LOCATE: Prediction of plastic hotspots in coastal regions using numerical simulations in a coupled system

Ivan Hernandez
Laboratorio de Ingeniería Marítima. Departamento de Ingeniería Civil y Ambiental

José María Alsina Torrent
Departament d'Enginyeria Gràfica i de Disseny

Resumen

Los mecanismos de transporte de basura marina flotante en zonas costeras no se conocen bien, y su seguimiento con modelos numéricos es complejo debido a la geometría, procesos hidrodinámicos y la influencia de los procesos costeros, con estos últimos siendo especialmente complicados de incorporar. La herramienta LOCATE fue desarrollada para simular el movimiento y la acumulación de partículas de plástico en zonas costeras, usando mallas anidadas de diferentes resoluciones y escalas espaciales (2,5 km, 350 m y 70 m) para tener en cuenta los procesos costeros. La herramienta LOCATE acopla datos hidrodinámicos eulerianos con un modelo lagrangiano, requiriendo configuración y optimización para un funcionamiento adecuado. El modelo ha sido aplicado a la costa de Barcelona donde la geometría de costa y procesos costeros pueden actuar como acumuladores de basura y las concentraciones encontradas son comparables a otras zonas altamente contaminadas.

Abstract

Transport mechanisms of floating marine litter (FML) in coastal zones are poorly understood. Tracking FML dispersion with numerical models is complex due to the geometry, hydrodynamic processes and the influence of coastal processes, the latter being especially challenging to incorporate. The LOCATE tool was developed to simulate the motion and accumulation of plastic particles in coastal areas, using nested grids of varying spatial scales and resolutions (2.5 km, 350 m and 70 m) to account for coastal processes. LOCATE couples Eulerian hydrodynamic data with a Lagrangian particle solver, thus requiring configuration and optimization. As proof of concept, the model has been applied to the Barcelona coastline where the coastal geometry and processes can behave as marine litter traps and concentrations are comparable to some other heavily polluted areas.

1. Introduction

Coastal regions can be heavily impacted by the accumulation of marine litter, affecting ecological resources such as aquatic and terrestrial coastal zone ecosystems, social activities such as recreation and sports and general wellbeing, or economic assets such as tourism and fisheries (Browne et al., 2015). Land-based sources of marine litter such as river discharges and other waterways such as storm and wastewater, are thought to be responsible for the marine litter arriving to coastal zones. Once in the coastal region marine debris may accumulate, return to the emerging beach or move towards the open sea to oceanic accumulation regions (gyres). Although mesoscale circulation transport mechanisms in the open ocean are relatively well known, the motion of plastic particles in coastal regions, beaching, and accumulation or exchange with the open sea are largely unknown (van Sebille et al., 2020).

Coastal transport processes occur in a narrow spatial region close to the shoreline roughly between 50 to 600m, depending on wave energy and local bathymetry, however, they can be very energetic. Most Lagrangian models of plastic particles do not resolve at these scales or use hydrodynamic inputs that do not consider coastal transport processes complexities (van Sebille et al., 2020). Additionally, the longevity of plastic in the environment and relatively high buoyancy of plastic particles, residence times in coastal environments can be large, potentially travelling long distances (Maximenko, et al., 2012). As a consequence, coastal numerical approaches that focus on small scales with a high spatial discretisation but small spatial domain will experience plastic particles moving outside of the domain boundaries relatively fast especially in energetic conditions.

In the case of the coastal areas of the city of Barcelona the presence of marine litter is well known among the beach users, which has become a frequent observation in many other areas across the world. Recent research, however, has found plastic concentrations in the Barcelona coastal region to be of similar magnitudes to the accumulation regions such as the Pacific and Atlantic gyres. A constant and high marine litter exchange has been suggested between the open sea and coastal regions, and between the emerging beach and the aquatic coastal zone (Sanchez-Vidal et al., 2021). Entry processes such as river discharge, stormwaters, direct release and transport mechanisms such as littoral drift, wave induced currents and particle beaching during storm conditions are considered responsible for high concentrations of marine litter in the region, illustrating that although there is clear evidence of the magnitude of the problem, the accumulation and transport mechanisms are largely unknown in coastal waters.

2. Method

2.1 Hydrodynamic data simulations

The LOCATE model is built by coupling Eulerian hydrodynamic information and the Lagrangian simulation of virtual particles using the hydrodynamic information, thus requiring that the two different submodels be configured and optimised to obtain optimal particle dispersion predictions. Coastal numerical simulations require high spatial coverages to simulate particle exchange between regions and high spatial resolution close to the coastlines to solve coastal processes. These requirements are met with the use of nested simulations which is one of the novel features of LOCATE.

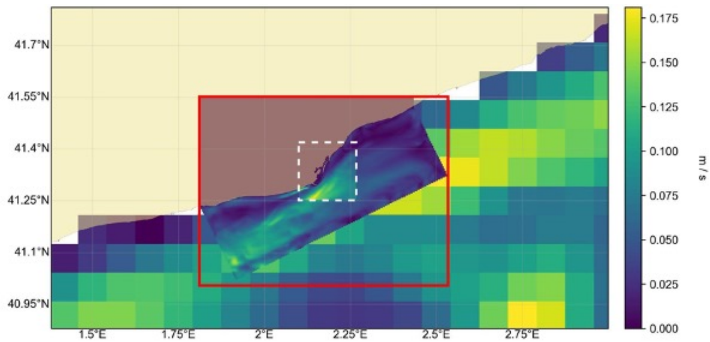

Figure 1. Overall current velocity map in nested hydrodynamic grids showing the coastal grid nested inside the regional domain (red rectangle), and the harbour grid nested inside the coastal grid (inner white dashed rectangle).

Regional Eulerian hydrodynamic simulations are obtained from Copernicus Marine Environment Monitoring Service (CMEMS) products whereas coastal hydrodynamic simulations use the open source Coupled Regional Modeling System (COAWST) system

(CMEMS, 2020; Warner, et al., 2010). The Lagrangian solver uses Probably a Really Efficient Lagrangian Simulator OceanParcels (OceanParcels), an open source model (van Sebille, 2020). Nested grids of different spatial scales (small for coastal and large for regional within the same domain) are used with different spatial resolution covering relatively large areas around the coastline with lower spatial resolution nested to smaller grid subsections with higher resolution at the coastline. The grid domains used are:

- Regional domain with a spatial grid size of 2500 m using hydrodynamic data obtained from CMEMS Iberia Biscay Irish – Monitoring Forecasting Centre (IBI MFC).
- Coastal domain with a spatial resolution of 350 m with inputs obtained from the COAWST model scheme which is nested into the regional domain (CMEMS IBI-MFC) and forced by metocean forcing.
- Harbour domain with a typical resolution of 70 m using model inputs obtained from the COAWST model scheme, nested into the coastal domain and forced by metocean forcing.

2.2 Lagrangian particle simulations

The open source numerical model OceanParcels was adapted to work at a regional coastal scale using the hydrodynamic outputs described above. OceanParcels is a Lagrangian model that allows user customisation of the different Python tools available therein to produce simulations of virtual plastic particle movement in space and time. The fundamental concept behind Parcels and any Lagrangian analysis is to integrate the advection equation (van Sebille et al., 2018):

$$\frac{dx}{dt} = u(x, t)$$

where x is the three-dimensional position of a virtual plastic particle in space, t is the time and $u(x,t)$ is the three-dimensional Eulerian flow velocity field. $u(x,t)$ incorporates the net current velocity and a wave induced drift. In Lagrangian particle simulations, diffusive processes can be modelled as a stochastic, random displacement of particle positions as a function of the local eddy diffusivity (van Sebille et al., 2018).

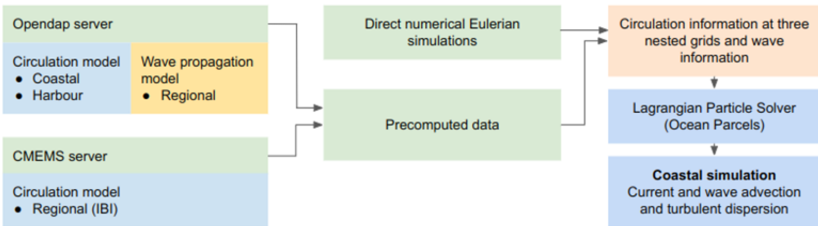

Figure 2. Schematic representation of the coupled LOCATE plastic dispersion model components.

2.3. Study domain and simulation parameters

The simulations were performed focused on a region close to the Barcelona city located around 41.81ºN and 40.88ºS, and 1.38ºW and 3ºE. Particles that moved out of the specified boundary (exported) were tagged with an 'out of bounds' particle variable and subsequently deleted from the domain, recording the last known location coordinates and timestamp. For subsequent analysis the coastline was demarcated into 16 zones to register particle beaching. Zones on land were based on current municipal demarcations or prominent features, such as port areas. The simulation period was of

260 days (01-02-2017 to 19-10-2017) with the end of the simulation period being determined by a limitation in data availability for the coastal and harbour domains. The release of particles was based on linearly interpolated observational data provided by Schirinzi, et al., 2020. To determine the efficacy of using nested domain grids the main simulation was duplicated, using the same parameters but without using nested domains, using instead only the regional domain (IBI).

2.4. Particle distance to shore

Particle distance to shore is not natively included in OceanParcels, however, its interpolation capabilities were used to calculate particle distance in real-time during a simulation based on high resolution data of the Catalan coastline available online as a linestring in a shapefile format not including islands or islets, using UTM-31N with Datum ETRS89 as the cartographic reference system using a scale of 1:50000. The minimum distance between each node in each grid and each point in the linestring was calculated using Python tools and data were saved in the same format and with the same dimensions as the hydrodynamic data.

2.5 Stokes drift and diffusion

In LOCATE a Stokes drift module is modelled using hydrodynamic data from the wave propagation model. A diffusion parameter (kh) is added to the model as a constant field for the zonal and meridional component, using a spherical mesh. For all simulations described herein the kh value is 10. When using a constant diffusion parameter, when the advective velocity is zero, particles that are located in land cells will keep moving due to pure stochastic movement from diffusion. To counter this, however, the beaching module removes the particle when it crosses the land-water boundary.

2.6 Particle beaching parameters

A sensitivity analysis to determine the parameters with which to define beaching was carried out using five different scenarios. The sensitivity analysis was performed in two parts. The first part used the two release points from the Llobregat and Besòs rivers used in the main simulation. The second part was a homogeneous particle release that used release points corresponding to the 152 nodes (out of 240 for the whole domain) on the regional domain that were on sea. In both cases, at each release point, five particles were released every hour for the period 01/03/2017 00:00:00 to 31/03/2017 23:00:00, a total of 3,720 particles from each point. In the first scenario of the sensitivity analysis there were 7,240 particles released per test, in the second scenario there were a total of 565,440 particles released per test. Scenario 1 defines beaching when a particle has a velocity close to 0 (1e-16) and as thus is considered stationary. Scenario 2 considers a particle to be beached when it physically crosses the land-water boundary, thus when distance to land is <= 0 m.

3. Results

Markers in Figure 3 represent particle release points, with a triangle up marker representing the Llobregat river, a triangle down marker representing the Besòs river, and the plus marker representing nodes on the regional domain for the homogeneous particle release tests.

Beaching rates of the tests of the homogeneous particle release as a control were substantially lower than when released from two points by the Llobregat and Besòs river mouths (87 % to 98 %). Test 1 shows over three times higher residency time than test 2 for release points on the river mouths. This difference is a little over 1.5 times between test 3 and 4 when the particle release was homogeneous. Going forward scenario 2 was selected as the beaching parameter for subsequent simulations.

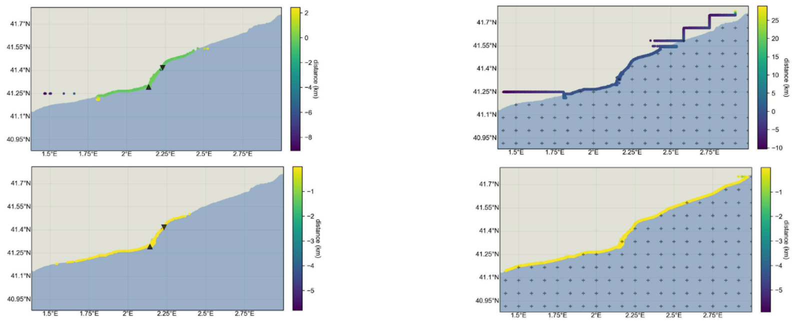

Figure 3. Locations of beached particles for beaching sensitivity tests for all the beaching scenarios with the release points included. Top-left: scenario 1, test 1. Top-right: scenario 2, test 4. Bottom-left; scenario 1, test 3. Bottom-right: scenario 2, test 4.

Test	Scenario	Release points	Beachin g %	Residence time (h)	Residence time SEM	Trajectory (km)	Trajectory SEM
1	1	2	87.22	3.25	0.79	3.79	0.98
2	2	2	89.72	1.00	0.65	1.20	0.80
3	1	152	15.58	141.50	0.44	174.38	0.55
4	2	152	19.30	89.67	0.39	111.56	0.48

Table 1. Beaching amount, median particle residence time and median particle trajectory with standard errors (SEM).

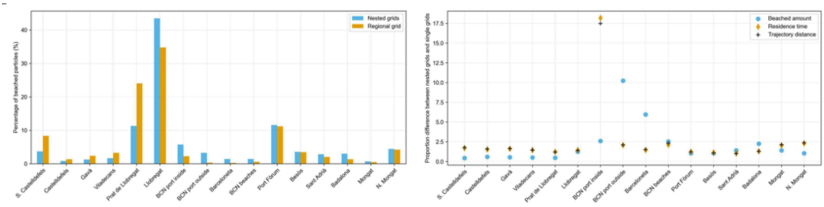

Figure 4a. Beaching amounts per demarcated zone as a percentage of the total amount of beached particles per simulation.
Figure 4b. Differences between the nested grids and regional grid only for beaching amount, residence time and trajectory distance.

There were a total of 552,480 particles simulated over the entire 260 day period. The overall beached amount for the simulation using nested grids was of 91.5 % (8.5 % exported particles), and for the simulation using a single regional grid was of 95.8 % (4.2 % exported particles). There are marked differences within some demarcated zones as seen in Fig 4 with the most notable ones being in the Llobregat river mouth with the nested grid simulation showing 8.8 % more beached particles, whereas the area adjacent to the south, Prat de Llobregat, had 12.7 % more particles from the regional only simulation.

As seen in Figure 4b the amount of beaching is over 10 times higher with the nested grid simulation on the outside of the port area, and 2.5 times higher inside the port area. Barceloneta beach also saw over 6 times as many beached particles with the nested grid simulations and the other city beaches over 2.5 times as many beached particles. While these proportions may seem high, it is worth noting that the amount of beached particles in these areas is lower than other areas such as those around the Llobregat river, where the sizable majority can be found. Residence time and trajectory distance are consistently higher for the nested simulation with the inside of the port area registering the highest proportion of over 18 times higher values.

4. Discussion

One of the main limitations of predicting plastic dispersion and transport in coastal regions is the time and spatial resolution of the hydrodynamic input data., with the main difficulty being the ability to obtain a higher resolution coastal output incorporating coastal processes. Coarser resolutions may underestimate along-shore and cross-shore fluxes and displacements as well as not offering an accurate representation of the coastal debris transport processes, while higher resolutions (< 100 m) open up transport pathways that allow for rapid alongshore and vertical fluxes (Dauhajre, McWilliams and Renault, 2019, van Sebille et al., 2020). The transport of plastic particles in coastal environments is largely influenced by wave-induced motions. Waves in coastal regions are highly non-linear as a consequence of wave-topography interaction. Depth-induced wave breaking plays an important role in the direct plastic motion (Deike et al., 2017) and indirectly in the induced mean motions (Svendsen, 1984). In a previous LOCATE-report a validation of the wave simulations for two time periods (May-June 2019 and January-February 2020) with field and satellite derived information was presented, showing reasonable agreement between numerical simulations and satellite derived wave height, improving importantly in the coastal domain with respect to the regional domain (Alsina et al., 2020).

Wave-induced Stokes drift is included in LOCATE with data from the wave propagation model although in coastal regions the role of Stokes drift on the dispersal of marine debris is not yet fully understood. Stokes drift is widely acknowledged to be one of the key components of many simulations of the drift of floating marine debris, with some studies showing possible overestimation of residence time if Stokes drift is not taken into account, as well as a reduction in beached amounts by 6-7 % (van Sebille, et al., 2020; Bosi, et al., 2021; Onink, et al., 2021).

The beaching sensitivity tests did not show marked differences between the different beaching scenarios within the particle release groups, although as expected beaching amounts were much lower in the homogeneous release tests corresponding to the regional domain nodes. Differences were more pronounced, however, when looking at particle residence time at sea and trajectory distance, which tend to be proportionally in tandem. Defining beaching using current velocity alone seems to cause an overestimation of residence time. One possible reason could be that particles close to the shoreline travel greater distances because of the dependency on the resolution of the grids, with the higher standard errors indicating a greater variability. The coarseness of the regional domain can be seen where no nesting of hydrodynamic data occurs, such as in the northern and southern parts of the domain away from the Barcelona port area on the top left map of Figure 3. This is less evident where the resolution is higher, such as areas close to the harbour, where the coastal and harbour grids apply yet there is still a jagged beaching pattern on the coastline in accordance with their respective resolutions on closer inspection. Defining beaching parameters has yet to be agreed between studies, with one recent global scale study having used a temporal and a spatial factor (a particle within 10 km of the shore for a 24 hour time period), although such studies rely on coarse resolution grids to determine the land-water boundary, and the scales of such studies may not be applicable to smaller scale coastal domains (Onink, et al., 2021). Using the interpolation capabilities of OceanParcels to calculate real-time distance of a particle to shore removes the limitation of the resolution of the hydrodynamic grids.

Recent modelling of marine debris in the Mediterranean Sea has identified the Catalan coast as one of the most polluted where the energetic North Current weakens resulting in debris being trapped in the vicinity (Liubartseva, et al., 2018). Further anthropogenic pressures on the study domain are also sustained from well known land-based litter inputs such as the Llobregat and Besòs rivers. The interpolation of non-continuous observational data may overestimate the actual amount of litter influx into the sea, however, the absence of data on some dates gives confidence that interpolating the observations can be reliable given that peaks for the Llobregat river followed seasonal events whereas the Besòs river did not follow such trends or pronounced variations (Schirinzi, et al., 2020).

Similarly to the beaching sensitivity tests, running a simulation using nested grids versus only the regional grid did not result in large differences in the beaching amount, with a little over 4 % difference. When analysing beaching amounts by demarcated zone, differences can be found south of the Llobregat release point. These zones displayed approximately half the beaching amount with the nested grid simulation than the regional grid only. Areas close to and adjacent to the port area displayed the opposite trend, with the external port area registering up to 10 times more beached particles from the nested grid simulation than the regional grid only which could be explained given the barrier between the inside and outside port areas. Beaching of virtual particles especially at small spatial scales such as coastal environments is still poorly understood and largely unexplored (Hinata, et al., 2017).

The increased residence time and trajectory distance inside the port area when using the nested grids could be due to the harbour area being resolved using the high resolution harbour grid, the limitation of the entry and exit point with the port having a narrow opening of approximately 560 m and the large perimeter of the shoreline inside the port area. In all zones, however, the residence time and trajectory distance was higher when using nested grids since all of the demarcated zones were covered (even in a small part south of Castelldefels and north of Mongat) by the coastal grid.

5. Conclusion

An open source floating marine plastic dispersion model which could be extrapolated to other coastal regions has been presented. The LOCATE model focuses on the dispersion of floating marine debris mainly in coastal waters and in the continental shelf region close to the coastline, studying the plastic litter exchange from coastal to offshore regions. While there are some shortcomings when simulating at coastal spatial scales, these can be overcome to some degree by nesting grids where possible, especially in areas of interest, such as the Barcelona city area. Beaching rates may not experience major differences when using nested or a regional only hydrodynamic grid overall, however, residence times and trajectory distances are affected by the higher resolutions of the smaller spatial scale grids. The motion of plastic particles reflects a complex transport pattern influenced by the combined influence of waves, current and the coastline orientation. The detailed influence of wave energy, wave incidence, current intensity, coastline orientation with respect to the wave incidence on particle beaching and particle export to open areas has been studied. Future work could include using a fully coupled wave-current interaction model where wave-induced currents are accounted for, or incorporating beach resolution hydrodynamic domains resolving down to 23 m which is currently being developed by the UPC.

Acknowlegment

The present study has been carried out in the framework of the TRACE (Tools for a better management of marine litter in coastal environments to accelerate the tRAnsition to a Circular plastic Economy) project. TRACE, TED2021-130515B-I00 funded by the MCIN/AEI/10.13039/501100011033 and the European Union within the "NextGenerationEU"/PRTR.

References

Alsina, J. M., Liste, M., Mestres, M., Samper, Y., et al. (2020). *Coupling nearshore hydrodynamic models and satellite derived hydrodynamic information. A case study in the Catalan coast* (LOCATE project report).

Bosi, S., Broström, G., & Roquet, F. (2021). The Role of Stokes Drift in the Dispersal of North Atlantic Surface Marine Debris. *Frontiers in Marine Science*, 8. https://doi.org/10.3389/fmars.2021.697430

Browne, M. A., Chapman, M. G., Thompson, R. C., Amaral Zettler, L. A., et al. (2015). Spatial and Temporal Patterns of Stranded Intertidal Marine Debris: Is There a Picture of Global Change? *Environ. Sci. Technol*. 49, 7082–7094. https://doi.org/10.1021/es5060572

CMEMS (2022). Copernicus MarineService. https://marine.copernicus.eu/

Chassignet, E. P., Xu, X., & Zavala-Romero, O. (2021). Tracking Marine Litter With a Global Ocean Model: Where Does It Go? Where Does It Come From?. *Frontiers in Marine Science*, 8(April), pp. 1–15. https://doi.org/10.3389/fmars.2021.667591

Delandmeter, P., & Van Sebille, E. (2019). The Parcels v2.0 Lagrangian framework: New field interpolation schemes. *Geoscientific Model Development*, 12(8), 3571–3584. https://doi.org/10.5194/gmd-12-3571-2019

Deike, L., Pizzo, N., & Melville, W. K. (2017). Lagrangian transport by breaking surface waves. *J. Fluid Mech*. 829, 364–391. https://doi.org/10.1017/jfm.2017.548

Hinata, H., MoriI, K., Ohno, K., Miyao, Y., et al. (2017). An estimation of the average residence times and onshore-offshore diffusivities of beached microplastics based on the population decay of tagged meso- and macrolitter. *Marine Pollution Bulletin*, 122(1–2), 17–26. https://doi.org/10.1016/j.marpolbul.2017.05.012

Liubartseva, S., Coppini, G., Lecci, R., & Clementi, E. (2018). Tracking plastics in the Mediterranean: 2D Lagrangian model. *Marine Pollution Bulletin*, 129(1), 151–162. https://doi.org/10.1016/j.marpolbul.2018.02.019

Maximenko, N., Hafner, J., & Niiler, P. (2012). Pathways of marine debris derived from trajectories of Lagrangian drifters. *Marine Pollution Bulletin*, 65(1–3), 51–62. https://doi.org/10.1016/j.marpolbul.2011.04.016

Onink, V., Jongedijk, C. E., Hoffman, M. J., Van Sebille, E., et al. (2021) . Global simulations of marine plastic transport show plastic trapping in coastal zones. E*nvironmental Research Letters*, 16(6), 1–9. https://doi.org/10.1088/1748-9326/abecbd

Puertos del Estado OPeNDAP Catalog (2022). https://opendap.puertos.es/thredds/catalog.html

Sanchez-Vidal, A. Uviedo, O., Higueras, S., Ballesteros, M., et al. (2021). Paddle surfing for science on microplastic pollution: a successful citizen science initiative. *EGU General Assembly 2021*, online, 19–30 Apr 2021, EGU21-10579, https://doi.org/10.5194/egusphere-egu21-10579

Schirinzi, G. F., Köck-Schulmeyer, M., Cabrera, M., González-Fernández, D. et al. (2020). Riverine anthropogenic litter load to the Mediterranean Sea near the metropolitan area of Barcelona, Spain. *Science of the Total Environment*, 714. https://doi.org/10.1016/j.scitotenv.2020.136807

Svendsen, I. A. (1984). Mass flux and undertow in a surf zone. *Coast. Eng*. 8, 347–365. https://doi.org/10.1016/0378-3839(84)90030-9

van Sebille, E., Aliani, S., Law, K.L., Maximenko, N., et al. (2020). The physical oceanography of the transport of floating marine debris. *Environ. Res. Lett.* 15, 023003. https://doi.org/10.1088/1748-9326/ab6d7d

van Sebille, E., Griffies, S. M., Abernathey, R., Adams, T. P., et al. (2018). Lagrangian ocean analysis: Fundamentals and practices. *Ocean Model*. 121, 49–75. https://doi.org/10.1016/j.ocemod.2017.11.008

Warner, J. C., Armstrong, B., He, R., & Zambon, J. B. (2010). Development of a Coupled Ocean-Atmosphere-Wave-Sediment Transport (COAWST) Modeling System. *Ocean Modelling*, 35(3), 230–244. https://doi.org/10.1016/j.ocemod.2010.07.010