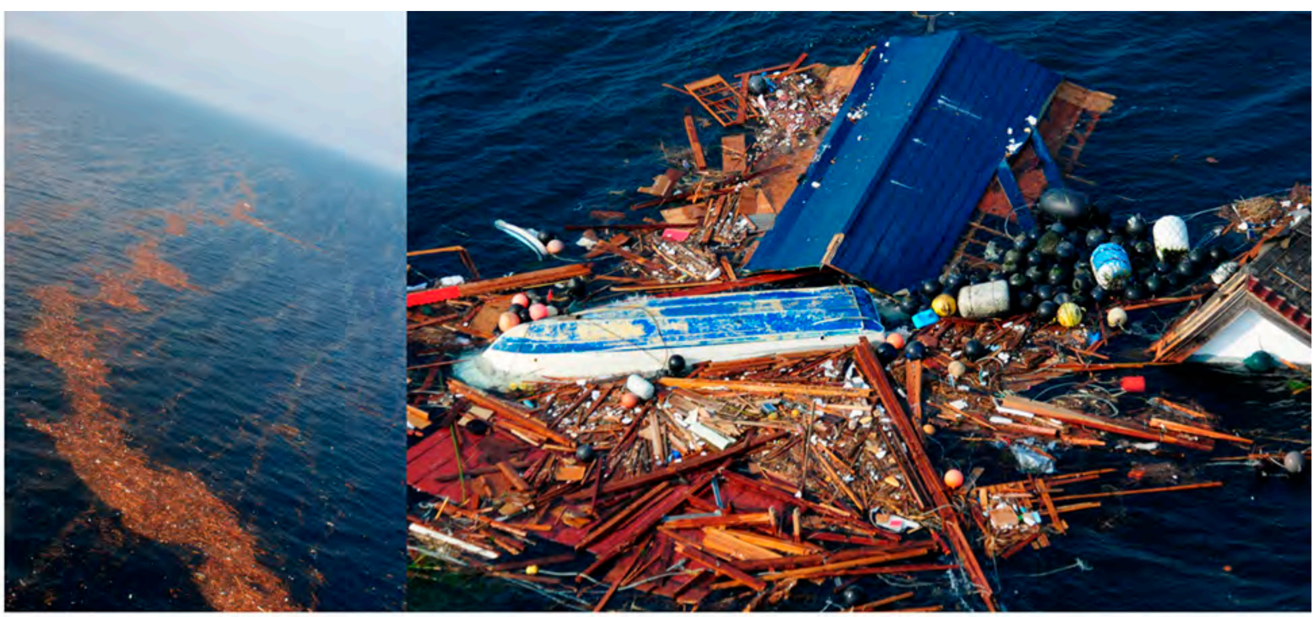

Fig. 1 An aerial view of debris near Sendai, Japan on March 13, 2011. (Photographs courtesy of the US Navy)

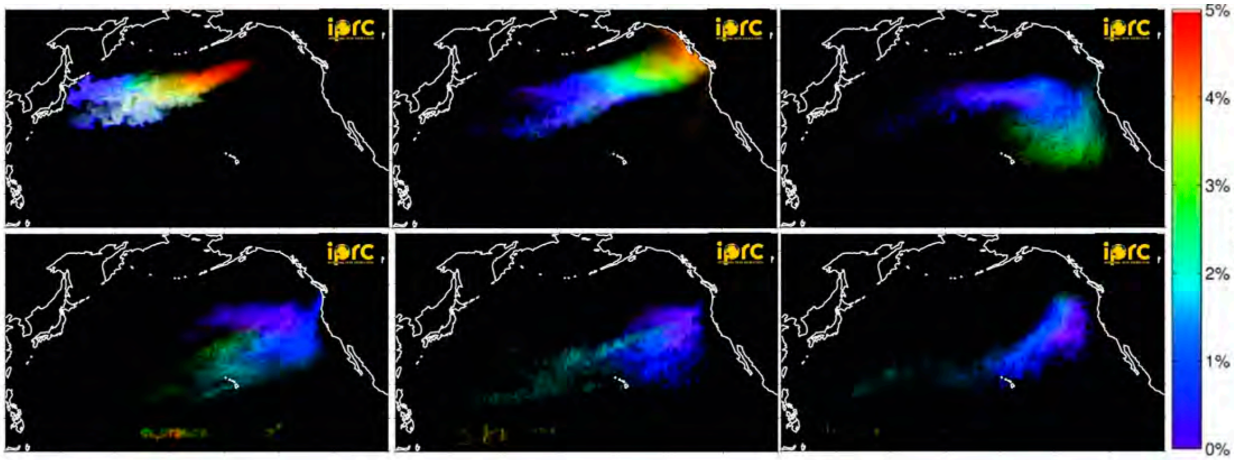

Fig. 2 Motion of JTMD in SCUD model simulations. Colors indicate windage of the debris. Shown are maps on September 1, 2011, March 1, 2012, September 1, 2012, March 1, 2013, September 1, 2013, and March 1, 2014.

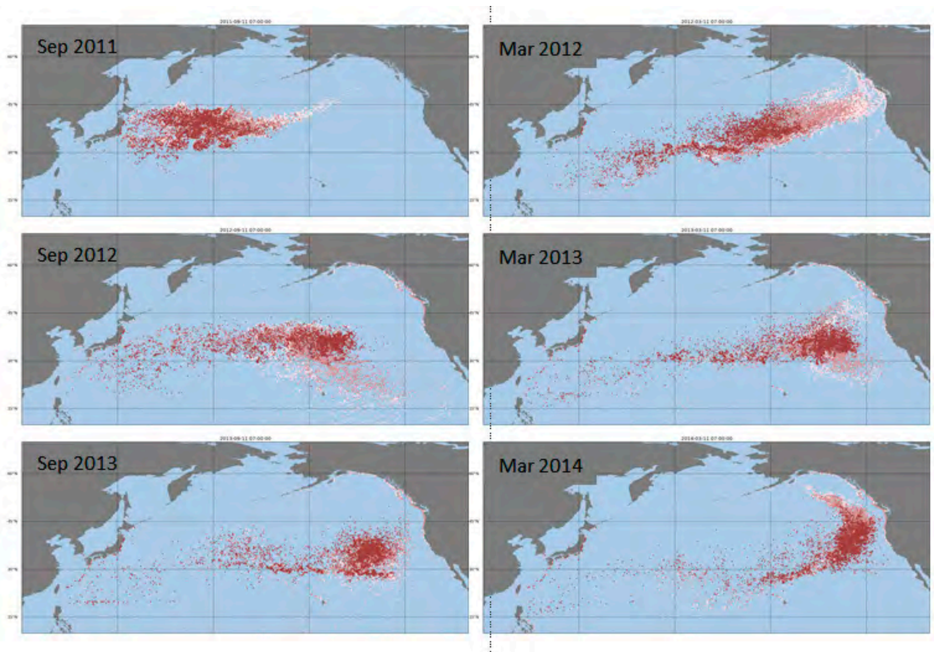

Fig. 3 GNOME modeled particles simulate the movement of tsunami debris of varying types – from high windage objects like styrofoam (white) to low windage objects like wood (red). These six panels show the distribution of the model particles every 6 months from September 2011 (6 months post-tsunami; top left) to March 2014 (3 years post tsunami; bottom right).

The NOAA ERD team is using the GNOME (General NOAA Operational Model Environment) that was initially developed for predicting trajectories of marine pollutants (primarily floating oil). GNOME utilizes surface currents from the 1/12° operational HYCOM model from the Naval Research Laboratory and 1/4° global product from the NOAA Blended Sea Winds. In each model experiment 40,000 particles (Fig. 3) were initialized at 8 sites along the Japan coast, spanning a distance of ~700 km.

Numerical experiments of the Japan modeling group included hindcast calculation from March 2011 to August 2013 followed by the forecast through May 2016. The hindcast (Fig. 4) was based on data assimilation in the North Pacific ocean general circulation model MOVE, operated by JMA/MRI, having 1/10° resolution in the west and relaxed to a 1/2° grid elsewhere, and forced by the JMA's operational atmospheric system JCDAS. The forecast has been performed using the K7 system, operated by JAMSTEC, and having a global 1° resolution. Particle motion was computed using the SEA-GEARN dispersion model, operated by JAEA. 153,600 particles were released in model experiments offshore of Iwate, Miyagi, and Fukushima prefectures (Kawamura *et al.*, 2014).

To account for a "windage" or a "leeway" (motion of floating objects under direct force of wind), a corresponding fraction (between 0 and 6%) of wind velocity, used to force the models, was added to the current vectors to produce drift velocities.

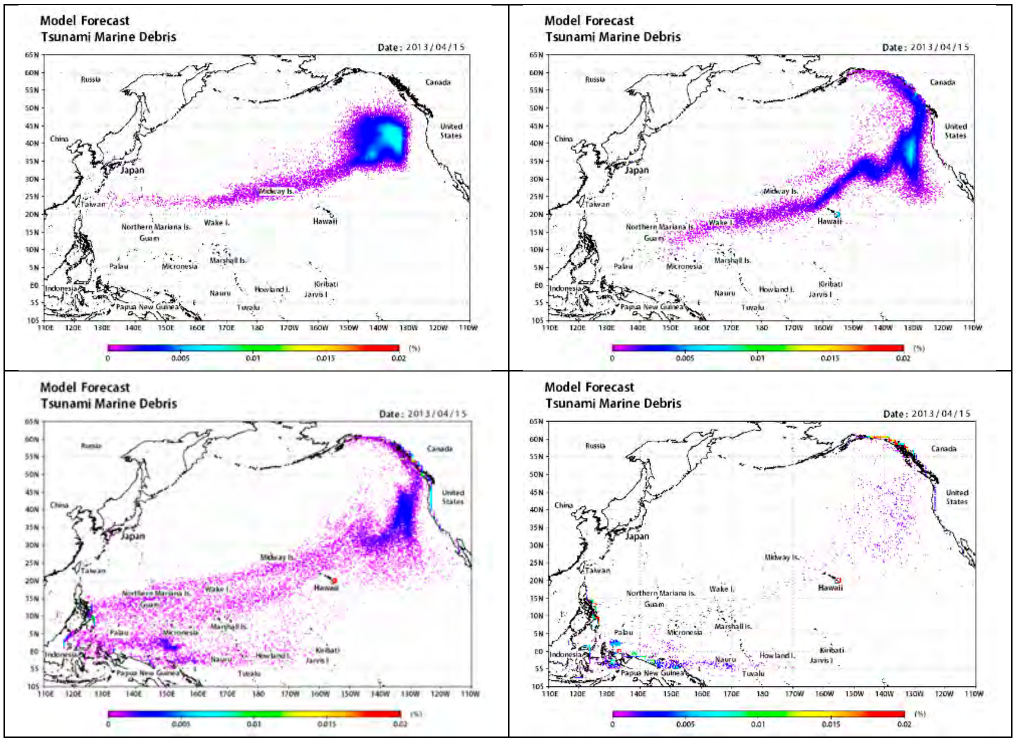

Fig. 4 *April 15, 2013 distributions of SEA-GEARN/MOVE-K7 model particles for four values of windage: 0, 2.5, 3.5, and 5%. Colors indicate concentration of particles on a computational grid.*

Model solutions

With all the complexity of the Kuroshio-Oyashio frontal zone, located east of Japan, climatological eastward currents and westerly winds lead all types of floating debris away from the eastern Japan coast toward the North America. (Figure 5 exemplifies this eastward drift with trajectories of particles calculated in the SEA-GEARN/MOVE-K7 system for 5% windage.) Nevertheless, details of the drift, such as speed, diffusivity, and long-tern destination are sensitive to the windage value. As illustrated by Figures 2–4 all three models unanimously suggest that in the first months after the March 11, 2011 tsunami JTMD was sorted according to the windage properties. High-windage tracers were moving faster and started reaching the U.S./Canada west coast before the end of 2011. Much of this JTMD (red color in Fig. 2, white in Fig. 3, and bottom right panel in Fig. 4) ended on shore and only a small proportion could possibly drift along the coastline toward the south and then recirculate west-southwest, between and around Hawaiian Islands. Low-windage tracers (blue in Fig. 2, red in Fig. 3, and top left panel in Fig. 4) moved much slower and, after entering the eastern North Pacific, most of this debris was pulled into the convergence, located between Hawaii and California and known as the "garbage patch" for observed persistently high concentrations of microplastic, fishing gear, and other types of semi-submerged debris.

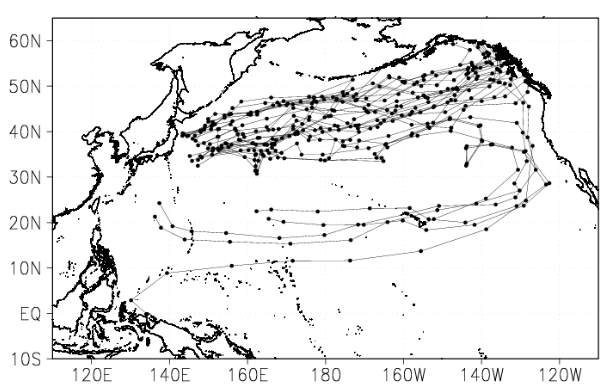

Fig. 5 *Trajectories of particles with 5.0% windage between April 2011 and September 2013 in the SEA-GEARN/MOVE-K7 model (Kawamura et al., 2014).*

In addition to common types, low-windage JTMD brought to the patch such unusual items as overturned boats, wood (*e.g.*, lumber from broken houses, electrical poles, and trees), propane cylinders, and a broad variety of other objects heavily overgrown with biofouling. Low-windage debris is hard to observe at sea but its presence in the areas projected by models was confirmed, for example, by unusually high number of collisions with woody debris, reported by participants of the Los-Angeles-Honolulu Transpac yacht race in summer of 2013. Dynamics of the gyre exhibit strong seasonality. In late summer–fall, the garbage patch is stabilized by the "subtropical high" and converging currents keep debris in the ocean and prevent it from flushing ashore. In winter–spring, however, the "Aleutian low" perturbs the circulation, so that stretched edges of the patch reach the U.S./Canada west coast in the east and Hawaii in the west and bring debris to the shores.

Model Comparison with Observations

Marine debris datasets, allowing quantitative comparison with model solutions, are very rare. In this project, we combined information from NOAA on Disaster Debris sightings, Japan's Office of Ocean Policy, and IPRC/UH dataset. To reduce the dependence on unknown windage parameters, the analysis was narrowed down to one type of JTMD: boats, skiffs, and vessels. The advantage of this choice is that boats are easier to trace back to their origin and, even when exact identification is not possible, the probability of significant dataset contamination by non-JTMD boats is small. The merged dataset, covering years 2011–2014, includes 277 reports, whose geographical distribution and timing are shown in Figure 6. There was a general transition from reports in the western Pacific in 2011 to the east in 2012–2013 and possibly to the southeast in 2013–2014. The pattern of the reports suggests strong interaction between two factors: the presence of JTMD and presence of the observer. The absence of the reports from high latitudes east of the date line is likely due to gaps in the observational network and bad weather conditions.

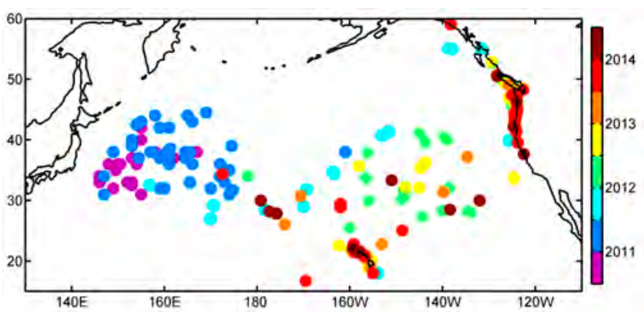

Fig. 6 Reported locations of boats/skiffs/ships and (colors) times of the reports. Color bar spans January 2011–December 2014 and labeled ticks mark central moments of the years.

Remarkably, 1 to 4 months after the tsunami (purple dots in Fig. 6) boat reports already demonstrated very strong dispersion. This could be due to the presence of two strong eastward jets, associated with the Kuroshio Extension and Subarctic Front, surrounded with much slower background flows. It could also result from a broad range of different windages. Indeed, depending on the orientation of the same boat in water (Fig. 7), its exposure to the wind and its resultant drift can be quite different.

The highest concentration of reports appears on the U.S./Canada west coast between 40°N (northern California) and 51°N (northern tip of Vancouver Island) where 79 boats were reported in 2011–2014 (Fig. 6). After applying a low-pass filter, observations combine into three main peaks with the maxima in summer 2012, winter–spring 2013, and spring–summer 2014 (Fig. 8). Remarkably, all three models used in this study reveal similar peaks. Additionally, the SEA-GEARN/MOVE-K7 system, which was designed to study JTMD motion in the northwestern Pacific in the first months after the tsunami, adequately captured the 2012 peak in North America.

Comparison between the models and reports led to a number of interesting conclusions. While boats and ships were originally expected to fall into a high-windage category, best correspondence was found for intermediate windage parameter values: 1.6% for SCUD and 2.5–3.5% for GNOME and SEA-GEARN/MOVE-K7. This is consistent with the conditions of the reported boats, many of which were damaged, filled with water, heavily fouled, and/or flipped over. There is a possibility that much of high-windage debris ended in remote areas of Alaska and northern British Columbia where observations are scarce. Interestingly, observed peaks lag behind model timelines by 1 to 3 months. This lag may reflect a delay between the moment of a boat landing and the time when it was reported. For example, a recent aerial survey of Vancouver Island (Clarke Murray *et al.*, 2015) revealed at least two new boats, missing from reports, whose arrival times will be hard to determine.

Knowing the correct windage range helps to improve modeling of JTMD trajectories, patterns, and timelines. Because of the differences in surface currents representation, optimal windage values can be different for different models. These differences combined with the incompleteness of the observational dataset can explain some inconsistencies between the amplitudes of individual peaks in Figure 8. By scaling the SCUD timeline (blue line in Fig. 8) we estimate that 400–700 boats remained floating at the end of 2014. Projected back to the start point, the model gives 500–1000 as an estimate of the initial number of floating boats in March 2011. Given the large error bars, these figures are not contradictions of other estimates. On November 16, 2011, the Japan Coast Guard detected 506 skiffs/vessels, drifting off the devastated shoreline. Ministry

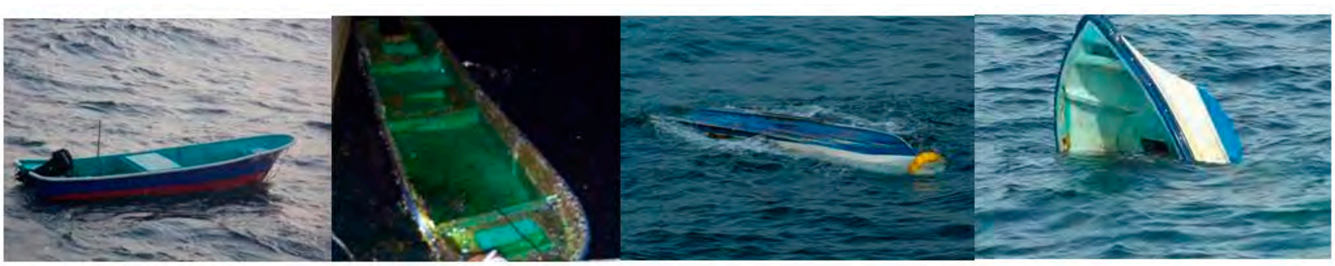

Fig. 7 Examples of JTMD boat orientation in water (from left to right): normal, upright but filled with water, upside down, and vertical. (Photographs courtesy of the Japan Coast Guard: http://www.kaiho.mlit.go.jp/info/kouhou/jisin/20110311miyagi/hyouryuu.htm)

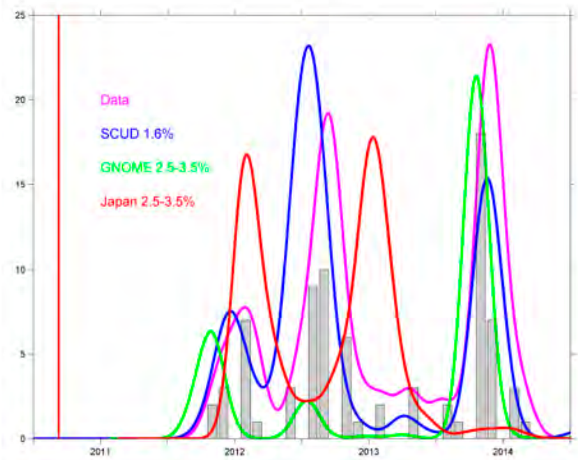

Fig. 8 Monthly counts of boats on the US/Canada west coast (gray bars) and low-pass filtered timelines of boat fluxes in observations (magenta) and model experiments with different windages: 1.6% for SCUD (blue) and 2.5–3.5% averages for GNOME (green) and SEA-GEARN/MOVE-K7 (red). Vertical red line marks March 11, 2011. Units on y-axis are boat counts for monthly reports and conventional for other timelines.

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 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% was still floating at the end of 2014. This means that boats from the 2011 tsunami, built to withstand rough ocean conditions, will likely continue coming to the U.S./Canada coastline for several years. At the same time, JTMD wandering in the gyre gradually mixes with marine debris from other sources and loses its identity.

Future progress in marine debris modeling requires radically improved at-sea and on-shore observing systems as well as better model description of processes on the sea surface (such as breaking wind waves) and their effects on floating objects.

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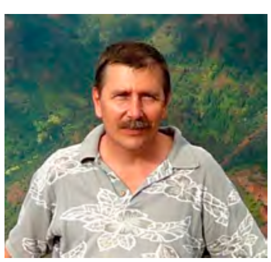

Dr. Nikolai Maximenko (maximenk@hawaii.edu) is a Senior Researcher at the International Pacific Research Center, University of Hawaii. As an oceanographer he studies near-surface circulation of the World Ocean and the role it plays in the motion of marine pollutions.

Dr. Amy MacFadyen (amy.macfadyen@noaa.gov) is a physical oceanographer at the Emergency Response Division of the NOAA Office of Response and Restoration. She provides scientific support for oil and chemical spill response, a key part of which is trajectory forecasting to predict the movement of spills.

Dr. Masafumi Kamachi (mkamachi@mri-jma.go.jp) is a Senior Director for Research Affairs at the Meteorological Research Institute, Japan Meteorological Agency. He is an oceanographic scientist, leading studies on the ocean data assimilation and prediction.

Drs. Maximenko, MacFadyen, and Kamachi are the PI's of the modeling component of the ADRIFT project.