AN OPEN-SOURCE SOFTWARE APPLICATION FOR DRIFTER TRAJECTORY PREDICTION IN THE MID-ATLANTIC BIGHT

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ABSTRACT OF THE THESIS

An Open-Source Software Application for Drifter Trajectory Prediction in the Mid-Atlantic Bight

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There are several different types of floatables in the ocean. Some of these floating particles or drifters are of high value to people and are worth using resources to track and recover, such as people, boats, or equipment. To recover a drifting particle, the rescue party would need to have some information on where the particle may be located and where it may be headed. Lots of effort in the oceanography world in recent years has gone into providing the kind of data that is invaluable for such a task. There are many ocean and atmospheric models well suited to specific regions, as well as oceanography equipment reporting data that are translated and recorded in a format people can use. Several of these data are now freely available online, and easy to access. We test HF Radar and the regional ocean model Doppio to track a surface drifter and a glider in

distress using the particle tracking framework OpenDrift. We found that HFR and Doppio do have some differences in trajectories but mostly agree in the 48-hour simulations. The tools used in this analysis are open source, and a collection of scripts is being made available for interested parties.

Acknowledgements

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The largest thanks to my wife, Carla. You helped me to choose this path and have been so supportive every step of the way. This has only been possible because of you.

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I. Introduction

The Atlantic Ocean meets one of the most densely populated regions in the US in the Mid Atlantic Bight (MAB). In 2010, 123.3 million people, or 39 percent of the nation's population lived in the coastal regions of the country, and this number is expected to see an 8% increase in 2020 [9]. This coastal population relies on the ocean for many purposes including shipping, recreation, commercial fishing, energy production and research. As the Mid Atlantic coastal ocean has such an impact on our lives on the eastern U.S. coast and beyond, much work has been done in recent years to improve our understanding of the oceanography and how that understanding can inform future research, policy, and decision-making. Efforts continue to monitor and model ocean currents to develop operational products to support the developing the Blue Economy through safety at sea and water quality initiatives. For example, the United States Coast Guard uses a tool, SAROPS (Search and Rescue Optimal Planning System) to save lives, and some of the data that is valuable in their search-and-rescue tool comes from High-Frequency Radar (HFR) [6]. Ocean current data are input to tools that can track vessels in distress and the fate of pollution or other water quality risks. Here we evaluate the use of an ocean drift tool, OpenDrift, with input from a network of HFR sites on the U.S. east coast, operational Regional Ocean Modeling System (ROMS)-based model Doppio, and surface drifter data. Through tools that combine many data sources, decision-makers can quickly utilize available ocean datasets to make more informed decisions in response to vessels adrift or directed resources to clean-up an unintended spill.

Gliders and other autonomous underwater vehicles experience the harsh environment of the sea over time and can become disabled for several reasons. These events require a fast recovery of the deployed asset. Such an event occurred on September 26, 2019 at 9:38 (GMT - 4:00), when Navy Glider 618 (ng618) stopped its mission due to a leak and underwent emergency recover procedure of inflating an internal air bladder to induce positive buoyancy, and thus became a surface drifter near the continental shelf break within the MAB. A costly piece of equipment such as this glider lost so far from shore requires a rapid response, given the high temporal and spatial variability of the surface currents in the MAB. Such a response includes securing a vessel to retrieve the glider and knowing where to send the vessel, which can change quickly in a matter of hours depending on the evolution of the surface currents. This event served as the motivation for the project described here where we customize a drifter forecasting package to take advantage of regional datasets. Since the glider became a drifter near the continental shelf break, several km from the shore, it was drifting on the edge of HFR coverage. Because this incident occurred far offshore at the edge of HFR coverage, we determined the times when HFR coverage was unavailable, and ran a drifter simulation for HFR and for Doppio during a period of good coverage (Fig. 1).

The glider was recovered just after its final GPS hit on 9/28/2019 04:53 UTC, this was a drifting period of roughly two days. We used a surface drifter as a ground truth in the study as well, which was well within HFR coverage to run more tests. The Doppio data product domain and a period of good coverage for HFR data are shown in Fig. 2, along with the track of the surface drifter.

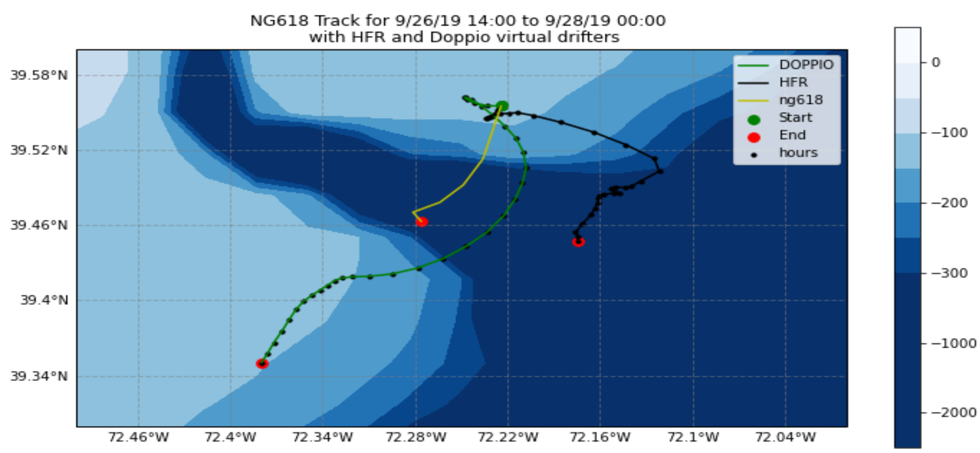


Figure 1: OpenDrift virtual drifter simulation covering the period of 9/26/2019 14:00 UTC to 9/28/2019 00:00 UTC. Actual glider track in yellow, Doppio virtual drifter in green, and HFR virtual drifter in black. Each simulation was started at the green point, the red points mark each end of track, and the black points signify each virtual drifter data point which are one hour apart.

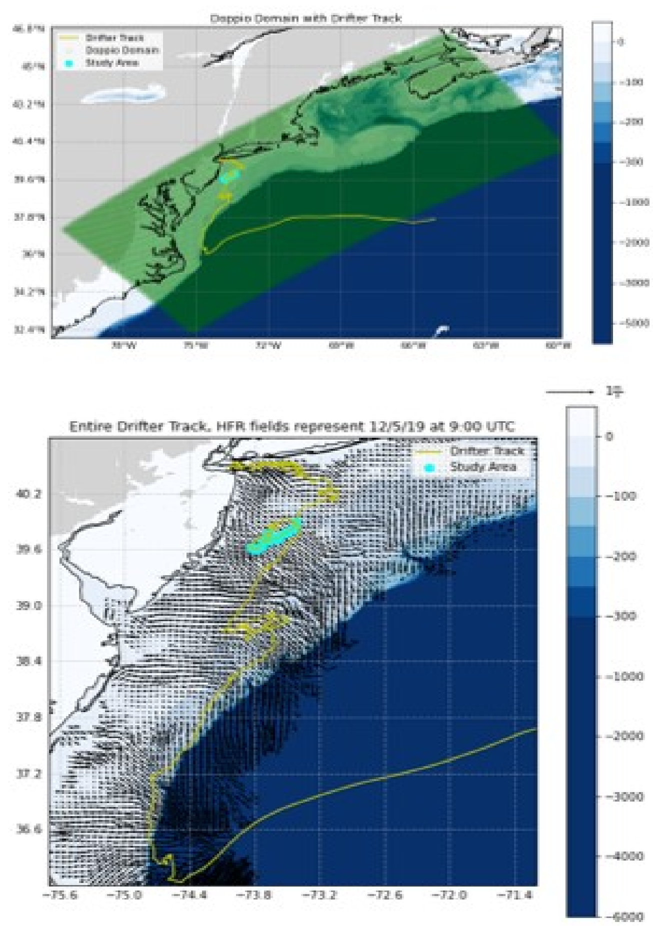


Figure 2: (Top) Doppio Domain filled in faded green. (Bottom) HFR coverage for a period of high coverage (12/5/2019 9:00 UTC). Both plots have drifter track in yellow with study area highlighted in cyan.

Mapping ocean currents at single time points can be informative to generally identify currents and frontal regions. However, this approach to visualizing and interpreting velocity data is not well suited to tracking or predicting trajectories of floating objects or particles (e.g., vessels adrift, oil spills and even people lost at sea). A time-evolving view of the current field is needed for projections of particle drift. This requires more sophisticated computer programming which can evaluate several points in time and advect and track the drifter(s) using ocean model data, HFR, drifter data, or other ocean data. An open source software package called OpenDrift, created by Knut-Frode Dagestad and Gaute Hope provides such programming utility [7].

Python and OpenDrift are completely open source and can be operated on most modern laptops. A free and easy to deploy tool that can track such floating particles using trusted data products can save precious time and resources for an emergency response such as a disabled scientific asset at sea. OpenDrift is a general framework which can ingest a wide range of forcing data to run drifter simulations. It is also highly configurable to utilize datasets which do not fit the many 'off the shelf' input data reader scripts within OpenDrift. In this work, we configured the OpenDrift tools for the unique datasets available in the MAB. We have adapted OpenDrift for use in the MAB, and written scripts which allow the user to specify longitude and latitude coordinates, number of desired virtual drifters, run time and time intervals, a hierarchy of models and data products, as well as the type of particle to be advected. Once these parameters are established, the drifter simulation runs and saves its output. The output can be used to create detailed plots of the drifter's track, as well as send the coordinates of its path to a recovery team at sea. Sections of code analyze the HFR data composition and run comparisons between HFR virtual drifter tracks, Doppio model virtual drifter tracks, and surface drifter data. These analyses test the ingestion of the Doppio model and show the type of analysis that is possible to execute in a relatively short amount of time. Stakeholders could use this tool to quickly get a detailed drifter track for a disabled vessel, piece of equipment or person drifting somewhere in the MAB. As shown here, this tool can be adapted to operate in a different region, or to analyze/validate additional models and datasets.

II. Tools Used

A. OpenDrift

OpenDrift is an open-source python package used for Lagrangian particle tracking in the ocean or atmosphere [7]. In this work I have adapted the OpenDrift system to use operationally available HFR surface current data and the assimilative model Doppio, which is available on the US East coast, and more specifically the MAB. This combination creates an easy-to-use and deploy analysis system for real time particle tracking and forecasting in the MAB. Forcing datasets of interest in the study were HFR and Doppio (hourly) dataset. Both systems have been supported and developed within the US Integrated Ocean Observing System (IOOS) Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS).

OpenDrift consists of a series of ‘models’ which are python classes emulating the physics of several drifter types. These models require certain variables to advect the seeded particles properly, such as wind in the x and y direction, surface current in the x, y and/or z direction, and stokes drift. These drifter models are advected by these forcing data which are loaded as objects called 'readers', which read in a data product that describes the ocean dynamics. To use this package, one installs the necessary components on their local machine or server and creates a python environment specific to OpenDrift. The user would then execute several commands to read data products from sources such as ocean models or High-Frequency Radar networks, then insert virtual particles on map coordinates and advect them according to the data product as well as a chosen physical model for the particle(s). There are several options available when running a simulation including number of seeded drifters, radius or spread of seeded drifters, time step per iteration, scheme of euler or runga-kutta, stokes drift on or off, current uncertainty, wind uncertainty, and several physical models with some additional options. When the options are set and it is run, the output file saves the latitudes, longitudes, times, and total drifter trajectories in a netcdf file. This output file can be used in numerous python plotting utilities to plot and analyze the data as needed. OpenDrift has its own quick-plotting methods of presenting its drifter simulations, but these methods are not as flexible as creating plots using matplotlib and similar python map tools.

In OpenDrift, seeded particles are first required to be identified as a type of particle model. The most basic model, OceanDrift, treats the seeded particles as passive tracers, which do not carry physical properties except for position, so they move with the ocean currents. OceanDrift was used in this study, as the surface drifter we were testing HFR and Doppio with is designed to move with the currents. There are other model options available depending on the studied object or substance, such as OpenOil for oil spills, Seaicedrift for ocean sea ice, ShipDrift for a disabled ship, etc. One or more readers can be added to advect the seeded particle(s). A reader in OpenDrift will usually read from a data product in the form of a THREDDS URL, netcdf file or a function. Depending on the data convention of the reader, one of the reader scripts included in the OpenDrift package may be sufficient, or it may be necessary to create a reader script to fit the data.

The reader used to read-in the HFR data is called 'reader_netCDF_CF_generic'. This is the default netcdf reader for data which is in Climate Forecast (CF) convention. The HFR data is available on a THREDDS server in a nedcdf format which is easily readable by OpenDrift. OpenDrift comes with a reader called 'reader_ROMS_native', which is designed to read-in data from ROMS output. As Doppio is a ROMS-based model, we tried to use this initially. At the time of this writing, the ROMS_native reader script is just over 550 lines, with several statements identifying data formats and defining variables. To read in the Doppio data, we needed to design a new script which uses most of the ROMS_native script but uses the naming conventions of the Doppio output, which differ from those assumed in the generic ROMS native reader. This new script was named 'reader_ROMS_DOPPIO'. A similar solution may be possible, depending on its format, for other data products that deal with ocean currents. There are several submodules, or reader scripts, which are included in OpenDrift to test and edit for different data.

B. ROMS-Based Model: Doppio

The Doppio model is an operational ROMS-based model for forecasting or nowcasting. Doppio is essentially the successor to an earlier model called ESPreSSO (Experimental System for Predicting Shelf and Slope Optics). ESPreSSO covers the MAB. Doppio was created to retain the utility of ESPreSSO while covering the MAB as well as the Gulf of Maine regions of the Atlantic [1] (Fig. 2). The data is in climate and forecast (CF) convention CF-1.4, SGRID-0.3. The grid has a 7 km resolution and 40 vertical levels. Boundary conditions are from operational global 1/12 Mercator forecasting system. The model assimilates near real-time observations of surface temperature from AVHRR, AMSR, WSAT, GeoSAT; HF Radar, along track sea surface height (Jason, CryoSAT, Altika); temperature and salinity vertical profiles from gliders, mooring and ship available through GTS, NERACOOS and ECOMON [8].

The ROMS-based regional circulation models before Doppio, like ESPreSSO, have been used for different kinds of studies like studying hurricanes, ecosystems, and tracking nutrients [1]. We chose Doppio for this study as it is a publicly available, widely trusted, data assimilative model, and has a proven pedigree of having high fidelity in the MAB.

C. High Frequency Radar (HFR) Network

The HF-Radar Network (HFRNet) acquires radial velocities of the ocean surface using Bragg scattering [2]. Currents are measured by individual sites through the HF-Radar network. There are over 40 land-based HFR sites in the MAB, and they have been used for applications such as oceanography research, offshore wind development, pollution and storm response, and search-and-rescue [5]. The radial data from overlapping radar sites is processed to produce near real-time surface current maps. The data is in convention CF-1.4, ACDD-1.3, and represents the upper 2.4 meters of ocean. Hourly radial data are processed by unweighted least squares on a 6km resolution grid of the U.S. East and Gulf Coast. The range of the radar are from a few km to 200km offshore, and they can collect data in bad weather conditions as well. There are periods when the coverage of HFR in a region can have gaps in space and time, as these systems rely on multiple HFR stations to measure a particular area, and report the data to get geometrically combined for two-dimensional surface current maps. To ensure accuracy and reliability, the data undergo quality control at various stages of processing: on-site during production of radials from raw signal voltages, upon acquisition of radial data by HFRNet, and during processing for production of surface current maps. The data were accessed via HFRNet THREDDS server hosted by Coastal Observing Research and Development Center (CORDC), Scripps Institution of Oceanography [4]:

(https://hfrnet-tds.ucsd.edu/thredds/catalog.html)

III. Methods

We tested the OpenDrift system by comparing virtual drifters created using an HFR network data product, as well as an operational model in the MAB, Doppio. we compared these virtual drifters to the data from the track of a surface drifter, or drifting buoy, 'noaa196390731-20191015T1901', made available by the National Oceanic and Atmospheric Administration (NOAA). It was released in New York Harbor in October 2019 by the St. Hubert Catholic High School for Girls and stopped transmitting in January 2020 after being pulled away from the shelf by the Gulf Stream, (Fig. 2). The drifter data is in convention CF-1.6, ACDD-1.3. The data was interpolated to 60-minute timesteps from the GPS hits. The drifter started in the New York/New Jersey Bight on October 15, 2019 at 19:00:00 and stopped transmitting January 11, 2020 at 06:00:00. The period of November 18, 2019 06:00:00 to November 22, 2019 06:00:00 was chosen to study as the drifter is well within HFR coverage. Having this data from the surface drifter gives us the ability to run a virtual drifter simulation using both HFR and Doppio and compare the two virtual drifter outputs with a real drifting object. HFR takes near real-time measurements of the surface currents, so if the HFR data product and Doppio data product are in reasonable agreement, we may feel confident using Doppio to track a particle in an area which does not have HFR coverage.

Since the motivation for the study was the tracking and rescue of ng618, the first test was the production of virtual drifter runs which start at the point the glider became a surface drifter. We produced plots of the HFR surface current velocity data to determine when shortage of coverage occurs (Fig. 3).

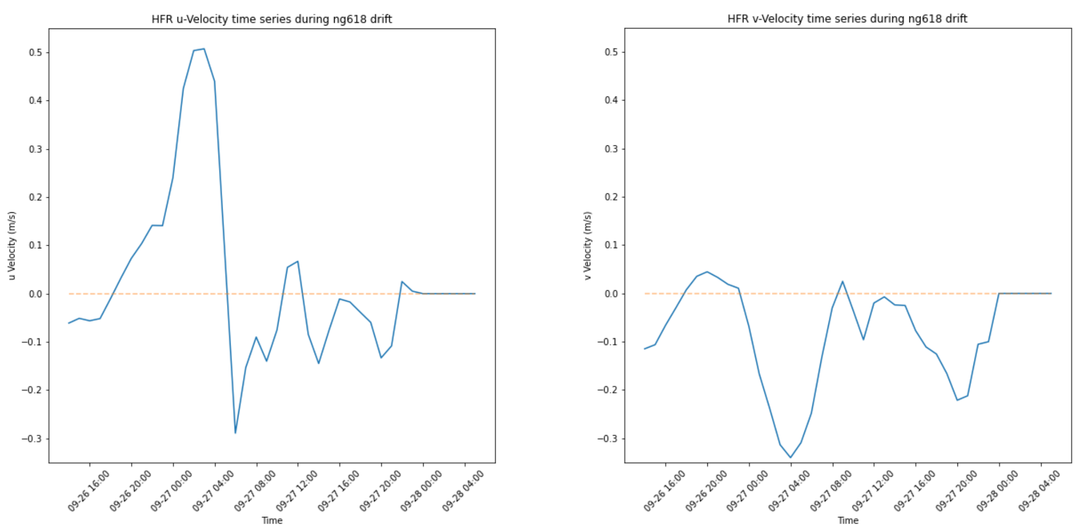


Figure 3: HFR velocity vector plots of u-velocity (top) and v-velocity (bottom). Dotted line is at 0. When the value is consistently 0, the coverage is not available at that time. The plot reveals that HFR coverage became unavailable 9/28/2019 00:00 UTC.

The plots reveal the HFR coverage shortage to be at the start of 9/28/2019 and looking into the dataset led us to confirm that the data drops 9/28/2019 00:00 UTC. Using bathymetry data provided by NOAA with a plot of ng618 and virtual drifters, we inferred that it became a drifter just near the edge of the MAB continental shelf (Fig. 1). It drifted towards the mouth of the Hudson Canyon, and this area is at the edge of HFR coverage, which can be seen in Fig. 2, south of the legend.

We used the surface drifter data as a ground-truth to test the OpenDrift software integration with HFR and Doppio data products. Using the time, longitude, and latitude coordinates of the surface drifter's starting point, we ran virtual drifters of HFR and Doppio in OpenDrift until the same ending time. To quantify the drift model performance, we calculated the separations and standard deviations of the HFR and Doppio runs from the surface drifter at every data point, which was each hour. We ran several configurations (described below) to test different drifter analysis techniques as well as some of the different features of OpenDrift available.

The first method of running the virtual drifters was the simplest: seed one virtual drifter in the exact time, longitude, and latitude as the corresponding coordinates of the surface drifter for both HFR and Doppio, set the time step to 60 minutes per data reported, and run for 48 hours. The data are saved as netcdf files and loaded into a separate script for plotting. This test produces one drifter track for HFR and one for Doppio, shown in Fig. 4.

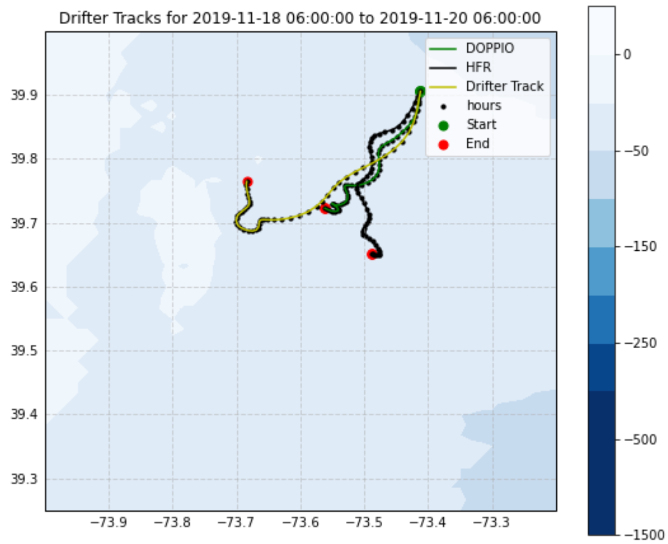


Figure 4: 48-hour virtual drifter simulations of HFR (black), Doppio (green), and surface drifter track (yellow).

Next, we seeded one virtual drifter for HFR and Doppio in a similar manner to the first method but run and reseed them at every 3-hour increment of the study, producing multiple datasets of drifters for analysis. This test produces several drifter tracks for HFR and Doppio, which start and end at different times, separated by 3-hour increments (Fig. 5). This test is more suited to closely following a single particle through time which has the luxury of giving gps hits, enabling frequent simulations.

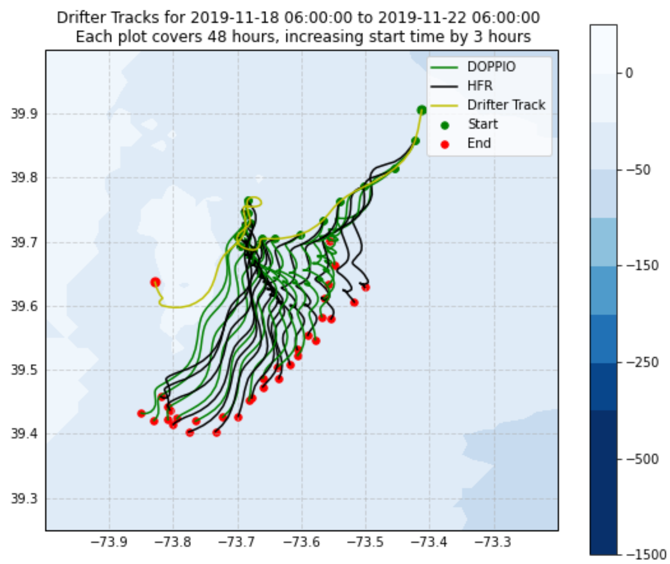


Figure 5: Multiple iterations of 48-hour virtual drifter simulations of HFR (black) and Doppio (green), surface drifter track (yellow). Each start time and corresponding end time are separated by 3 hours.

We then ran an ensemble of 50 virtual drifters for HFR and for Doppio over the duration of the test period, all starting and ending at the same time. This test produces several drifter tracks for HFR and Doppio, which all start within a 1km radius of the start point of the surface drifter, and all terminate at the same time, shown in figure 4.

We introduced an added parameter of diffusion, or current uncertainty, of 5 cm/s for the ensemble simulations and the simulations separated by 3-hour iterations. This presents a random variance in any direction at each time step of 5cm/s. Measurements made in a Coastal Ocean Dynamics Experiment (CODE) drifter reveal a range of 2 cm/s to 5 cm/s uncertainty related to the measured currents of the water, so 5 cm/s was chosen when running the OpenDrift analysis [3]. The difference of introducing this current uncertainty is illustrated in figure 5.

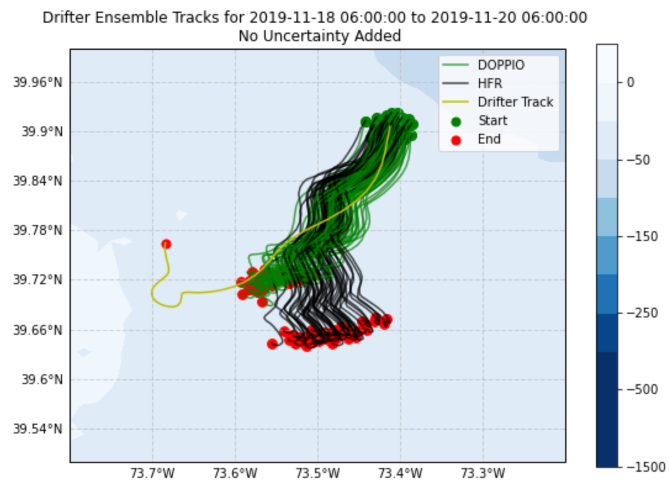


Figure 6: Ensemble of 50 virtual drifter simulations for HFR (black), 50 drifters for Doppio (green), and surface drifter track (yellow).

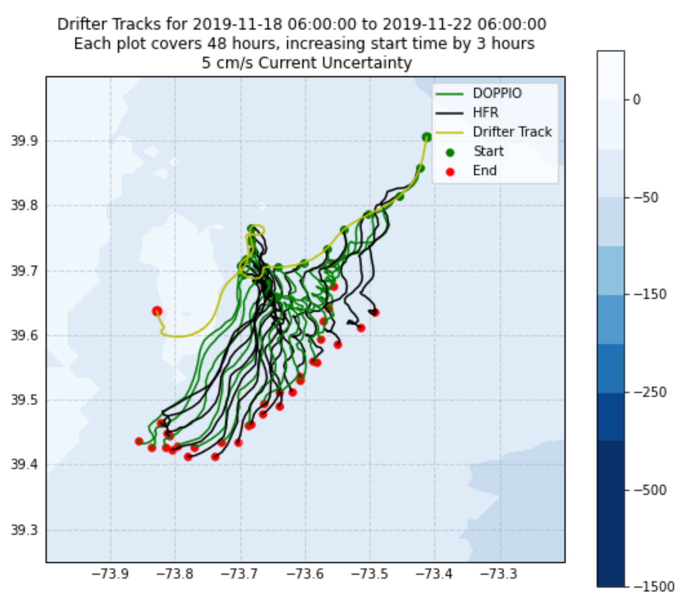


Figure 7: Multiple iterations of 48-hour virtual drifter simulations of HFR (black) and Doppio (green), surface drifter track (yellow). Each start time and corresponding end time are separated by 3 hours and include 5 cm/s added value of current uncertainty in the simulation.

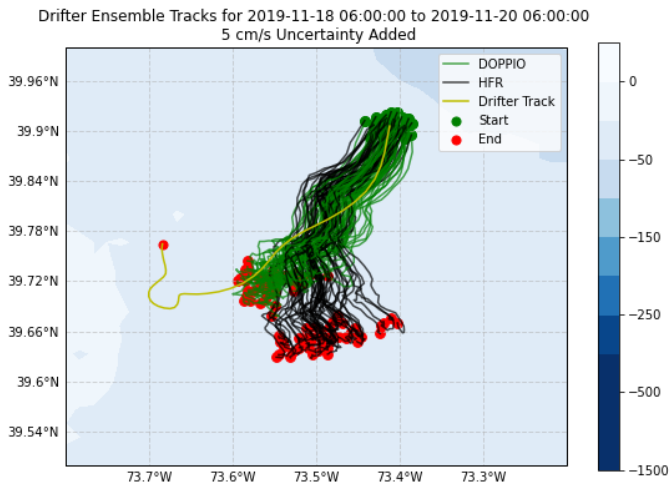


Figure 8: Ensemble of 50 virtual drifter simulations for HFR (black), 50 drifters for Doppio (green), and surface drifter track (yellow). Virtual drifters include the added current uncertainty value of 5 cm/s.

IV. Results

Plotting the output from any of the OpenDrift runs shows us qualitatively how the HFR and Doppio data products perform alongside the trajectory of the surface drifter, (e.g. Fig. 4). Using the marked hour dots on this spatial plot, we can see that the track of the surface drifter seems to be moving more rapidly than the virtual drifters, evidenced by the wider spacing between each hour dot. A more quantitative comparison can be made by calculating the distance between longitude and latitude pairs of the virtual drifter datasets from those of the surface drifter for each time step and plot the results. The standard deviation is especially useful with an ensemble of drifters with added diffusion to the run.

For the 50-drifter ensemble simulations (Fig. 9), the mean separation of both HFR and Doppio are around 13 km from the surface drifter after 24 hours. After 48 hours, Doppio's mean separation is 12.04 km, and HFR's is 21.07 km. The mean standard deviation for Doppio is 1.73 km and HFR's is 1.64 km. When adding current uncertainty to the simulations, the means are slightly changed with Doppio's mean after 48 hours being 12.26 km and HFR's 21.03 km. The mean standard deviation for Doppio is 1.9 km and HFR is 1.79 km.

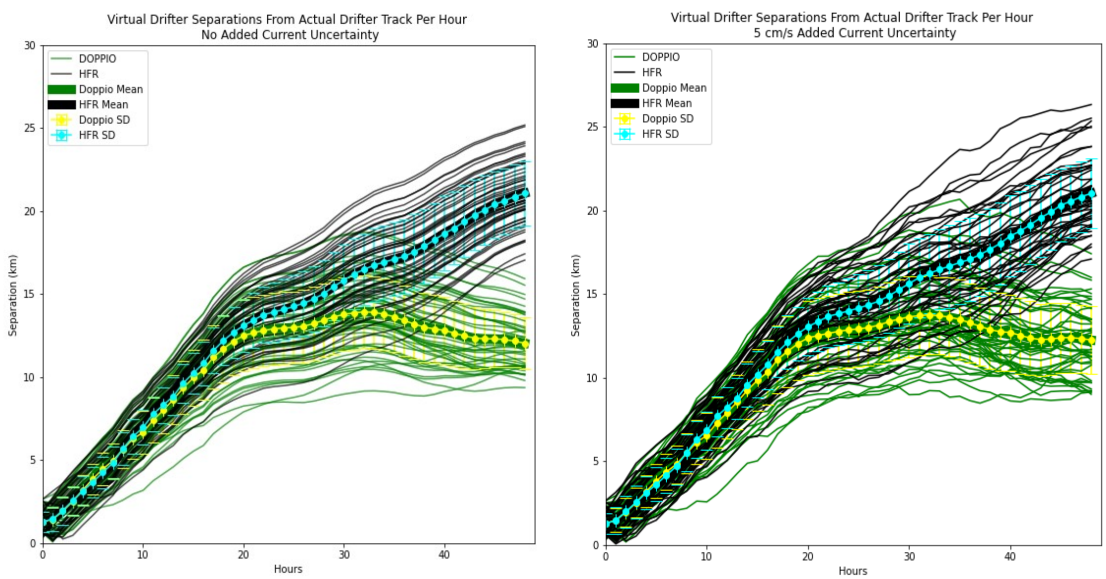
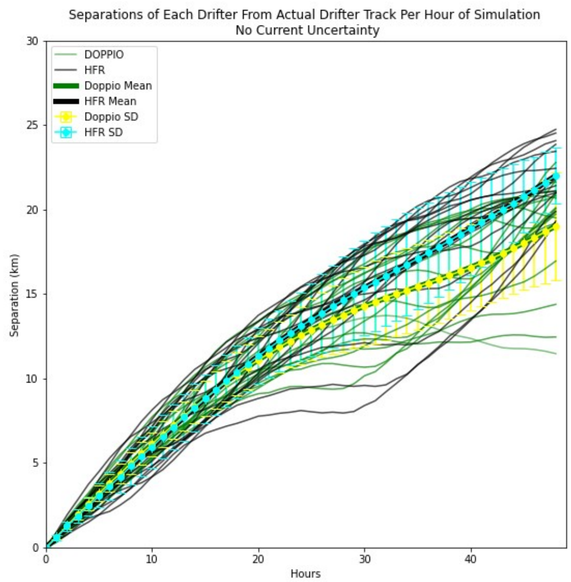


Figure 9: (Left): separations of 50 drifter ensemble simulation from surface drifter with standard settings (i.e. no current uncertainty added). (Right): separations of 50 drifter ensemble simulation from surface drifter with 5 cm/s added current uncertainty.

For the virtual drifter simulations of 48 hours beginning every 3 hours (Fig. 10), the mean separation of both HFR and Doppio are around 13 km from the surface drifter after 24 hours. After 48 hours, Doppio's mean is 19.02 km, and HFR's is 22.01 km. The mean standard deviation for Doppio is 1.67 km, and HFR's is 1.86 km. With the added current uncertainty value of 5 cm/s, Doppio's mean separation is 18.15 km, and HFR's is 21.38 km. The mean standard deviation for Doppio is 1.69 km and HFR's is 1.98 km.



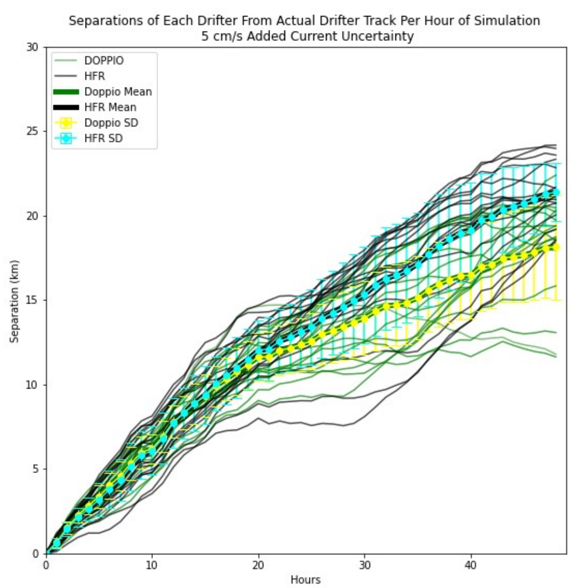


Figure 10: (Top): separations of 3-hour iteration simulations from surface drifter with standard settings (i.e. no current uncertainty added). (Bottom): separations of 3-hour iteration simulations from surface drifter with 5 cm/s added current uncertainty.

V. Conclusions

The virtual drifters produced from HFR and Doppio have been around a separation of 13km of the surface drifter track after most of the 24-hour periods in the study. Doppio's mean separation from the surface drifter ranged from 12 km to 19 km. HFR's mean separation from the surface drifter ranged from 21 km to 22km. These values of separations are higher than previously studied drifter separations which were roughly 14 km after 48 hours [6]. Doppio drifters were in close agreement with HFR drifters up to 24 hours, then diverged and performed better after 48 hours, though Doppio had a larger range of outcomes. Through these observations, we can determine that Doppio may be a good choice in the absence of HFR, to assist in tracking a floating particle in the MAB using OpenDrift. One can investigate OpenDrift models for an application that may improve results, such as oil spill, shipwreck, larvae transport, life raft, or person-in-water models. One or more readers are required to supply some or all of these variables to the seeded particles, and depending on the data convention or format of the desired reader's data product, a python script may need to be created or edited for it to work as intended.

VI. Discussion

Time spans of 48 hours were chosen for the drifter simulations, since the longer a simulation runs, the higher the chance for it to stray from the objects' true path.

An opportunity to use this tool arose when someone overturned their boat in the MAB on July 22, 2020. They made it to shore safe but reached out to request tracking the boat. Word of this was relayed to our group on August 2, 2020. We used a new series of scripts to use the particle model ShipDrift to try and predict the boat's trajectory using only one point of coordinates and over a relatively long period of time for a drifter simulation. The readers used for this work (HFR + Doppio) do not contain some variables needed to fully utilize the ShipDrift particle model, so the simulation advected the drifter using only the x and y seawater velocities. We simulated one drifter in HFR and one in Doppio, starting July 22, 2020 21:00 and ending 8/2/2020 16:00 (Fig. 11). We later learned that someone had sighted the missing boat, but only stated they sighted it "early Sunday PM" (8/2/2020 PM) and included the longitude and latitude at the time of the sighting, so we added the coordinates of the boat sighting to Fig.11.

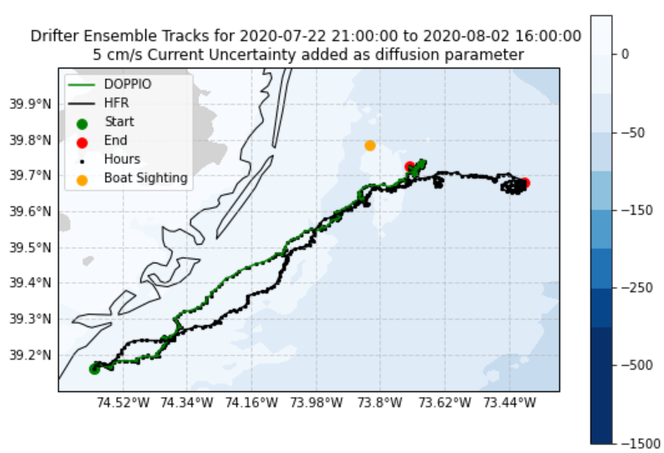


Figure 11: OpenDrift drifter simulation for overturned boat case. Doppio (green), HFR (black) and boat sighting (orange dot).

The next step for this work is to create a concise, easy-to-use and employ code which would use a generic set of models and readers and require only simple parameters be filled by the user, such as longitude, latitude, and time coordinates. The goal of this is that anyone can use it for tracking drifters without installing python and OpenDrift, and taking time to familiarize themselves with the software and create multiple scripts to be able to track their drifter.

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