ARTICLE IN PRESS

Marine Pollution Bulletin xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Marine Pollution Bulletin

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

# Numerical simulations of debris drift from the Great Japan Tsunami of 2011 and their verification with observational reports☆

Nikolai Maximenko[a,*], Jan Hafner[a], Masafumi Kamachi[b], Amy MacFadyen[c]

[a] International Pacific Research Center, School of Ocean & Earth Science & Technology, University of Hawaii at Manoa, United States
[b] Japan Agency for Marine-Earth Science and Technology, Japan
[c] US National Oceanic and Atmospheric Administration, Office of Response and Restoration, Emergency Response Division, United States

ARTICLE INFO

*Keywords:*
Numerical modeling
Data analysis
Ocean surface circulation
Marine debris drift
Tsunami debris
Debris pathways
Sensitivity to windage
Debris reports
Model calibration/validation
Model-data comparison
New methods

ABSTRACT

A suite of five ocean models is used to simulate the movement of floating debris generated by the Great Japan Tsunami of 2011. This debris was subject to differential wind and wave-induced motion relative to the ambient current (often termed "windage") which is a function of the shape, size, and buoyancy of the individual debris items. Model solutions suggest that during the eastward drift across the North Pacific the debris became "stratified" by the wind so that objects with different windages took different paths: high windage items reached North America in large numbers the first year, medium windage items recirculated southwest toward Hawaii and Asia, and low windage items collected in the Subtropical Gyre, primarily in the so-called "garbage patch" area located northeast of Hawaii and known for high concentrations of microplastics. Numerous boats lost during the tsunami were later observed at sea and/or found on the west coast of North America: these observations are used to determine optimal windage values for scaling the model solutions. The initial number of boats set adrift during the tsunami is estimated at about 1000, while about 100 boats are projected to still float in year 2018 with an e-folding decay of 2 to 8 years.

## 1. Introduction

The tragic March 11, 2011, Great Japan Tsunami took more than 15,000 lives and generated an estimated 1.5 million tons of floating debris off eastern Honshu (Ministry of the Environment, Japanese Agency, 2012), an amount comparable to the annual budget of plastic marine debris generated in and along shores of the entire North Pacific (Jambeck et al., 2015). Pathways of general marine debris are hard to study, in part because the debris sources are scattered over large distances and long periods of time. Accumulation regions for microplastics (particles of fragmented plastic less than 1 cm in size) have been studied more than those of other types of debris (Law et al., 2010; Eriksen et al., 2013; van Sebille et al., 2015), but account for only a tiny fraction of the debris input. The Great Japan Tsunami provided a unique opportunity to better understand how ocean debris drifts by following individual items and "waves" of debris deposition around the North Pacific. Even in areas heavily polluted with general debris from routine activities, many Japan tsunami marine debris (JTMD) items could be easily identified. In some places, "waves" of JTMD were obvious because of a dramatic increase in all categories of debris (Murray et al., 2018).

The unique dataset collected over the past six years has revealed the complex dynamics of JTMD travel across the ocean (Carlton et al., 2017). At the same time, it has also revealed weaknesses of the present observing system that largely relies on motivated observers, whose availability varies widely and is sparse in many parts of the Pacific and its shores. Numerical models were used to fill in the gaps in observations and help to construct the "big picture" of JTMD transport and deposition.

Presented here are results from five different ocean models and systems, their calibration/validation using observational reports, and their estimates of the total amounts and fate of JTMD.

The paper is organized as follows. The next section describes the models and setups of the numerical experiments as well as the model initializations and the unification of model solutions for comparative analyses. Section 3 describes the dynamics of JTMD in the model solutions. Section 4 introduces the observational dataset and compares the distributions of JTMD boat reports at sea and on the US/Canada west coast with model concentrations and fluxes. In Section 5, optimally scaled model solutions show estimates of the initial number of

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

* Corresponding author.
*E-mail address:* maximenk@hawaii.edu (N. Maximenko).

https://doi.org/10.1016/j.marpolbul.2018.03.056
Received 22 June 2017; Received in revised form 28 February 2018; Accepted 28 March 2018

JTMD boats and their possible fate. Section 6 concludes the paper and discusses some remaining questions and future work.

## 2. Model configurations

A suite of five numerical models, developed independently by participating groups in Japan and the United States, was run to produce an ensemble of solutions that were used to characterize the drift of JTMD, compare with observational reports and assess robustness of conclusions. In each model, the velocity of the debris drift was calculated from surface currents; the effect of the direct wind-forcing on the drift was accounted for by adding to the drift a fraction of the wind velocity, characterized by a "windage" parameter. Because the models represent near-surface, wind-driven currents differently, the same object could have different windage values in different models.

### 2.1. SCUD model

The *SCUD* model (Surface CUrrents from Diagnostic) was developed at the International Pacific Research Center (IPRC) of University of Hawaii, USA, (Maximenko and Hafner, 2010) to produce 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 uses two satellite data sets: sea level anomaly from altimetry, processed by the AVISO, and surface winds from QuikSCAT (1999–2009) and ASCAT (since 2007) satellites (the latter was calibrated using nearly two years of the overlap with QuikSCAT). Model currents are calculated from a combination of the mean geostrophic flow, derived from the mean dynamic topography (Maximenko et al., 2009), its anomaly, and locally induced wind-driven currents. The latter implicitly include the Ekman currents, Stokes drift, and other motions correlated with the local wind. The model coefficients are tuned using velocities of nearly 20,000 drifting buoys of the Global Drifter Program[1] collocated in time and space with satellite observations. The SCUD model produces daily, near-real time and nearly global maps on a ¼-degree grid that are available on the IPRC/APDRC[2] servers. SCUD and its precursors were used to successfully describe the global distribution of microplastics (Maximenko et al., 2012). Model solutions helped to explain historical data (Law et al., 2010; van Sebille et al., 2015) and to coordinate expeditions that empirically verified the existence of garbage patches in the Southern Hemisphere (Eriksen et al., 2013).

### 2.2. SCUD-HYCOM model

The spatial grid of SCUD (1/4°) adequately resolves such important ocean scales as the deformation radius and size of mesoscale eddies in the North Pacific (Chelton et al., 2011); the resolution also corresponds to the parameters of the ocean observing system. However, such resolution may be too coarse for simulations in coastal areas and especially those around islands. To increase the resolution of JTMD drift in coastal areas and its accumulation on shorelines, the SCUD model was blended with HYCOM[3] (Bleck and Boudra, 1981) data, increasing the original ¼° grid of SCUD to 1/12°. The blending was limited to 100-km coastal bins with the relative weight of HYCOM progressively increasing toward the coast. An additional 100-km buffer zone that removed biases and adjusted the model's response to local winds was added to calibrate the current velocities of the two models. This buffer zone provided a seamless transition between the SCUD and HYCOM solutions. Hereafter, we will refer to this blended model as *SCUD-HYCOM*.

[1] http://www.aoml.noaa.gov/phod/dac/index.php.

[2] http://apdrc.soest.hawaii.edu/.

[3] http://hycom.org/hycom/overview.

### 2.3. MOVE/K-7/SEA-GEARN system

The MOVE/K-7/SEA-GEARN (hereafter, *MOVE*) drift/dispersion model was created in Japan by a team of scientists from the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), the Japan Atomic Energy Agency (JAEA), the Meteorological Research Institute (MRI) of the Japan Meteorological Agency (JMA), and the Japan Aerospace Exploration Agency (*JAXA*) in order to examine JTMD positions in the North Pacific as well as its landing sites and dates on coastlines. Numerical experiments included hindcasts from March 2011 to July 2013, followed by forecast runs through May 2016. The hindcasts were based on 3dVAR data assimilation in the North Pacific ocean general circulation model MOVE (Usui et al., 2006), operated by JMA/MRI. 3dVAR provides a kind of optimal interpolation in space, ignoring temporal variations and (for each time moment) processing observations fitting into the associated assimilation time window. The resolution of this model is 1/10° west of the dateline and relaxed to a 1/2° grid elsewhere. The model is forced by fluxes produced by the JMA's operational atmospheric system JCDAS. The forecast phase of simulations, including ocean currents and winds, was performed using the K7 atmosphere-ocean-land coupled system, operated by JAMSTEC, with a global 1° resolution (Sugiura et al., 2008). Kawamura et al. (2014) analyzed trajectories of 153,600 particles released offshore of Iwate, Miyagi, and Fukushima prefectures using the SEA-GEARN dispersion model, operated by JAEA. Results of the model have been also reported by the Japan Ministry of Environment (2014)[4].

### 2.4. FORA-WNP30 re-analysis

FORA-WNP30 (hereafter, *FORA*) is a 30-year, four-dimensional, variational ocean re-analysis of the western North Pacific. This dataset is produced with the MOVE/MRI·COM-4dVAR system. The ocean circulation model is MRI·COM (e.g., Tsujino et al., 2010) and the assimilation system is the same as that in MOVE except that the assimilation method is 4dVAR (Usui et al., 2015). Overall, FORA-WNP30 reproduces well the basic features of the interannual to decadal variability in the western North Pacific. 4dVAR is an optimum space-time interpolation and extrapolation of observational data, using a numerical model. Compared to 3dVAR, 4dVAR generally produces more accurate spatial patterns and temporal tendencies. Usui et al. (2017) provided a detailed description of the 4dVAR method adopted in the re-analysis, its validation through comparison with independent observations, and analyses of the interannual to decadal variability.

### 2.5. GNOME model

*GNOME* (General NOAA Operational Modeling Environment) is the modeling tool developed and used by the Office of Response and Restoration's (OR&R) Emergency Response Division (ERD) of the US National Oceanic and Atmospheric Administration (NOAA) to predict trajectories of oil, debris, and other floating marine pollutants.[5] GNOME is essentially a stand-alone particle tracking model and is not implicitly tied to a specific ocean model. In this application, GNOME utilized surface currents from the 1/12° operational HYCOM[6] model from the Naval Research Laboratory and 1/4° global wind product from the NOAA Blended Sea Winds.[7] After the Great Japan Tsunami of 2011, results of the GNOME hindcast experiments, based on trajectories of 40,000 particles, initialized at 8 sites along the Japan coast, were mapped with the NOAA Environmental Response Management Application (ERMA) and used to coordinate the response to potential JTMD.

[4] http://www.kantei.go.jp/jp/singi/kaiyou/hyouryuu_eng/gaiyou.pdf.

[5] https://gnome.orr.noaa.gov/.

[6] http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html.

[7] http://www.ncdc.noaa.gov/oa/rsad/air-sea/seawinds.html.