2016 NOAA Marine Debris Program Report

Modeling

Modeling Oceanic Transport of Floating Marine Debris

May 2016

National Oceanic and Atmospheric Administration
National Ocean Service

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Cover photo National Oceanic and Atmospheric Administration.

For citation purposes, please use:
National Oceanic and Atmospheric Administration Marine Debris Program. 2016 Report on Modeling Oceanic Transport of Floating Marine Debris. Silver Spring, MD. 21 pp

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Acknowledgements

The National Oceanic and Atmospheric Administration (NOAA) Marine Debris Program would like to acknowledge William L. Balthis (National Centers for Coastal Ocean Science – Center for Coastal Environmental Health and Biomolecular Research) for his effort in synthesizing the wide range of modeling research and efforts into this paper, and Peter Murphy for providing guidance and support throughout this process. Special thanks go to Dr. Amy MacFadyen, Dr. James Potemra, and Laurent Lebreton for reviewing this paper and providing helpful comments. An additional thank you goes to Krista Stegemann for a copy/edit review of this report and Catherine Polk for graphic design. Funding for this project was provided by the NOAA Marine Debris Program.

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EXECUTIVE SUMMARY

Man-made debris in the ocean is now found from the poles to the equator and from shorelines, estuaries, and the sea surface to the ocean floor (STAP, 2011). General oceanic circulation patterns, particularly surface currents, greatly affect the redistribution and accumulation of marine debris in the world's oceans, as do the mass, buoyancy, and persistence of the material (Moore, Moore, Leecaster & Weisberg, 2001). Because of the relatively sparse amount of directly observable data on marine debris relative to the immensity of the ocean and the need to predict its movement, numerical models are used to simulate the transport of floating marine debris. Computer modeling simulations, based on data from about 12,000 satellite-tracked drifters deployed since the early 1990s as part of the Global Drifter Program (GDP, 2011), indicate that debris tends to accumulate in a limited number of subtropical convergence zones associated with persistent, long-term currents in the world's oceans (Wakata & Sugimori, 1990; Kubota, Takayama & Namimoto, 2005; Maximenko & Niiler 2008). Recent analyses of data on floating debris in the Pacific Ocean (Eriksen et al., 2013; Law et al., 2014), Atlantic Ocean (Law et al., 2010; Morét-Ferguson et al., 2010), and the world's oceans combined (Eriksen et al., 2014) have confirmed these modeling results. Modeling simulations can help to understand not only the likely fate of debris from known point sources, population centers, or extreme events such as hurricanes and tsunamis, but also to identify potential sources of debris. This paper reviews and briefly describes some of these methods, gives examples of their application for modeling the movement and transport of marine debris, and attempts to identify gaps in knowledge and recommend potential areas of further research.

The following overview presents some of the numerical modeling techniques that have been applied to simulate the transport of marine debris. The primary approach to modeling the transport of drifting objects, with marine debris being one application, typically has involved the use of particle tracking models (PTMs) to estimate or simulate the movement of 'particles' over time. This movement depends on transport (advection) by ocean surface currents, and some PTMs may incorporate additional factors such as movement resulting from the proportion of buoyant objects floating high in the water and exposed to the wind (windage), or a random motion component (turbulent diffusion).

The surface currents used to drive PTMs have been derived using a number of different methods. The main approaches identified from this review of the literature include:

- Surface current modeling: focuses only on the surface layer, where most floating debris is found. Surface currents can be estimated in various ways:
    - Currents can be inferred from the paths of drifters, either ship drift data or satellite-tracked drifters.
    - Currents can be estimated from long-term historical measurements of temperature, salinity, depth, and sea level pressure.
    - Currents can be calculated from satellite-derived measurements of sea-surface height and wind stress.
- Ocean general circulation models (OGCMs): solve equations of motion in horizontal and vertical dimensions and include both physical and thermodynamic processes. OGCMs provide the surface currents layer used to simulate debris transport. A number of systems have been developed to update (through a process called data assimilation) these models with satellite and in situ measurements in near-real time. Many of these model outputs are available online.

Because some of the terms used in this report may be unfamiliar to readers, a glossary of terms is provided at the end of this document. Terms or acronyms found in the glossary are indicated by an asterisk on first use, unless defined explicitly in the text.

BACKGROUND

Marine debris is one of the most pervasive pollution problems affecting the world's oceans and waterways. Debris makes its way into the marine environment by way of numerous land-based and at-sea sources. Besides the negative visual and aesthetic impacts of marine debris, there can be a number of other detrimental effects in terms of potential harm to marine life by ingestion or entanglement (NOAA MDP, 2014a, 2014b), hazards to navigation (Johnson, 2001), acting as a pathway or vehicle for invasive species (Ruiz, Carlton, Grosholz & Hines, 1997; USEPA 2012), or posing a chemical hazard due to the sorption of organic contaminants to plastic debris (Van et al. 2011; Rochman, Hoh, Hentschel & Kaye, 2013). Some types of debris may sink to the bottom or be washed up on beaches and shorelines, but a large proportion can remain suspended in the water column or floating at the surface for days or years and can be transported over great distances.

Modeling the transport and fate of marine debris must take into account winds, ocean surface currents, and other factors including the type of debris. Lightweight, buoyant materials such as some plastics tend to float high in the water so that they are pushed along partially by winds as well as surface currents. Such materials are referred to as having high "windage." Other, heavier buoyant materials such as wooden construction debris float just below the surface (low windage) and so are influenced primarily by surface currents. Still other types of debris, such as derelict fishing gear, may be suspended lower in the water column and drift mainly with subsurface currents. Since subsurface currents generally move at a much slower speed than surface currents, the vertical position of debris in the water column influences how fast it gets transported from a point of origin (source) to its final destination (receptor). Additionally, the characteristics of debris items can change over time; encrusting organisms can affect the buoyancy of objects, large items can be broken into smaller fragments, and different types of materials can degrade at varying rates.

Numerical models can be utilized to simulate the movement of debris for a number of different purposes. Models can be used to interpolate or interpret sparse data in a consistent way. Due to the relative immensity of the ocean, observations of marine debris or other floating/drifting objects, and direct measurements of ocean surface currents that move them, are relatively sparse. Models can be used to "fill in the gaps" where few observations are available. We can also use models to evaluate "what if" scenarios by varying conditions or parameters one at a time and observing the outcome. It may be of interest, for example, to vary the amount of windage of simulated debris items to estimate its effect on travel time. Furthermore, models can make predictions, either forecasting the likely state of the system at some time in the future, or simulating the current state based on past observations. We often know either where debris originates (a spill or natural disaster) or where it ends up (beached debris). Models can be applied to forecast the probable trajectories of debris of known origin, or to identify potential sources of debris by predicting the likely paths taken to reach a known destination.

> **"...attempting to simulate ocean circulation... is much more complex since it must take into account a large number of effects..."**

The equations governing motion in the ocean are continuous. Solving them on a computer, however, requires discretizing, selecting distinct points from the range. This creates a system of distinct grid points on which to solve them. Modeling of marine debris transport by ocean currents is often carried out within an Eulerian-Lagrangian* framework, which is related to the frame of reference of an observer. The Eulerian perspective describes the current velocity (speed and direction) at a fixed point (or points) over time, while the Lagrangian approach follows the trajectory, or path, of a debris "particle" being carried along by currents over time. These two points of view can be visualized by imagining river flow: an observer standing on a rock in the middle of the river describes the current velocity at that particular point (Eulerian perspective), while a boater being carried along by the current experiences the flow from a Lagrangian viewpoint. In the context of marine debris modeling, current velocities are obtained, by various methods, for points or nodes on a discrete (Eulerian) grid over a series of time steps. The resulting current velocities may then be used to calculate the trajectory of an object over time, in a technique sometimes referred to as Lagrangian particle tracking. The location of a particle at the end of each time step becomes the start point for the next time step, and the process is repeated. Most of the particle tracking models presented in this paper use Lagrangian particle tracking techniques (i.e., describing the trajectories of individual particles). However, some techniques use an Eulerian approach, which describes the concentration of passive tracers at every (Eulerian) grid point at each time step. Both of these particle tracking techniques are relatively straightforward, in the sense that the equations describing transport of an object (or concentration of tracers) depend only on current velocity at each time step (although some models also incorporate terms for other factors such as windage, diffusion, or vertical mixing). In contrast, attempting to simulate ocean circulation, whether focused only on currents in the surface layer or circulation throughout the water column, is much more complex since it must take into account a large number of effects, some of which are described below.

Oceanic Circulation - A Balancing Act

Ocean dynamics are governed by Newton's laws of motion, expressed as a set of equations (i.e., primitive equations) that describe relationships among a number of variables, including pressure, density, wind stress (friction between wind and ocean), temperature, and salinity. The dominant influences that drive oceanic circulation are gravity, wind stress, and the apparent forces resulting from the earth's rotation (Stewart, 2008). Steady ocean currents (those that persist over time in a prevailing direction) result from a balance between these forces (Sudre, Maes & Garcon, 2013). Also at play are the Sun, moon, and other celestial bodies which exert a gravitational pull on the ocean. Changes in their relative positions with respect to the Earth, due to both the Earth's rotation and orbital movements, lead to tides, tidal currents, and tidal mixing in the interior of the ocean. Gravity also affects the buoyancy of parcels of water depending on their density, which in turn depends on temperature, salinity, and pressure. Horizontal pressure gradients are caused by differences in water density or variations in sea surface elevation.

Wind stress from prevailing winds (westerlies at mid-latitudes, easterly trades at lower latitudes), through friction on the ocean surface, causes currents by transferring horizontal momentum to the ocean. All currents are subject to the Coriolis effect*, which arises from the rotation of the earth and causes flow to be deflected. Because of the Coriolis effect, the shallow layer of surface water set in motion by the wind is deflected to the right of the wind direction in the Northern Hemisphere (setting up a clockwise rotation pattern) and to the left of the wind direction in the Southern Hemisphere (causing a counter-clockwise rotation) (Figure 1a). At the surface, the balance between frictional wind stress and the Coriolis effect results in wind-driven, or Ekman*, flow (Figure 1b), giving rise to circular current systems known as gyres*. The deflection towards the center causes water to move towards the central region of a gyre. This mounding of water towards the center of a gyre results in the sea

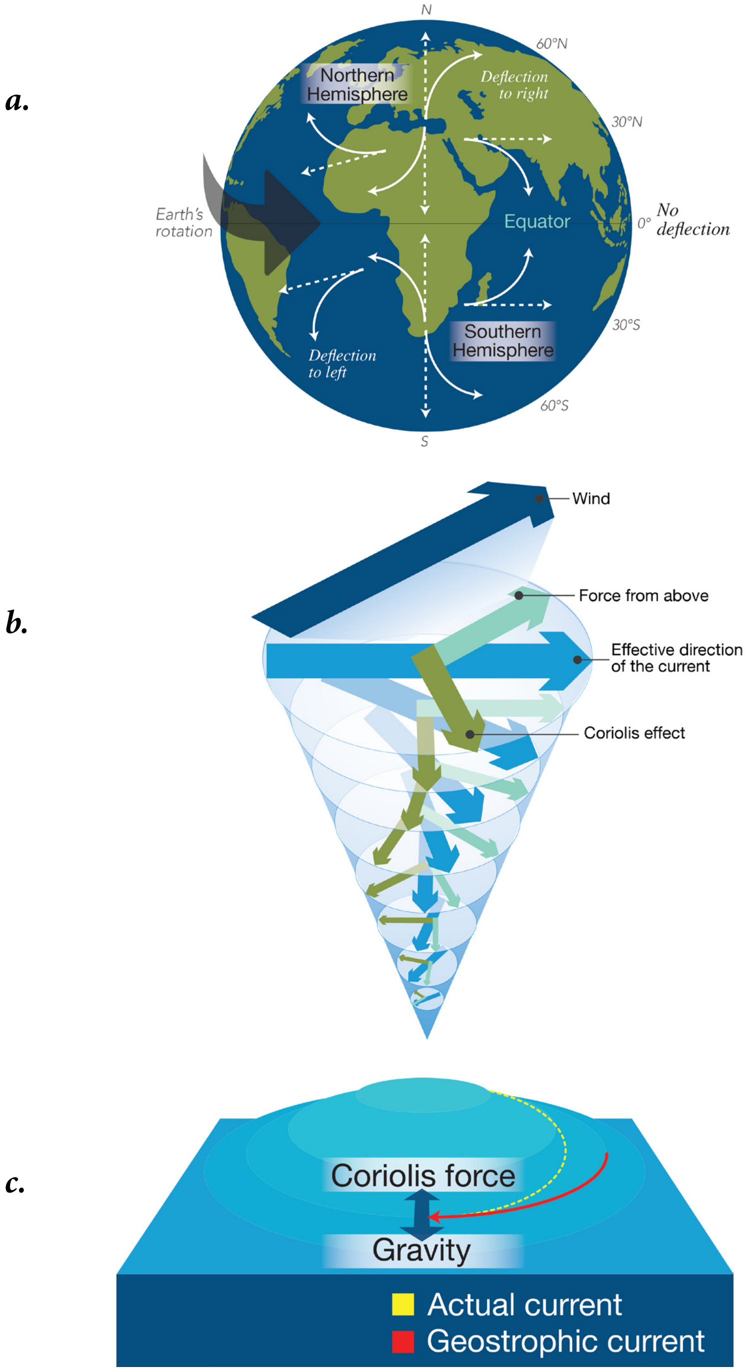

Figure 1. Dominant influences driving large-scale ocean surface currents: a) Earth's rotation, b) surface winds, c) gravity.

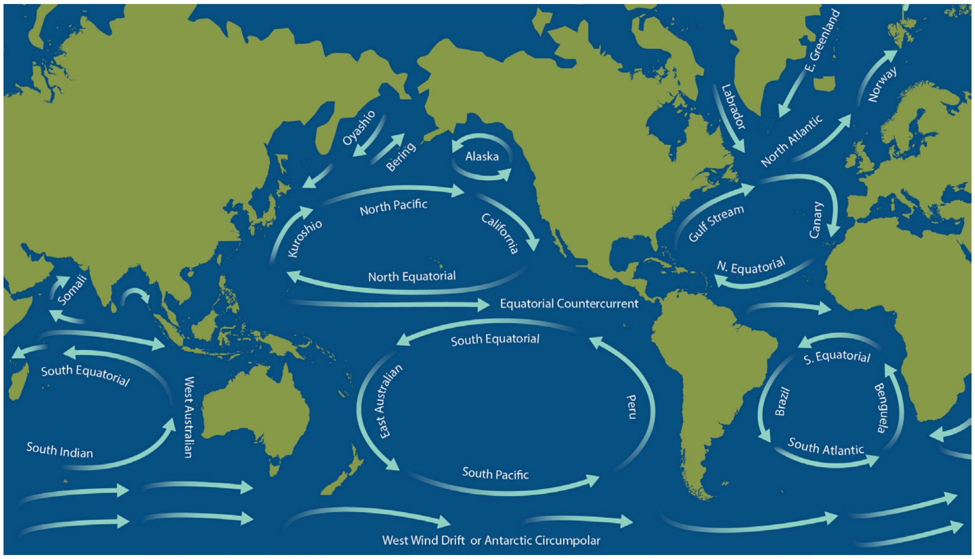

Figure 2. The time-averaged, surface circulation of the ocean during the northern hemisphere's winter, deduced from a century of oceanographic expeditions.

surface being higher in elevation (up to a meter or so) than the surrounding sea surface, which creates a horizontal pressure gradient. Since the force of gravity causes water to move from a high to low pressure area, there is a flow outward and down slope from the center of the gyre. As the water moves, it is deflected by the Coriolis effect. Eventually, the outward-directed pressure gradient force balances the apparent force due to the Coriolis effect and water flows around the gyre, parallel to contours of elevation of sea level. The horizontal movement of surface water resulting from a balance between the pressure gradient force and the Coriolis force is known as geostrophic flow* (Figure 1c). Large-scale circulation patterns can be inferred from sea surface height just as meteorologists use sea level pressure maps to derive wind.

In the global ocean, these influences give rise to large-scale circulation patterns constrained by the continental masses bordering the major ocean basins. Major boundary currents such as the Kuroshio Current and the Gulf Stream link up with equatorial and other currents to form large oceanic gyres (Figure 2). In the North Pacific, the prevailing winds form two large oceanic gyres, each bounded by major current systems (Figure 3). These major currents delineate three major oceanographic zones: a subtropical zone to the south, a subpolar zone to the north, and a transition zone between them (Howell, Bograd, Morishige, Seki, & Polovina, 2012).

"The dominant influences that drive oceanic circulation are gravity, wind stress, and the apparent forces resulting from earth's rotation (Stewart, 2008)."

Oceanic gyres can retain debris, since the Ekman flow deflects water towards the center of the gyre, as described above. However, zones of subtropical convergence and transition, such as where the North Pacific Subtropical and Subpolar Gyres collide and interact, have been identified as areas important to the concentration and accumulation of marine debris. Along the North Pacific Transition Zone (Figure 3), westerly winds force Ekman transport of cool, saline water to the south. Since this water is more dense, it sinks beneath the warmer subtropical waters associated with the Subtropical Frontal Zone. The horizontal convergence causes objects that are sufficiently buoyant (to overcome the vertical flow of sinking water) to accumulate in the Subtropical Convergence Zone (Pichel et al., 2007; Howell et al., 2012). In addition to this large-scale frontal convergence zone, other areas of accumulation exist, such as the one associated with a climatological high pressure zone in the oceanic region between California and Hawaii (i.e., North Pacific Subtropical High). Debris accumulates in this convergence zone since the wind around high pressure areas in the Northern Hemisphere rotates clockwise and the Ekman currents of the ocean are deflected to the right of the downwind direction (Wakata & Sugimori, 1990). This corresponds to the area shown in Figure 3 as the Eastern Garbage Patch.

The circulation patterns presented above describe long-term global or basin-scale ocean currents. It is important to note, however, that ocean circulation operates at different scales, both temporally and spatially. Current velocities also vary with depth. For example, the wind-driven surface layer can have currents that move at velocities of 20 cm/s or more, but these velocities decrease with depth. Hence, debris objects that change buoyancy over time and sink lower in the water column will experience currents of different velocity and direction. Also, instabilities in the large-scale circulation, interactions between currents and bottom topography (bathymetry), and direct effects of the wind can create swirling currents, or eddies. The size and persistence of eddies varies. Some, called mesoscale eddies, are tens to hundreds of kilometers in diameter, and can persist for several days to several months. The resolution of an ocean model is determined by the spacing of grid points and also by the time step (the interval between one set of solutions and the next). Hence, a model with widely spaced grid points and a large time step may be suitable only for resolving long-term average flow on a global or basin-wide scale. Other, higher-resolution models are able to represent mesoscale circulation

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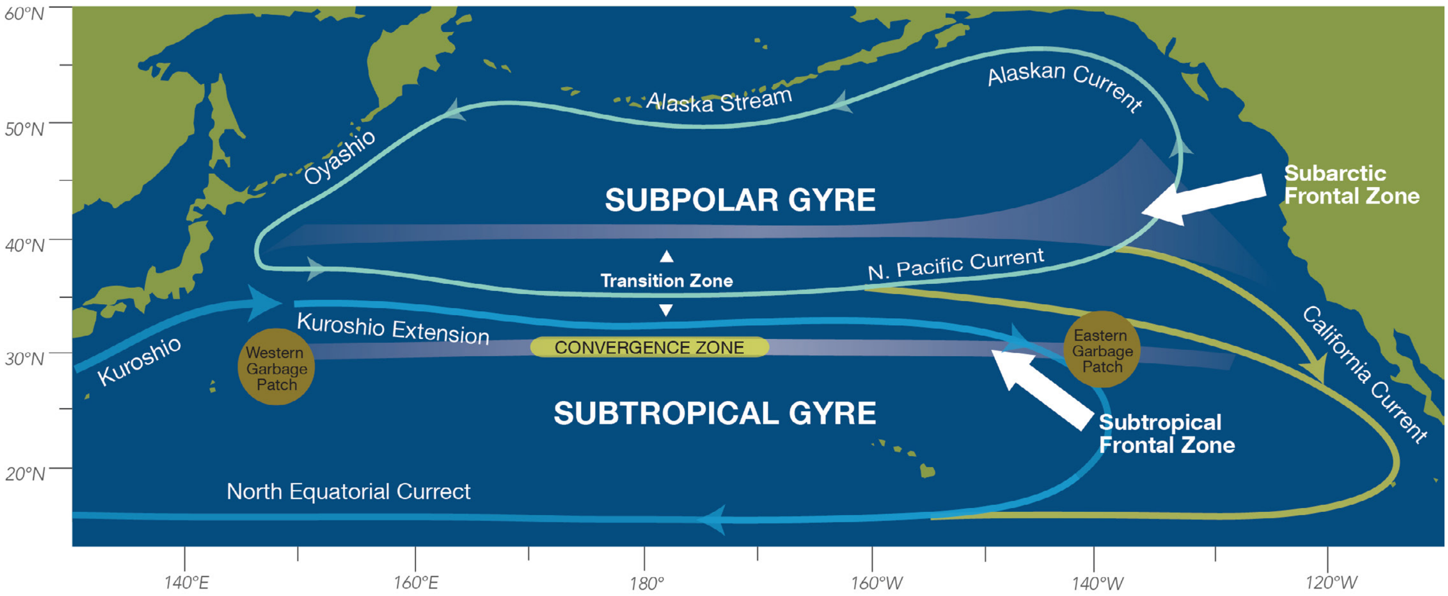

Figure 3. Schematic representation of the major oceanic currents and zones in the North Pacific.

(so-called 'eddy-resolving' models), or model circulation regionally within an ocean basin, sea, or gulf and over a shorter time period.

> **"Different kinds of models require various types of information, and the methods for acquiring the data have evolved with the development of new technologies."**

Types and Sources of Data

Numerical ocean models require input of measured data for model setup, initialization, and validation. Different kinds of models require various types of information, and the methods for acquiring the data have evolved with the development of new technologies. Current velocities can be measured directly using (Lagrangian) drifters, or measured at fixed (Eulerian) locations using moored current meters. Currents can also be calculated from measurements of the physical factors that drive them. For example, long-term geostrophic currents can be obtained by calculating variations in sea surface height (and resulting pressure gradients) from in situ measurements of temperature and salinity with depth. Such measurements have been compiled in the Levitus (1982) Climatological Atlas of the World Ocean, which provided monthly global temperature and salinity climatologies with a spatial resolution of 1x1 degree at 19 depth levels (surface – 1000m). The Levitus Atlas has been updated as the World Ocean Atlas, and the most recent version provides higher vertical resolution for all variables, with 102 vertical levels from the surface to 5500m depth (WOA, 2013). Other products, such as the International Comprehensive Ocean-Atmosphere Data Set (ICOADS), provide observations and monthly summaries of sea surface temperature, sea level pressure, surface winds, and other measurements.

With the advent of satellite remote sensing, many of these quantities can be measured directly on a global scale and made available in near-real time. Sea surface height can be measured using altimetry, which involves sending a microwave pulse to the ocean's surface and recording the time it takes to return. Altimetry measurements from NASA satellites, such as Topex/Poseidon*, Jason-1/2*, and the European Space Agency (ESA) ERS-1/2*, make it possible to measure sea surface height to within a few centimeters. Satellites such as NASA's Quikscat/Seawinds* and ESA's ERS-1/2 can also measure ocean near-surface wind speed and direction using a microwave radar sensor called a scatterometer. Such measurements of sea surface height and winds are made available online. Global surface current products calculated directly from satellite altimetry and ocean vector winds are also provided, for example, by OSCAR* (Ocean Surface Current Analysis – Real Time), which provides long-term, monthly, or 5-day mean surface currents from 1992 to the present on a 1° grid (OSCAR, 2014). A similar global surface current product is provided by Mercator/SURCOUF (Larnicol et al., 2006) and AVISO* (Sudre & Morrow 2008).

SYNTHESIS OF LITERATURE

Overview

Different approaches have been used to model the general circulation and associated transport of material in the ocean. Because marine debris modeling techniques make use of these approaches, either separately or in various combinations, they are reviewed briefly below.

First, we describe a number of methods for modeling surface currents, which are mainly a combination of Ekman currents driven by local wind and geostrophic currents maintained by the balance between pressure gradients and the Coriolis force (Maximenko & Niiler, 2008), as described above. These methods include the calculation of surface currents from long-term historical data, direct estimation of surface currents from the paths of drifters, and currents derived from satellite-based measurements of the ocean surface.

Next, a class of ocean general circulation models (OGCMs) that simulate motion throughout the water column in three dimensions are introduced. Brief descriptions of these methods along with specific applications to the problem of modeling marine debris are presented below. For more information on these approaches, the reader is referred to the citations given in the text, as well as reviews of techniques for application to marine debris by Potemra (2012) and overviews of satellite-based methods of estimating ocean surface currents by Sudre and Morrow (2008), Dohan and Maximenko (2010), Dohan et al. (2010), and Freeman et al. (2010).

The surface current velocities obtained from these various methods typically are coupled with a particle tracking model (PTM), which describes the resulting transport of a given "particle" of debris over the selected or modeled time step. Alternatively, the evolution of tracer distribution and density over time throughout the model domain can be estimated with a statistical model.

Surface Currents

Drifters

For many years, ocean surface currents have been estimated directly by how they carry drifting objects, from the well-known "message in a bottle" to glass balls used by Japanese fishermen that have washed up on beaches in California. An early source of ocean current information was based on the collection of ship drift data, in which currents were estimated from the difference between a ship's predicted course and its actual speed and direction (Meehl, 1982). With the development of satellite tracking capability in the 1970s, it became possible to track drifting buoys, or "drifters". Many competing drifter designs were developed and evaluated, and a uniform design was proposed in 1992 (Sybrandy & Niiler, 1992; see sidebar). The design of satellite-tracked drifters was standardized and a global array of drifters was deployed in the world's oceans as part of the Global Drifter Program (GDP, 2011). Drifters provide direct measurements of ocean surface currents, which are composed mainly of Ekman and geostrophic components (see glossary). The successive drifter position measurements can be used to calculate surface layer current velocities or to calibrate or validate ocean surface current models. While these global arrays of drifters describe large-scale global and basin-wide ocean currents, drifters can also provide insight into processes, such as ocean eddies, which operate on the mesoscale (50-500 km, lasting 10-100 days, with currents of a few kilometres per hour). The paths of drifters also suggest the likely paths of floating marine debris.

Various approaches have been used to model the movement or dispersion of drifters. Wakata and Sugimori (1990) used a global ship drift dataset of surface current velocities on a 5° x 5° latitude-longitude grid (Meehl, 1982) as input to a Lagrangian PTM (based on Newton's equation of motion and conservation laws) to investigate the trajectories and density distribution of simulated drifters. Their overall results agreed well with the observed trajectories of satellite-tracked drifters in the North Pacific described by Kirwan, McNally, Reyna, and Merrell (1978). The simulations also confirmed areas of debris accumulation in the North Pacific, reported by Mio, Takehama, and Matsumura (1988), as well as other areas of accumulation in the center of the South Atlantic Ocean and the Indian Ocean west of Australia.

Kirwan et al. (1978) described the large-scale near-surface circulation of the eastern North Pacific based on the trajectories of 23 satellite-tracked drifters. Embedded in the main flow were numerous mesoscale eddies. In subsequent studies, Kirwan, Merrell, Lewis, Whitaker, and Legeckis (1984) and Kirwan, Lewis, Indest, Reinersman, and Quintero (1988) developed a model to describe such mesoscale features, specifically Loop Current eddies in the Gulf of Mexico. Modeling of mesoscale eddies is more complex than large-scale currents, since the model must describe not only the movement or translation of the eddy center, but also

> **"The typical modern drifter is a high-tech version of the "message in a bottle." It consists of a surface buoy and a subsurface drogue (sea anchor), attached by a long, thin tether. The buoy measures temperature and other properties, and has a transmitter to send the data to passing satellites. The drogue dominates the total area of the instrument and is centered at a depth of 15 meters beneath the sea surface."**

the circulation characteristics of the eddy itself. Additional investigations of Loop Current eddies were carried out by Glenn and Forristall (1990) and Glenn and Ebbesmeyer (1993), who also estimated model parameters based on satellite-tracked drifter trajectories. Eddies may "pinch off" from the main, large-scale current flow, and can transport debris within mesoscale patches as they propagate or migrate over large distances (Howell et al., 2012).

More recently, the paths of more than 10,000 satellite-tracked drifting buoys were combined with information from satellite altimetry, winds, and gravity measurements to create high-resolution maps (½° grid) of the mean dynamic ocean topography (sea surface height adjusted for variations in the shape of the earth due to gravity) and to derive the mean geostrophic (resulting from pressure gradients) and Ekman (wind-driven) circulation in the upper ocean (Maximenko et al., 2009). The combination of drifter and satellite data revealed new features of the ocean surface mesoscale circulation and yielded ocean dynamic topography patterns at a spatial resolution higher than that achievable from satellite data alone and with better accuracy than those obtainable from drifter data alone.

In a subsequent study, Maximenko, Hafner, and Niiler (2012) used the same satellite-tracked drifter trajectories to develop a statistical model describing the movement of drifters over time. The observed displacement of each drifter was used to calculate the probability of a statistical drifter, or tracer, to move into or over ½° bins surrounding its original position. The model was then initialized with uniformly-distributed "drifters" and the evolution of drifter density with time over the (Eulerian) grid was tracked for up to 1,000 years, under the assumption that the prevailing winds and currents remain steady during the simulation period. Similar to the results of Kubota et al. (2005), the simulations resulted in areas of accumulation corresponding roughly to the centers of the five subtropical gyres and associated areas of convergence.

The (Surface CUrrents from Diagnostic) SCUD model utilized AVISO satellite altimetry to determine the geostrophic current component, and used QuikSCAT (satellite scatterometry) ocean surface wind data to calculate the wind-driven Ekman component (Maximenko & Hafner, 2010). Maps of total currents were produced daily on a ¼° latitude/longitude grid starting in August 1999 and running to November 2009, the time span of QuikSCAT data. SCUD coefficients were derived such that model estimates matched closely with the velocities of surface drifters obtained from the Global Drifter Program. The goal of the project was to diagnose near-surface currents consistent with trajectories of Lagrangian drifters using satellite observations (Maximenko & Hafner, 2010). Recently, the SCUD model has been used to to forecast potential trajectories of Japan tsunami marine debris (JTMD*) from the March 2011 Tohoku tsunami (Maximenko & Hafner, 2012). In contrast to Lagrangian PTMs, the SCUD model tracks virtual tracer distributions over the Eulerian grid, as in Maximenko et al. (2012). The first version of the model tracked debris solely using ocean currents, while the refined model includes tracers sensitive to windage. The accuracy of the SCUD model deteriorates near shore due to higher errors in satellite data (due to intrinsic difficulties in corrections applied for atmospheric effects) and increased complexity of oceanographic and tidal dynamics (Carson et al., 2013).

The Ocean Surface CURrent Simulations (OSCURS) numerical model (Ingraham & Miyahara, 1988) is a research tool originally developed to investigate how ocean currents might have influenced various fish populations in the North Pacific Ocean and Bering Sea. The model allows oceanographers and fisheries scientists to perform retrospective analyses of daily ocean surface currents anywhere in a 90-km North Pacific Ocean-wide grid from Baja California to China and from 10°N to the Bering Strait from 1901 to the present (Ingraham, 1997). OSCURS derives mean geostrophic currents from long-term average density distributions, computed from historical averages of measured temperature and salinity versus depth. These were combined with wind speed and direction calculated from daily sea-level pressure data to obtain surface current velocities. The OSCURS model was developed for the North Pacific and Bering Sea and calibrated or "tuned" with satellite-tracked drifter data for the Gulf of Alaska (Ingraham & Miyahara, 1989). Incorporating drifter data allows the parameters of the model to be adjusted so that modeled outputs agree more closely with actual measurements. Surface current velocities calculated on the OSCURS grid are used to obtain the continuous trajectory of drifting objects (i.e., Lagrangian PTM, as described previously). OSCURS has been used to hindcast* the drift trajectories of 1,300 shoes spilled from a shipping container lost at sea in the North Pacific (Ebbesmeyer & Ingraham, 1992) and later used to model trajectories of intentionally released drift bottles (Ebbesmeyer et al., 1993) and accidentally released bathtub toy animals (similar to the shoe spill), with adjustments for increased windage of the plastic toys (Ebbesmeyer & Ingraham, 1994). The model has also been applied to estimate the orbital period (the time required for one complete rotation) of the Pacific Subpolar Gyre based on subsequent sightings of the aforementioned toys and other objects (Ebbesmeyer, Ingraham, Royer, & Grosch, 2007). The OSCURS model has been applied to simulate the dispersal of marine debris (derelict fishing nets) in the North Pacific (Ingraham & Ebbesmeyer, 2001) and to forecast possible paths of JTMD (Ebbesmeyer & Ingraham, 2012). To account for the varying amounts of windage on the different debris items, model parameters for current speed and angle were adjusted systematically to determine which model trajectories ended near reported landfall locations.

> **"The combination of drifter and satellite data revealed new features of the ocean surface mesoscale circulation..."**

Kubota (1994) used the same Lagrangian PTM as Wakata and Sugimori (1990) and derived surface current velocities in an approach similar to that used in the OSCURS model, but used different data sets on which to base calculations. Geostrophic surface currents were calculated on a 1°x 1° latitude-longitude grid (~100km at mid-latitudes) from temperature and salinity data found in the Levitus (1982) atlas. Winds were obtained from monthly wind data (1° grid) in the Comprehensive Ocean-Atmosphere Data Set (COADS) derived from ships, fixed research vessels, buoys, and other devices (Slutz et al., 1985). The data were used to derive Ekman drift, geostrophic currents, and combined currents in order to provide a mechanism for the observed accumulation of floating debris (documented by Mio et al. (1988)) in the North Pacific, especially north of Hawaii.

Kubota et al. (2005) carried out a similar set of simulations, but using satellite-derived measurements. Geostrophic currents were calculated from TOPEX/POSEIDON altimetery and surface winds were derived from ERS-1/2 scatterometry. Simulations, which were run on a 1° x 1° grid (~100km) and initiated with pseudo-marine debris distributed uniformly over the grid, identified areas of accumulation associated with the five subtropical gyres and zones of convergence, most notably an area of accumulation northeast of Hawaii.

Martinez, Maamaatuaiahutapu, and Taillandier (2009) investigated the accumulation and convergence of floating debris in the eastern-central region of the South Pacific subtropical gyre, using a PTM coupled to surface currents derived in several different ways. In an initial experiment, surface currents were calculated from satellite altimetry (combined TOPEX/POSEIDON and ERS-1/2) and sea surface wind data (ERS-1/2 scatterometry) on a 1/3° grid. Comparisons were made to results obtained using a lower-resolution product (OSCAR, 1° grid), also derived from satellite altimetry and scatterometry winds. While they noted differences in simulation results, the same large-scale trends in drift trajectories were found: convergence, eastward drift, accumulation.

Ocean General Circulation Models (OGCMs)

Prior to the proliferation of numerical ocean simulation models, a number of simplified analytic and mechanistic models of basin-scale ocean circulation were developed to describe wind-driven flow (Sverdrup, 1947; Stommel, 1948; Welander, 1959), abyssal circulation (Stommel & Arons, 1960), and thermohaline effects (Wyrtki, 1961). The first numerical simulation ocean model was developed by Kirk Bryan and Michael Cox (Bryan & Cox, 1967, 1968; Bryan, 1969) at the Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton and is the predecessor to many ocean general circulation models (OGCMs) in use today. Most ocean simulation models solve the basic equations of motion (i.e., primitive equations) on a horizontal grid (Figure 4a), where the spacing of grid points determines the horizontal resolution of the model. Vertical processes (Figure 4b) are handled in various ways, by using several horizontal levels (velocities computed at specific depths, z-coordinate), layers of different density (isopycnal, ρ-coordinate), or a fixed number of levels regardless of depth (terrain-following, σ-coordinate).

Such models contribute greatly to our understanding of oceanic circulation, but all numerical simulation models are limited in the degree to which they are able to represent the effects of processes that determine how and where water will move. The complex dynamics of ocean circulation occur on spatial scales from millimeters to hundreds of kilometers and temporal scales from seconds to decades and beyond (Potemra, 2012). Limits on computing resources require that sub-grid scale processes be simplified or approximated (i.e., parameterized) to estimate their effects. Hence, practical models must necessarily be simpler than the real ocean.

Within the context of marine debris transport modeling, OGCMs provide the surface current velocities that can be used to drive PTMs. There has been an increase over the past 20 – 30 years in the amount and availability of satellite-derived measurements of sea-surface height (SSH), sea-surface temperature (SST), surface winds, and satellite-tracked drifter trajectories. Systems have been developed for assimilating satellite data, drifter data, and in situ vertical profiles of salinity, temperature, and depth obtained from ship-deployed instruments. While these in situ data are generally too sparse to characterize the horizontal variability, they provide valuable information about the vertical stratification (Chassignet et al., 2007). Since OGCMs incorporate multiple vertical levels, the surface currents they provide are connected to and reflect the influence of processes or features (for example, mixing, stratification, or bottom topography) below the surface layer.

A number of ocean modeling systems now exist, which can assimilate the available data in near-real time and provide daily outputs of model runs. Many of the global OGCMs in use today operate at a horizontal grid resolution of 1/10° or less, which is sufficient to resolve mesoscale eddies (see previous section for description). One such eddy-resolving numerical circulation model, the HYbrid Coordinate Ocean Model (HYCOM*; Bleck et al., 2002), has been applied to global ocean simulations at a resolution of 1/12° (6.5km on average), with higher resolutions in basin-specific and regional applications (e.g., 1/25°, or ~3.5km, in the Gulf of Mexico). High-resolution regional models can be nested within basin-scale or global models, with the larger scale model providing initial conditions or boundary conditions for the nested model.

> **"... all numerical simulation models are limited in the degree to which they are able to represent the effects of processes that determine how and where water will move."**

HYCOM uses a hybrid vertical coordinate system, where vertical coordinates remain isopycnic (following surfaces of constant density) in the open, stratified ocean. However, they transition smoothly to z-coordinates in the weakly-

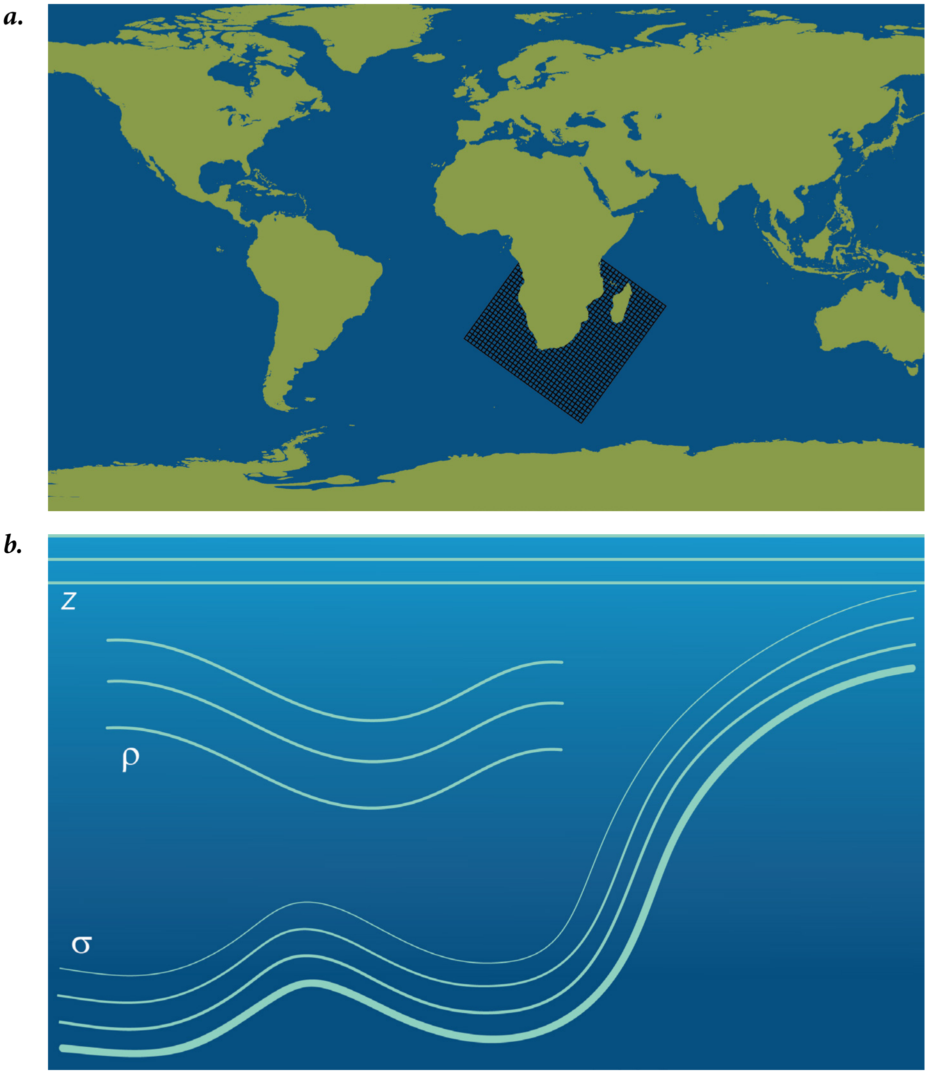

Figure 4. Illustrations of a) horizontal (global and nested regional) grids, b) approaches for handling vertical processes.

stratified upper-ocean mixed layer, to terrain-following sigma coordinates in shallow-water regions, and back to level coordinates in very shallow water (Chassignet, Smith, Halliwell, & Bleck, 2003; Chassignet et al., 2006; Chassignet et al., 2007; Wallcraft, Carroll, Kelly, & Rushing, 2003).

HYCOM is being used by a broad partnership of institutions in the United States to build global, basin-scale, and regional ocean current and water properties prediction systems (Chassignet et al., 2006; Chassignet et al., 2007) in the context of a coordinated international effort, The Global Ocean Data Assimilation Experiment (GODAE). The HYCOM system integrates the numerical model with information about the ocean surface's space-time variability obtained from instruments aboard satellites, vertical profiles from expendable bathythermographs (XBT), conductivity-temperature-depth (CTD) profilers, and profiling floats (e.g., Argo, which measures temperature and salinity in the upper 2000 m of the ocean), as well as from statistics determined using past observations in a process called data assimilation. A technique commonly used in weather forecasting and prediction, the purpose of data assimilation is to determine a best possible ocean state using observations and short range forecasts. This approach combines information from past observations brought forward in time by a model (background, or first guess) with information from new observations. This best estimate of the current state of the system, called an analysis, is then used as the starting point for the next analysis cycle. In HYCOM, the analysis computes corrections to the first-guess fields using all of the observations (e.g., temperature, salinity, SSH, velocity) that have become available since the last analysis was made (Cummings, 2005).

> **"A number of ocean modeling systems now exist, which can assimilate the available data in near-real time and provide daily outputs of model runs."**

Data-assimilative ocean modeling systems can provide short-term forecasts (typically several days). In most of the studies reviewed in this paper, these models have been used in hindcasting debris transport, over the time period for which data are available, up to the present. However, these types of models can also be employed to do statistical probability modeling to make predictions much in the same way the historical data has been used.

> **"most of the studies reviewed... have been used in hindcasting debris transport..."**

Linked Ocean General Circulation Models - Particle Tracking Models

Yoon, Kawano, and Igawa (2010) simulated marine debris drift and beaching in the Japan Sea using a Lagrangian PTM coupled to ocean current velocities provided by the Japan Sea Forecasting System from the Research Institute for Applied Mechanics ocean circulation model (RIAM OCM) and to wind data from the Global Spectral Model of the Japan Meteorological Agency. The RIAM OCM is an example of a z-coordinate model, where the model operates on multiple horizontal layers in the vertical dimension. This is the simplest choice of vertical coordinate, where z represents the vertical distance (i.e., depth) from a resting ocean surface at z = 0 (Griffies et al., 2000). The RIAM OCM operates at a horizontal resolution of 1/12° (~6km at mid-latitudes).

Isobe, Kako, Chang, and Matsuno (2009) adopted the Princeton Ocean Model (POM; Blumberg & Mellor, 1987), a regional, terrain-following model, with a horizontal grid spacing of 1/12° (~9km), to compute the current field covering the Yellow Sea, the East China Sea, and part of the North Pacific. Terrain-following models are particularly useful for studying regional ocean circulation in coastal areas since they provide a smooth representation of the ocean bottom topography (see for example, Veneziani, Edwards, Doyle, and Foley (2009)), and subtle details in ocean bathymetry can make the difference between erroneous and accurate simulations of the large-scale circulation (Gille & Smith, 2003). Using surface currents obtained from the POM, Isobe et al. (2009) then used a two-way PTM to specify statistically significant starting locations (sources) of drifting objects carried by ocean currents. First, a backward-in-time PTM was used to identify multiple candidate sources for an initial ending location (receptor) by releasing virtual particles carried by modeled ambient currents with direction reversed in sign for both horizontal current components. The number of particles at each source suggests the probability of the object sources. Second, using a forward-in-time PTM, particles were released from all source candidates identified in the backward-in-time PTM to specify statistically significant object sources: after a specified amount of time, a candidate source is considered statistically significant if the true (known) receptor falls within a region that is two times the standard deviation of the distance between simulated particle positions and their averaged position (Isobe et al., 2009). In a subsequent study, Kako, Isobe, Seino, and Kojima (2010a) compared model outputs obtained as described above to the results of a beach debris survey carried out every two months from 2007 through 2008. Additionally, they applied an inverse method using the beach survey results to compute the quantity of debris (object outflows) originating from each source detected in the two-way PTM.

Building on the previous two studies described above, Kako et al. (2011) and Kako, Isobe, Kataoka, and Hinata (2014) validated the source quantities (outflows) of marine debris estimated by the inverse method by hindcasting quantities of debris actually observed using the forward-in-time PTM. Particle outflows computed using the inverse method are given for each source and month, and particle motion is governed by surface currents computed in an ocean circulation model (POM) driven by QuikSCAT/SeaWinds data. Quantity of beach debris was also forecast using the same ocean circulation model, but short-term (34-day) forecast wind data from the Japan Meteorological Business Support Center (JMBSC) were used in lieu of driving the model by QuikSCAT/Seawinds observed data. The hindcast computation was conducted in parallel with the forecast computations, and the hindcasted particle positions at the beginning of each forecast computation were used for the initial condition in forecasting the particle positions. Model hindcast performance was validated (that is, model predictions compared to observations) by estimating the area covered by debris on the surveyed beach using sequential snapshots taken by a webcam (Kako et al., 2010b).

Hardesty and Wilcox (2011) investigated potential sources and receptors of floating marine debris around the Australian continent using a 2-way PTM together with an eddy-resolving (1/12° in the Australian region studied) OGCM based on the Modular Ocean Model (MOM4; Griffies, Harrison, Pacanowski, & Rosati, 2004), which is an example of a z-coordinate model as described above. Release points of virtual particles were based on debris data collected by various organizations involved in beach cleanups and state agencies that have operating marine debris monitoring programs. In one simulation, the PTM was run backward in time from four of the beach cleanup sites to identify possible sources. Additional experiments ran the PTM forward in time to simulate releases from locations (sources) at the boundary of the Australian Exclusive Economic Zone and from major population centers along the Australian coast. The PTM allowed for specifying various values of windage (i.e., leeway drift, influence of the drag force exerted directly by winds). They ran the particle tracking code using five different windage values for each release area, tracking the released particles over 80 days. The model was also run twice (January and July) each year (1994-2007) to consider potential influence of seasonal variation in ocean currents on marine debris sources and receptors for each release.

The General NOAA Operational Modeling Environment (GNOME*) is an interactive environmental simulation system designed for the rapid modeling of pollutant trajectories in the marine environment (Zelenke, O'Connor, Barker, Beegle-Krause, & Eclipse, 2012) that has also recently been applied to the modeling of JTMD. GNOME is a modular and integrated software system that accepts input in the form of maps, bathymetry, numerical circulation models, location and type of spilled substance, oceanographic and meteorological observations, and other environmental data. Spilled substances are modeled in GNOME as point masses, or particles, whose trajectories depend on "movers", which include winds, currents, and horizontal diffusion.

For the JTMD application, GNOME used currents from HYCOM, described previously. GNOME produced a regular series of hindcasts of the probable location of debris since the last update cycle. In addition to particle trajectories forced by HYCOM surface currents, observed near real-time winds (NOAA blended winds product) were incorporated into the model runs and combined with estimated debris windage based on USCG Search and Rescue research data. Simulated particles were randomly assigned windage values from 1-5%, meaning that they were moved not only by ocean currents, but were also moved by 1-5% of wind speed in the downwind direction (NOAA MDP, 2014c).

Lebreton, Greer, and Borrero (2012) simulated the transport and accumulation of marine debris, particularly floating plastic, by extracting surface currents from the HYCOM system (Cummings, 2005), and then coupling the velocity data extracted from HYCOM to the Lagrangian PTM Pol3DD (Black, 1996). The Pol3DD model tracks virtual particles to simulate waterborne dispersion of material including neutrally buoyant anthropogenic material, larvae, oil spills, outfall discharges, and estuarine or beach sediment transport (Lebreton et al., 2012). While the full HYCOM model contains 32 vertical layers, only velocities in the surface layer were considered as the principal

Model Name	**SCUD**	**OSCURS**	**GNOME**
Model Full Name	**Surface CUrrents from Diagnostic**	**James Ingraham**	**General NOAA Oceanographic Modeling Environment**
Lead Scientists	Nikolai Maximenko, Jan Hafner	NOAA Alaska Fisheries Science Center \ Resource Ecology and Fisheries Management	NOAA Office of Response & Restoration Team
Organization	University of Hawaii	North Pacific Ocean, Bering Sea	
Areas Primarily Used	• Pacific Ocean • Indian Ocean	• US Navy Fleet Numerical Meteorology & Oceanography Center sea level pressure data • Long term average distributions/measurements of forcing	• Global oceans, though most applications in territorial waters of United States
Forcing Data Sources Commonly Used (in known debris applications)	• AVISO for currents and • QuikSCAT for winds, With debris coefficients tuned to velocities from Global Drifter Program	• US Navy Fleet Numerical Meteorology & Oceanography Center sea level pressure data	• Varied: GNOME can integrate forcing data from multiple sources
Example Applications	• Japan Tsunami Marine Debris (JTMD) • General N. Pacific debris concentration and movement patters • MH370 debris hindcast	• Long term average distributions/measurements of forcing	• Oil spill modeling • Incident debris modeling • Ad-hoc support of response agency trajectory requests • JTMD
Website	http://apdrc.soest.hawaii.edu/datadoc/scud.php	http://www.afsc.noaa.gov/REFM/docs/oscurs/get_to_know.htm	http://response.restoration.noaa.gov/gnome

Transport model approaches frequently used to estimate debris movement.

driver of floating particles. Their simulation results were in agreement with both measured and modeled descriptions of concentrations of floating debris, showing areas of accumulation associated with the five major ocean-wide gyres (North Atlantic, South Atlantic, North Pacific, South Pacific, and Indian Ocean). In contrast to models starting from initial uniform distribution of floating objects (for example, Maximenko et al. (2012), described in the previous section), Lebreton et al. (2012) evaluated scenarios of debris input determined by the relative proportion of impervious watershed area, coastal population density, or global shipping routes to produce more realistic estimates of the relative concentrations of debris in accumulation zones. Lebreton and Borrero (2013) used a similar modeling approach to simulate dispersion and transport of JTMD. Their results suggested that some isolated debris items would be shed from the clockwise-rotating North Pacific gyre/accumulation zone and pushed towards the west coast of North America or the windward shores of the Hawaiian Islands. However, the bulk of the material would eventually accumulate in areas of subtropical convergence associated with the North Pacific Subtropical and Subpolar gyres, adding significantly to the total mass of debris contained in the "Great Pacific Garbage Patch".

The Government of Japan and Kyoto University researchers have conducted simulations of JTMD drift and transport using the Japan Meteorological Research Institute (MRI) Multivariate Ocean Variational Estimation system (MOVE; Usui et al., 2006). The OGCM used in the MOVE system is the eddy-resolving (1/10°) Meteorological Research Institute Community Ocean Model (MRI COM; Tsujino et al., 2010). Data assimilation and forecast experiments were performed by using the coupled atmosphere-ocean 4D-VAR data assimilation system developed by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) to reproduce the dynamic state of the seasonal to interannual time-scale global climate and to create a comprehensive reanalysis and forecast dataset of ocean currents and ocean surface winds (MOEJ 2014). Additionally, particle diffusion simulations were carried out using a particle random-walk model, the SEA-GEARN, developed at the Japan Atomic Energy Agency (JAEA). The SEA-GEARN uses ocean current data calculated by an OGCM as input variables. Wind drift current and leeway, with parameters determined for various kinds of debris by the Japan Coast Guard, also were incorporated into the experiments (MOEJ 2014). Model predictions were validated against information on sightings of debris reported by ships, as well as high-resolution image analysis based on synthetic aperture radar (SAR) satellite observations.

CONCLUSION

State of the Science

Although knowledge of large-scale ocean surface currents has existed since the Age of Sail in the 16th to 19th centuries, the increased accuracy and availability of oceanographic measurements in recent decades has helped to refine and improve surface current models.

Modeling simulations using a Lagrangian PTM driven by currents derived from ship drift data (Wakata & Sugimori, 1990) suggested regions of the world's oceans (5° x 5° global grid) where surface currents would result in areas of debris accumulation. Subsequent studies using in situ measurements of temperature, salinity, and depth to calculate geostrophic currents and surface winds to derive Ekman currents together with a PTM also suggested zones of accumulation, focusing on the North Pacific Ocean basin at a spatial resolution of approximately 1° x 1° (Ingraham & Miyahara, 1988; Kubota, 1994). These latter studies initially did not incorporate an adjustment for windage of drifting objects, although later applications of the OSCURS model (Ebbesmeyer & Ingraham, 1994, 2012; Ebbesmeyer et al., 2007) added a windage factor, used to tune model parameters so that simulations matched closely the known trajectories of debris items. Simulated release locations of virtual drifters were uniformly distributed over the model grid (Wakata & Sugimori, 1990; Kubota, 1994), targeted on known debris spill locations (e.g., Ebbesmeyer & Ingraham, 1994), or evenly spaced along a specific length of coastline (e.g., area of the Japanese coast impacted by the 2011 tsunami; Ebbesmeyer & Ingraham, 2012).

Using altimetry data to calculate geostrophic currents and scatterometry to derive wind-driven Ekman currents, PTM simulations were initialized with virtual particles distributed uniformly on each 1° x 1° grid in the North Pacific Ocean (Kubota et al., 2005). The simulations resulted in areas of accumulation corresponding roughly to the North Pacific Subtropical Convergence Zone (see Figure 3), with dense concentrations in the area of the North Pacific Subtropical High (Eastern Garbage Patch, Figure 3). Additional simulations revealed similar convergence features in mid-latitude regions of other ocean basins. Currents derived from satellite altimetry and scatterometry were also used to drive a PTM in simulations of debris drift and accumulation in the South Pacific Ocean (Martinez et al., 2009). The simulations were initiated with virtual particles homogeneously distributed on a 1/3° grid, and also with targeted releases from South America, Australia, New Zealand, and South Pacific Island nations. The results suggested that debris would be transported and concentrated in the eastern portion of the South Pacific Subtropical Gyre. Windage of drifting objects was not considered in either study.

> **"The availability of global satellite measurements represented a significant advance in our ability to model ocean surface currents and floating debris with greater accuracy."**

Besides the Lagrangian particle-tracking approaches described above, which describe the trajectories of virtual particles, statistical models have also been developed to describe the evolution of tracer density over an Eulerian grid. One such statistical model of drifter spread (Maximenko et al., 2012) used satellite-tracked drifter trajectories to calculate the probability of a drifter to move between bins of size ½° x ½° over a time step of 5 days for 10 years, starting from a condition of uniform tracer distribution. Rather than following individual trajectories of many simulated drifters over time, these kinds of statistical models describe the distribution and density of tracers throughout the grid domain at each time step. The Surface CUrrents from Diagnostic model (SCUD model) combines satellite altimetry, scatterometry, and gravity measurements to calculate surface current velocities, but with model parameters tuned to reproduce velocities derived from trajectories of standard drifters drogued at 15 meters depth (Maximenko & Hafner, 2010).

The approaches for modeling surface currents based on long-term average conditions provide a means of predicting the likely paths of marine debris, with the models often tuned, calibrated, or adjusted using information on reported sighting locations. These models are not able to represent small-scale oceanic processes, such as mesoscale eddies, nor do they model coastal processes, such as tides, freshwater inputs, and estuarine circulation. Hence, such models are not accurate in nearshore areas or in areas where mesoscale turbulence might be expected to have a large or frequent impact on overall patterns of water movement (Walter, Scandol, & Healey, 1997). The value of these models is in their ability to forecast or predict the transport of debris resulting from long-term mean circulation patterns.

In contrast to forecast models based on long-term mean currents, OGCMs are regularly updated with satellite-derived surface measurements of SSH, SST, and winds, as well as in situ vertical profile measurements of temperature, salinity, and depth, and simulate three-dimensional dynamics. OGCMs simulate the state of the ocean at a particular instant in time, based on the most recent (near real-time) measurements. Hence, in most of the examples presented in this paper, OGCMs have been used in hindcasting applications, although statistical methods can be used to produce forecasts, as pointed out previously. Besides their capacity to model the ocean in three dimensions, another advantage of OGCMs is their ability to resolve finer-scale (mesoscale) processes, with some regional models capable of 1/25° to 1/36° horizontal resolution and 20 to 30 vertical layers.

Several different OGCMs have been used as sources of information on surface currents to drive PTMs, depending on the specific application.

For the Yellow Sea, East China Sea, Japan Sea, and the Asian-Australian region studies presented earlier, surface currents were derived from the z-coordinate RIAM OCM (Yoon et al., 2010) and MOM (Hardesty & Wilcox, 2011), or the terrain-following POM (Isobe et al., 2009; Kako et al., 2010a; Kako et al., 2011; Kako et al., 2014). Simulated releases were from uniform initial distribution, or targeted releases from large cities, major rivers, or other known sources of debris (e.g., beach debris survey locations). One- and two-way PTMs were used in these studies, but the ability of the two-way PTM approach to identify statistically-significant sources provides an advantage over one-way PTMs (Isobe et al., 2009). Some of these studies incorporated adjustments for windage or investigated effects of release quantities, debris types, and buoyancy ratios on movement and beaching characteristics of debris. Horizontal spatial resolution of these models has ranged from 1/6° – 1/12°.

Surface currents provided by HYCOM on a 1/12° global grid have been used to drive PTMs in other studies that investigated different debris release quantities (Lebreton et al., 2012; Lebreton & Borrero, 2013) or windage values for various debris types (NOAA MDP, 2014c). The latter used HYCOM currents together with the GNOME pollution spill model to investigate the movement of JTMD. In this application, 1,000 simulated particles were released from each of 8 locations on the Japan coastline where tsunami wave heights were 3.5 meters or greater. In another investigation, the Japan Meteorological Institute's MRI COM provided surface currents for simulations of JTMD transport (MOEJ, 2014). Surface currents from an eddy-resolving (1/10° grid) ocean model were used together with a PTM (which also incorporates windage) to provide short-term forecasts. The results of these short-term forecasts provided initial conditions for long-term forecasts (more than 2 years) using surface currents from a coupled ocean-atmosphere model ("K7"; Sugiura et al., 2008).

Recommendations

Future research should focus on improvements to existing models, particularly nesting of high-resolution regional models within basin-scale or global models. Global and basin-scale models have suggested regions of convergence where debris is likely to be concentrated. Higher-resolution models targeting specific areas could be useful in providing insight into finer-scale patterns of debris accumulation or dispersion. The North Pacific Ocean has been the focus of many studies, and for good reason: it is the largest of the world's oceans and is located in the more highly-developed northern hemisphere. However, additional studies of other ocean basins, particularly those with a regional application, could help to shed light on local patterns of transport and fate. Approaches similar to those applied in the Yellow Sea and Japan Sea (Isobe et al., 2009; Kako et al., 2010a; Kako et al., 2011; Kako et al., 2014) using a two-way PTM to identify statistically-significant sources of debris could be useful in focusing efforts to reduce debris loadings.

Long-term historical measurements of temperature, salinity, depth, and winds from a variety of sources have

Key Outputs

- Increased accuracy and availability of oceanographic wind and current measurements has provided opportunity for significant and relatively rapid improvement in modeling.
- Improved understanding and quantification of windage has improved application of wind data to better estimate the speed and direction of debris movement, and its eventual fate.
- For long term forward-looking estimates, modeling methods that use statistical long term averages of forcing (currents & winds) or drifter data can give a good picture of debris movement based on those averages. However, they cannot anticipate fine scale temporal or spatial variations in forcing (e.g. to estimate the weather for some time in the future, looking at an almanac can tell you the general trends for a given location and timeframe, but not a specific forecast for a given day in the future).
- For short-term trajectories, modeling approaches that use detailed forecasts of currents & winds (forcing) can provide fine scale temporal and spatial projections of debris movement, but are limited by the availability and duration of those forecasts, typically only 72 hours into the future as of this writing.
- Additional research & data on the behavior and life cycles of debris over time will improve modeling. The effects of bio-fouling and degradation and the resulting change in the behavior of an object over time can have a significant impact on the object's fate and movement.
- Improved communications and information sharing between the modeling community and those collecting real-world observations of debris concentrations and behavior have the potential to help validate and even improve modeling processes, products and accuracy.

been used to calculate geostrophic and Ekman currents, and have provided a means of forecasting large-scale movement of debris. However, there are now several decades of satellite altimetry, scatterometry, gravity measurements, and drifter trajectories from which to derive surface currents and circulation patterns, as well as additional in situ measurements of temperature, salinity, and other parameters. With the development of systems to assimilate the data and to provide increased accessibility of the data online, maps of ocean surface currents can be produced with ever-higher levels of accuracy. Similarly, operational OGCMs provide near-real time depictions of ocean circulation with high resolution (1/36° for some regional models). While most of the applications in this paper have used such models to hindcast debris, the forecasting capability of these models should improve as model outputs increase and as a long-term record of these kinds of data expands. The use of coupled atmosphere-ocean models to extend forecasting ability (as in MOEJ, 2014) should be explored further.

Also needed are experiments that provide insight into the life cycle of different kinds of debris. Effects of windage, encrusting organisms, and degradation on debris behavior should be explored, and models could be refined to include these effects on different debris types. Investigations into nearshore and surf-zone dynamics of debris movement, deposition, and refloating also could help to inform marine debris models. Additionally, increased interaction and communication between modelers and individuals involved in the collection of data related to marine debris monitoring and detection could help to refine modeling efforts. Accurate data on observed debris concentrations can either validate or improve parameters and starting conditions for models, while model outputs can be helpful in focusing monitoring and detection efforts.

Global circulation debris models are all likely to give similar results in terms of convergence zones and areas of accumulation. A gap exists, however, in terms of linking with information on real-world observations of relative debris concentrations and particle densities measured in the field that could provide a source of model calibration data. A number of at-sea field data collection efforts have been undertaken, involving researchers from various organizations and institutions. Some examples include: Sea Education Association (Law et al., 2010; Law et al., 2014; Morét-Ferguson et al., 2010), Five Gyres Institute, Algalita Marine Research and Education, and related efforts (e.g., Eriksen et al., 2013; Eriksen et al., 2014). Establishing a common measurement protocol, debris definition, and data storage and retrieval system to give modelers access to systematic, coherent data sets on floating marine debris is needed.

CITED REFERENCES

Black, K.P. (1996). Lagrangian dispersal and sediment transport model POL3DD (Occasional Report No. 21). New Zealand: Department of Earth Sciences, University of Waikato.

Bleck, R., Halliwell, G. R., Jr., Wallcraft, A. J., Carroll, S., Kelly, K., & Rushing, K. (2002). Hybrid coordinate ocean model (HYCOM) user's manual: details of the numerical code. Retrieved from http://hycom.org

Blumberg, A. F., & Mellor, G. L. (1987). A description of a three-dimensional coastal ocean circulation model. In N. Heaps (Ed.), Three- Dimensional Coastal Ocean Models (208 pp.). American Geophysical Union.

Bryan, K., & Cox, M. D. (1967). A numerical investigation of the oceanic general circulation. Tellus, 19, 54-80.

Bryan, K., & Cox, M. D. (1968). A nonlinear model of an ocean driven by wind and differential heating: Part II. An analysis of the heat, vorticity, and energy balance. Journal of the Atmospheric Sciences, 25, 968-978.

Bryan, K. (1969). A numerical method for the study of the world ocean. Journal of Computational Physics, 4, 347–376.

Carson, H. S., Lamson, M. R., Nakashima, D., Toloumu, D., Hafner, J., Maximenko, N., & McDermid, K. J. (2013). Tracking the sources and sinks of local marine debris in Hawaii. Marine Environmental Research, 84, 76-83.

Chassignet, E. P., Smith, L. T., Halliwell, G. R., Jr., & Bleck, R. (2003). North Atlantic simulations with the hybrid coordinate ocean model (HYCOM): impact of the vertical coordinate choice, reference density, and thermobaricity. Journal of Physical Oceanography, 34, 2504-2526.

Chassignet, E. P., Hurlburt, H. E., Smedstad, O. M., Halliwell, G. R., Wallcraft, A. J., Metzger, E. J., Blanton, B. O., Lozano, C., Rao, D. B., Hogan, P. J., & Srinivasan, A. (2006). Generalized vertical coordinates for eddy-resolving global and coastal ocean forecasts. Oceanography, 19(1), 118-129.

Chassignet, E. P., Hurlburt, H. E., Smedstad, O. M., Halliwell, G. R., Hogan, P. J., Wallcraft, A. J., Baraille, R., & Bleck, R. (2007). The HYCOM (HYbrid Coordinate Ocean Model) data assimilative system. Journal of Marine Systems, 65, 60-83.

Coe, J. M., & Rogers, D. B., (Eds.). (1997). Marine debris: Sources, impacts and solutions. New York: Springer-Verlag.

Cummings, J.A. (2005). Operational multivariate ocean data assimilation. Quarterly Journal of the Royal Meteorological Society, 131(3), 583–3604.

Dohan, K., & Maximenko, N. (2010). Monitoring ocean currents with satellite sensors. Oceanography, 23(4), 94–103.

Dohan, K., Lagerloef, G., Bonjean, F., Centurioni, L., Cronin, M., Lee, D., Lumpkin, R., Maximenko, N., & Uchida, H. (2010). Measuring the global ocean surface circulation with satellite and in situ observations. In J. Hall, D.

E. Harrison, & D. Stammer (Eds.), Proceedings from OceanObs '09: Sustained Ocean Observations and Information for Society (Vol. 2). Venice, Italy: ESA Publication WPP-306.

Ebbesmeyer, C. C., & Ingraham, W. J. (1992). Shoe spill in the North Pacific. EOS, Transactions, American Geophysical Union, 73(34), 361-365.

Ebbesmeyer, C., Ingraham, W. J., Jr., McKinnon, R., Okubo, A., Strickland, R., Wang, D. P., & Willing, P. (1993). Bottle appeal drifts across the Pacific. EOS, Transactions, American Geophysical Union, 74(16), 193-194.

Ebbesmeyer, C. C. & Ingraham, W. J. (1994). Pacific toy spill fuels ocean current pathways research. EOS, Transactions, American Geophysical Union, 75(37), 425-430.

Ebbesmeyer, C. C., Ingraham, W. J., Jr., Royer, T. C., & Grosch, C. E. (2007). Tub toys orbit the Pacific Subarctic Gyre. EOS, Transactions, American Geophysical Union, 88(1), 1-3.

Ebbesmeyer, C. C., & Ingraham, W. J. (2012). Beachcomber's Alert [Blog posts]. Retrieved from http://beachcombersalert.blogspot.com/

Eriksen, M., Maximenko, N., Thiel, M., Cummins, A., Lattin, G., Wilson, S., Hafner, J., Zellers, A., & Rifman, S. (2013). Plastic pollution in the South Pacific subtropical gyre. Marine Pollution Bulletin, 68, 7176.

Eriksen, M., Lebreton, L. C. M., Carson, H. S., Thiel, M., Moore, C. J., Borerro, J. C., Galgani, F., Ryan, P. G., & Reisser, J. (2014). Plastic pollution in the world's oceans: More than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. PLoS ONE, 9(12), e111913. doi:10.1371/journal.pone.0111913.

Freeman, A., Zlotnicki, V., Liu, T., Holt, B., Kwok, R., Yueh, S., Vazquez, J., Siegel, D., & Lagerloef, G. (2010). Ocean measurements from space in 2025. Oceanography, 23(4), 144–161.

GDP (2011). Satellite-tracked surface drifting buoys from The Global Drifter Program. Retrieved from http://www.aoml.noaa.gov/phod/dac/

Gille, S. T., & Llewellyn Smith, S. G. (2003, April). Bathymetry and ocean circulation. Paper presented at the GEBCO Centenary Conference, Monaco. Retrieved from http://www.gebco.net/about_us/presentations_and_publications/

Glenn, S. M., & Forristall, G. Z. (1990). Observations of Gulf Stream Ring 83-E and their interpretation. Journal of Geophysical Research, 95(C8), 13043-13063.

Glenn, S. M., & Ebbesmeyer, C. C. (1993). Drifting buoy observations of a loop current anticyclonic eddy. Journal of Geophysical Research, 98(Cll), 20105-20119.

Griffies, S. M., Harrison, M. J., Pacanowski, R. C, & Rosati, A. (2004). A technical guide to MOM4, GFDL Ocean Group Technical Report no. 5. NOAA/Geophysical Fluid Dynamics Laboratory. Retrieved from: http://mdl-mom5.herokuapp.com/web

Griffies, S. M., Böning, C., Bryan, F. O., Chassignet, E. P., Gerdes, R., Hasumi, H., Hirst, A., Treguier, A. M., & Webb, D. (2000). Developments in ocean climate modelling. Ocean Modelling, 2, 123–192.

Hardesty, B. D., & Wilcox, C. (2011). Understanding the types, sources and at-sea distribution of marine debris in Australian waters: Final report to the Department of Sustainability, Environment, Water, Health, Population and Communities. Australia: Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Howell, E. A., Bograd, S. J., Morishige, C., Seki, M. P., & Polovina, J. J. (2012). On North Pacific circulation and associated marine debris concentration. Marine Pollution Bulletin, 65, 16-22.

Ingraham, W. J., Jr., & Miyahara, R. K. (1988). Ocean surface current simulations in the North Pacific Ocean and Bering Sea (OSCURS—Numerical Model) (155 pp.). NOAA Technical Memorandum, NMFS F/NWC-130.

Ingraham, W. J., Jr., & Miyara, R. K. (1989). Tuning of OSCURS numerical model to ocean surface current measurements in the Gulf of Alaska (67 pp.). NOAA Technical Memorandum, NMFS F/NWC-168.

Ingraham, W. J. (1997). Getting to know OSCURS, REFM's ocean surface current simulator: Alaska Fisheries Science Center quarterly report (14 pp.). Retrieved from http://www.afsc.noaa.gov/REFM/docs/oscurs/get_to_know.htm

Ingraham, W. J., & Ebbesmeyer, C. C. (2001). Surface current concentration of floating marine debris in the North Pacific Ocean: 12-year OSCURS model experiments. In N. McIntosh, K. Simonds, M. Donohue, C. Brammer, S. Mason, & S. Carbajal (Eds.), Proceedings from the International Marine Debris Conference: Derelict Fishing Gear and the Ocean Environment (pp. 90-115). Honolulu, Hawaii.

Isobe, A., Kako, S., Chang, P. H., & Matsuno, T. (2009). Two-way particle-tracking model for specifying sources of drifting objects: Application to the East China Sea Shelf. Journal of Atmospheric and Oceanic Technology, 26, 1672-1682.

Johnson, L. D. (2001). Navigational hazards and related public safety concerns associated with derelict fishing gear and marine debris. In N. McIntosh, K. Simonds, M. Donohue, C. Brammer, S. Mason, & S. Carbajal (Eds.), Proceedings from the International Marine Debris Conference: Derelict Fishing Gear and the Ocean Environment (pp. 67-72). Honolulu, Hawaii.

Kako, S., Isobe, A., Seino, S., & Kojima, A. (2010a). Inverse estimation of drifting-object outflows using actual observation data. Journal of Oceanography, 66, 291-297.

Kako, S., Isobe, A., Yoshioka, S., Chang, P. H., Matsuno, T., Kim, S. H., & Lee, J. S. (2010b). Technical issues in modeling surface-drifter behavior on the East China Sea Shelf. Journal of Oceanography, 66, 161-174.

Kako, S., Isobe, A., Magome, S., Hinata, H., Seino, S., & Kojima, A. (2011). Establishment of numerical beach-litter hindcast/forecast models: An application to Goto Islands, Japan. Marine Pollution Bulletin, 62, 293–302.

Kako, S., Isobe, A., Kataoka, T., & Hinata, H. (2014). A decadal prediction of the quantity of plastic marine debris littered on beaches of the East Asian marginal seas. Marine Pollution Bulletin, 81, 174–184.

Kirwan, A. D., McNally, G. J., Reyna, E., & Merrell, W. J., Jr. (1978). The near-surface circulation of the eastern North Pacific. Journal of Physical Oceanography, 8, 937-945.

Kirwan, A. D., Jr., Merrell, W. J., Jr., Lewis, J. K., Whitaker, R. E., & Legeckis, R. (1984). A model for the analysis of drifter data with an application to a warm core ring in the Gulf of Mexico. Journal of Geophysical Research, 89, 3425-3428.

Kirwan, A. D., Jr., Lewis, J. K., Indest, A. W., Reinersman, P., & Quintero, I. (1988). Observed and simulated kinematic properties of loop current rings. Journal of Geophysical Research, 93(C2), 1189-1198.

Kubota, M. (1994). A mechanism for the accumulation of floating marine debris north of Hawaii. Journal of Physical Oceanography, 24, 1059-1064.

Kubota, M., Takayama, K., & Namimoto, D. (2005). Pleading for the use of biodegradable polymers in favor of marine environments and to avoid an asbestos-like problem for the future. Applied Microbiology and Biotechnology, 67, 469–476.

Larnicol, G., Guinehut, S., Rio, M. H., Drevillon, M., Faugere, Y., & Nicolas, G. (2006). The global observed ocean products of the French Mercator project. In proceedings from the Symposium on 15 Years of Progress in Radar Altimetry. Venice, Italy: European Space Agency Special Publication SP-614.

Law, K. L., Morét-Ferguson, S. E., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., & Reddy, C. M. (2010). Plastic accumulation in the North Atlantic Subtropical Gyre. Science, 329(5996), 1185-1188.

Law, K. L., Morét-Ferguson, S. E., Goodwin, D. S., Zettler, E. R., DeForce, E., Kukulka, T., & Proskurowski, G. (2014). Distribution of surface plastic debris in the Eastern Pacific Ocean from an 11-year data set. Environmental Science and Technology, 48(9), 4732-4738.

Lebreton, L. C. M., Greer, S. D., & Borrero, J. C. (2012). Numerical modelling of floating debris in the world's oceans. Marine Pollution Bulletin, 64, 653-661.

Lebreton, L. C. M., & Borrero, J. C. (2013). Modeling the transport and accumulation floating debris generated by the 11 March 2011 Tohoku tsunami. Marine Pollution Bulletin, 66, 53-58.

Levitus, S. (1982). Climatological atlas of the world ocean (Professional Paper 13, 173 pp.). Princeton, N.J.: NOAA/ERL GFDL.

Martinez, E., Maamaatuaiahutapu, K., & Taillandier, V. (2009). Floating marine debris surface drift: Convergence and accumulation toward the South Pacific subtropical gyre. Marine Pollution Bulletin, 58, 1347–1355.

Maximenko, N., & Niiler, P. (2008). Tracking ocean debris. IPRC Climate, 8(2), 14-16.

Maximenko, N., Niiler, P., Rio, M. H., Melnichenko, O., Centurioni, L., Chambers, D., Zlotnicki, V., & Galperin, B. (2009). Mean dynamic topography of the ocean derived from satellite and drifting buoy data using three different techniques. Journal of Atmospheric and Oceanic Technology, 26, 1910-1919.

Maximenko, N., Hafner, J., & Niiler, P. (2012). Pathways of marine debris derived from trajectories of Lagrangian drifters. Marine Pollution Bulletin, 65, 51–62.

Maximenko, N., & Hafner, J. (2010). SCUD: Surface CUrrents from Diagnostic model (IPRC Technical Note No. 5, 19 pp.).

Maximenko, N., & Hafner, J. (2012, September). Monitoring marine debris from the March 11, 2011 tsunami in Japan with the diagnostic model of surface currents. Poster session presented at the 20 Years of Progress in Radar Altimetry Symposium, Venice, Italy. Retrieved from http://www.aviso.altimetry.fr/en/user-corner/science-teams/sci-teams/ostst-2012/ostst-2012-posters.html

Maximenko, N., & Niiler, P. (2008). Tracking ocean debris. IPRC Climate, 8(2), 14-16.

Meehl, G. A. (1982). Characteristics of surface current flow inferred from a global ocean current data set. Journal of Physical Oceanography, 12, 538-555.

Mio, S., Takehama, S., & Matsumura, S. (1988). Distribution and density of floating objects in the North Pacific based on 1987 sighting survey. In R . S . Shomura, & M. L. Godfrey (Eds.), Proceedings from the Second International Conference on Marine Debris. Honolulu, Hawaii: Department of Commerce NOAA Technical Memorandum NMFS, NOAA-TM-NMFS-SWFSC-154.

MOEJ. (2014). Prediction of trajectory of 3.11 tsunami debris by running simulation models (51 pp.). Ministry of the Environment, Government of Japan.

Moore, C. J., Moore, S. L., Leecaster, M. K., & Weisberg, S. B. (2001). A comparison of plastic and plankton in the North Pacific Central Gyre. Marine Pollution Bulletin, 42(12), 1297-1300.

Morét-Ferguson, S., Law, K. L., Proskurowski, G., Murphy, E. K., Peacock, E. E., & Reddy, C. M. (2010). The size, mass, and composition of plastic debris in the western North Atlantic Ocean. Marine Pollution Bulletin, 60(10), 1873-1878.

NOAA MDP. (2014a). Report on the occurrence and health effects of anthropogenic debris ingested by marine organisms (19 pp.). Silver Spring, MD: National Oceanic and Atmospheric Administration Marine Debris Program. Retrieved from http://marinedebris.noaa.gov/research-impacts/what-we-know-about-entanglement-and-ingestion

NOAA MDP. (2014b). Report on the entanglement of marine species in marine debris with an emphasis on species in the United States (28 pp.). Silver Spring, MD: National Oceanic and Atmospheric Administration Marine Debris Program. Retrieved from http://marinedebris.noaa.gov/research-impacts/what-we-know-about-entanglement-and-ingestion

NOAA MDP. (2014c). Modeled movement of the marine debris generated by the March 2011 Japan tsunami. Informational poster, National Oceanic and Atmospheric Administration Marine Debris Program. Retrieved from http://marinedebris.noaa.gov/tsunamidebris/debris_model.html

OSCAR. (2014). Near-realtime global ocean surface currents derived from satellite altimeter and scatterometer data, Ocean Surface Current Analysis – Real time (OSCAR) website. Retrieved from http://www.oscar.noaa.gov

Pichel, W. G., Churnside, J. H., Veenstra, T. S., Foley, D. G., Friedman, K. S., Brainard, R. E., Nicoll, J. B., Zheng, Q., & Clemente-Colón, P. (2007). Marine debris collects within the North Pacific Subtropical Convergence Zone. Marine Pollution Bulletin, 54, 1207-1211.

Potemra, J. T. (2012). Numerical modeling with application to tracking marine debris. Marine Pollution Bulletin, 65, 42-50.

Rochman, C. M., Hoh, E., Hentschel, B. T., & Kaye, S. (2013). Long-term field measurement of sorption of organic contaminants to five types of plastic pellets: Implications for plastic marine debris. Environmental Science and Technology, 47, 1646-1654.

Ruiz, G. M., Carlton, J. T., Grosholz, E. D., & Hines, A. H. (1997). Global invasions of marine and estuarine habitats by non-indigenous species: Mechanisms, extent, and consequences. American Zoologist, 37, 621-632.

Slutz, R. J., Lubker, S. J., Hiscox, J. D., Woodruff, S. D., Jenne, R. L., Joseph, D. H., Steurer, P. M., & Elms, J. D. (1985). Comprehensive ocean-atmosphere data set (Release 1) [268 pp.]. Boulder, CO: NOAA Environmental Research Laboratories, Climate Research Program, NTIS PB86-105723.

STAP. (2011). Marine debris as a global environmental problem: Introducing a solutions based framework focused on plastic: A scientific and technical advisory panel (STAP) information document (32 pp.). Washington, DC: United Nations Environment Programme (UNEP), Global Environment Facility.

Stewart, R. H. (2008). Introduction to physical oceanography. Texas A&M University, Department of Oceanography. Retrieved from http://oceanworld.tamu.edu/resources/ocng_textbook/PDF_files/book_pdf_files.html

Stommel, H. (1948). The westward intensification of wind-driven ocean currents. Transactions, American Geophysical Union, 29(2), 202–206.

Stommel H., & Arons, A. B. (1960). On the abyssal circulation of the world ocean—II. An idealized model of the circulation pattern and amplitude in oceanic basins. Deep-Sea Research, 6, 217–233.

Sverdrup, H.U. (1947). Wind-driven currents in a baroclinic ocean: with application to the equatorial currents of the eastern Pacific. Proceedings of the National Academy of Sciences, 33(11), 318-326.

Sudre, J., & Morrow, R. A. (2008). Global surface currents: A high-resolution product for investigating ocean dynamics. Ocean Dynamics, 58, 101–118.

Sudre, J., Maes, C., & Garcon, V. (2013). On the global estimates of geostrophic and Ekman surface currents. Limnology and Oceanography: Fluids and Environments, 3, 1-20.

Sugiura, N., Awaji, T., Masuda, S., Mochizuki, T., Toyoda, T., Miyama, T., Igarashi, H., & Ishikawa, Y. (2008). Development of a four-dimensional variational coupled data assimilation system for enhanced analysis and prediction of seasonal to interannual climate variations. Journal of Geophysical Research, 113, C10017.

Sybrandy, A. L., & Niiler, P. P. (1992). WOCE/TOGA Lagrangian drifter construction manual. WOCE Rep. 63, SIO Ref. 91/6 (58 pp.). La Jolla, California: Scripps Inst. of Oceanogr.

Tsujino, H., Motoi, T., Ishikawa, I., Hirabara, M., Nakano, H., Yamanaka, G., Yasuda, T., & Ishizaki, H. (2010). Reference manual for the Meteorological Research Institute Community Ocean Model (MRI.COM) (Version 3): Technical Reports of the MRI, 59. Tsukuba, Japan: Meteorological Research Institute.

USEPA. (2012). Pathways for invasive species introduction. Retrieved from: http://water.epa.gov/type/oceb/habitat/pathways.cfm

Usui, N., Ishizaki, S., Fujii, Y., Tsujino, H., Yasuda, T., & Kamachi, M. (2006). Meteorological Research Institute multivariate ocean variational estimation (MOVE) system: Some early results. Advances in Space Research, 37, 806-822.

Van, A., Rochman, C. M., Flores, E. M., Hill, K. L., Vargas, E., Vargas, S. A., & Hoh, E. (2011). Persistent organic pollutants in plastic marine debris found on beaches in San Diego, California. Chemosphere, 86, 258–263.

Veneziani, M., Edwards, C. A., Doyle, J. D., & Foley, D. (2009). A central California coastal ocean modeling study: 1. Forward model and the influence of realistic versus climatological forcing. Journal of Geophysical Research, 114, C04015.

Wakata, Y., & Sugimori, Y. (1990). Lagrangian motions and global density distributions of floating matter in the ocean simulated using shipdrift data. Journal of Physical Oceanography, 20, 125-138.

Wallcraft, A., Carroll, S. N., Kelly, K. A., & Rushing, K. V. (2003). Hybrid Coordinate Ocean Model (HYCOM) Version 2.1 – User's Guide. Retrieved from https://hycom.org

Walter, E. E., Scandol, J.P., & Healey, M.C. (1997). A reappraisal of the ocean migration patterns of Fraser River sockeye salmon (Oncorhynchus nerka) by individual-based modelling. Canadian Journal of Fisheries and Aquatic Sciences, 54, 847-858.

Welander, P. (1959). On the vertically integrated mass transport in the oceans. In B. Bolin (Ed.), The atmosphere and the sea In motion: Scientific contributions to the Rossby memorial volume (pp. 95-101). New York: Rockefeller Institute Press.

WOA. (2013). Boyer, T., & Mishonov, A. (Ed. & Technical Ed.). World Ocean Atlas 2013 Product Documentation (14 pp.). 14 pp.

Wyrtki, K. (1961). The thermohaline circulation in relation to the general circulation in the oceans. Deep-Sea Research, 8(1), 39-64.

Yoon, J. H., Kawano, S., & Igawa, S. (2010). Modeling of marine litter drift and beaching in the Japan Sea. Marine Pollution Bulletin, 60, 448–463.

Zelenke, B., O'Connor, C., Barker, C., Beegle-Krause, C. J., & Eclipse, L. (Eds.). (2012). General NOAA Operational Modeling Environment (GNOME) technical documentation (105 pp.). U.S. Dept. of Commerce, NOAA Technical Memorandum NOS OR&R 40. Seattle, WA: Emergency Response Division, NOAA. Retrieved from http://response.restoration.noaa.gov/gnome_manual

GLOSSARY

AVISO - Archiving, Validation and Interpretation of Satellite Oceanographic data. Aviso distributes satellite altimetry data from Topex/Poseidon, Jason-1, ERS-1 and ERS-2, EnviSat, and Doris precise orbit determination and positioning products.

Coriolis effect - Apparent force that must be included if Newton's laws of motion are to be used in a rotating system. First described by Gustave Gaspard Coriolis (1792–1843) in 1835, the force acts to the right of the direction of body motion for counterclockwise rotation and to the left for clockwise rotation. On Earth, an object that moves along a north-south path, or longitudinal line, will be apparently deflected to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. The deflection is related to the motion of the object, the motion of the Earth, and latitude.

Ekman flow - The Ekman spiral, named after Swedish scientist Vagn Walfrid Ekman (1874-1954) who first theorized it in 1902, is a consequence of the Coriolis effect. When surface water molecules move by the force of the wind, they drag deeper layers of water molecules with them. Each layer of water molecules is moved by friction from the shallower layer, and each deeper layer moves more slowly than the layer above it, until the movement ceases at a depth of about 100 meters (330 feet). Like the surface water, however, the deeper water is deflected by the Coriolis effect—to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. As a result, each successively deeper layer of water moves more slowly to the right or left, creating a spiral effect. Because the deeper layers of water move more slowly than the shallower layers, they tend to "twist around" and flow opposite to the surface current.

ERS-1/2 - European Remote Sensing satellites (ERS-1, ERS-2).

Eulerian-Lagrangian - In fluid dynamics the Eulerian-Lagrangian specification of the flow field is a way of looking at fluid (or particle) motion. In the Eulerian framework, velocities of the flow are given at fixed points in space as time varies (this can be visualized as measuring the flow of a river from a fixed location on the riverbank). In the Lagrangian framework, the observer follows an individual fluid parcel as it moves through space and time (this can be visualized as sitting in a boat and drifting down a river).

Geostrophic flow - The horizontal movement of surface water arising from a balance between the pressure gradient force and the Coriolis force.

GNOME - General NOAA Operational Modeling Environment. GNOME is an interactive environmental simulation system designed for the rapid modeling of pollutant/particle trajectories in the marine environment.

Gyre - Component of a large system of circular ocean currents formed by global wind patterns and forces created by Earth's rotation. There are five major ocean gyres: North Atlantic, South Atlantic, Indian, North Pacific, and South Pacific.

Hindcast - A way of testing a mathematical model. Known or closely estimated inputs for past events are entered into the model to see how well the output matches the known results.

HYCOM - HYbrid Coordinate Ocean Model. An eddy-resolving numerical Ocean General Circulation Model (OGCM*).

Jason-1/2 – NASA's altimetry satellites, used to measure sea surface height. Jason-1 and Jason-2 are the successors to TOPEX/POSEIDON.

JTMD - Japan Tsunami Marine Debris.

OCGM - Ocean General Circulation Model.

OSCAR - Ocean Surface Current Analysis - Real time. A collaborative project to derive ocean surface currents from satellite altimeter and scatterometer data.

OSCURS - Ocean Surface CURrent Simulations.

PTM - Particle Tracking Model.

QuikSCAT/SeaWinds - NASA's Quick Scatterometer satellite. The SeaWinds instrument on the QuikSCAT satellite is a specialized microwave radar that measures near-surface wind speed and direction under all weather and cloud conditions over Earth's oceans.

SCUD - Surface CUrrents from Diagnostic model. A simple diagnostic model that utilizes AVISO satellite altimetry to determine geostrophic current component, and QuikSCAT ocean surface wind data to calculate the wind-driven Ekman component.

Stokes drift - The average velocity of a particle floating at the ocean surface, caused by wave motion. A particle on the surface experiences a net Stokes drift velocity in the direction of wave propagation.

TOPEX/POSEIDON - A joint satellite altimetry mission between NASA, the U.S. space agency, and CNES, the French space agency, to measure sea surface height (i.e., map the ocean surface topography).

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