ABSTRACT

Plastic debris has become an issue of ecologic concern, as studies have found that plastic, which has been accumulating in the marine environment since it became commercialized after World War II, has negative environmental effects and a wide range of biologic impacts when ingested. Determining how plastic debris enters the food web is the first step in evaluating the potential for plastic to magnify throughout the food web, eventually effecting humans. This study addresses this issue by using methodology established by Moore *et al*. (2001; 2002) and Collignon *et al.* (2012) to determine the ratios (by count and by weight) of neustonic plastic to zooplankton along the Eastern Seaboard of the US, in the Atlantic Ocean. Samples analyzed in this study were collected by SEA Education Association class C-297 Marine biodiversity and Conservation along a cruise track from St. Petersburg, FL to Woods Hole, MA, with varying distances from shore, between April 16 and May 20, 2021. Neuston tows were performed using a 333 micrometer neuston tow net, and were processed by hand.

To determine the origin of plastic recovered at sea, this study utilizes a novel approach to the identification of plastic debris source regions by using a Python-coded program (OpenDrift) to hindcast the neuston tow samples analyzed in this study to identify likely geographic locations, using oceanographic and atmospheric conditions, and Lagrangian particle trajectory modelling. This work sets the stage for future conservation work in marine plastics, to mitigate the exposure of marine organisms and the food web to the negative effects of plastics and their additives.

Neustonic Plastic Along the Eastern Seaboard: Evaluating Potential Ecologic Impacts using Zooplankton to Plastic Ratios, and Identification of Regional Source Areas Using OpenDrift Modelling

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1. INTRODUCTION

Marine plastic debris is a major concern for the environment; however, the effects and the quantification of plastic abundances are still under investigation by scientists globally. Plastics today are produced in mass quantities, and many plastic products are non-recyclable. These single-use plastics, the product of a linear economy, end up in landfills and wastewater. From there, they find their way into the terrestrial, atmospheric, and marine environments. Marine plastics have become an area of public and scientific concern, as plastic debris has been found to have negative effects on organisms: and humans rely on fisheries as a major protein source (World Wildlife Find, n.d.). To evaluate this issue, this study fills the gaps between previous studies that quantify the amount of plastic in different study regions, and those investigating effects of plastic ingestion on organisms.

Plastic has not been around very long, geologically speaking. While the Earth is 4.5 billion years old, plastic has only existed for a negligible period of that time: since the invention of Celluloid in 1869 by John Wesley Hyatt (Freinkel, 2011). The plastic industry began to evolve quickly over the following years, and exploded during World War II (Freinkel, 2011, Law, 2017). During this time, plastics were used in everything from soldiers’ combs to Teflon to parts for bombs (Freinkel, 2011). After Victory over Japan Day, plastics swiftly entered the consumer market and became commercialized (Freinkel, 2011). This quickly led to the development of single-use plastic products such as Ziploc bags, Saran Wrap, Tupperware containers, TV dinner containers, and polystyrene “Styrofoam” cups, which exploded in popularity due to the lack of need for clean-up (Freinkel, 2011; Law, 2017). While this seemed amazing at the time, and alleviated the need for many natural resources such as tortoiseshell, the effects of these plastics on our environment are now being felt, decades later.

Plastics are long, flexible molecules consisting of hydrogen and carbon atoms. While these elements are abundant in nature, the polymer chains that make-up plastic are often formulated by the processing of various monomers, which are derived from fossil fuels (Freinkel, 2011; Law 2017). Each type of plastic is treated with different chemicals for different desirable properties, affecting their color, brittleness and ductility, UV resilience, and more (Law, 2017). These chemical inclusions are called “additives” (Freinkel, 2011). Plastic polymer chains are man-made and do not have natural breakdown pathway. Thus, when exposed to the environment, their base hydrocarbon structure can persist for decades (Freinkel, 2011). Their additives, on the other hand, which give plastics their wonderful properties, readily leach into the environment (Freinkel, 2011).

In the marine environment, this longevity of plastic debris puts megafauna at risk of entanglement and drowning (Law *et al.* 2010; Law, 2017). Plastic is also ingested by fauna, leading to digestion issues (blockages and lacerations) and starvation (Law *et al.* 2010; Law, 2017). It may even provide vessels for microorganisms to invade new territories and potentially become invasive species (Law *et al.,* 2010; Law, 2017).

The risk of ingestion of microplastic particles by marine organisms is often underestimated, and presents a significant ecological impact with heretofore unknown ramifications (Law, 2017). Since plastics are durable, they have been found to get stuck in the digestive tracts of fauna often causing death (Law, 2017). Smaller particles can accumulate in an organism which then have the potential to biomagnify through the food web.

In addition to the accumulation of the plastic itself, additives contained in plastics may release toxins into the body or environment during breakdown which have been found to have possible endocrine disruption and carcinogenic effects (Godswill and Godspel, 2019). Microplastics can further break down into nanoplastics (1-1000 micro m), which are capable of travelling between cell membranes and may even interact with proteins (Holloczki and Gehrke, 2019). The concentrations of plastic in marine fauna, as well as these effects, increase in organisms at higher trophic levels. This is especially concerning for humans, as we fish down from the top of the food chain and consume top predators potentially containing the highest concentrations of plastic debris. Humans rely on seafood as a global food source (World Wildlife Fund, n.d.) so it is important to determine possible significant health impacts of plastic on the food web.

In order to evaluate the potential for plastic to bioaccumulate in marine fauna, the quantities of microplastic in comparison to the food source must be evaluated. Zooplankton, one of the main microorganism types at the base of the food web, is a major source of food for other organisms. Since zooplankton and neustonic plastics are similar in size (including microplastics of sizes less than 5 millimeters), there is potential for confusion of microplastic for zooplankton by marine fauna (Di Mauro, 2017).

While studying plastics in the marine environment, it is pertinent to consider the origin of the debris. While plastic debris research only began a few decades ago, it has been established that more plastic is produced annually and, accordingly, more plastic is entering the marine environment (Law *et al.*, 2010; Law, 2017). When comparing current and past research, it is difficult to tell whether differences in plastic to plankton ratios are due geographic differences, difference in plastic debris amounts, or even if there is an increase in marine plastic debris over time correlating with increased plastic production. When comparing plastic to zooplankton ratios, it is also important to take into account the effects of diurnal vertical migration, as zooplankton are more abundant in the neuston layer at night than during the day, resulting in a change of plastic to zooplankton ratios between night and day (Moore *et al.*, 2001).

In order to isolate the “problem regions” of plastic debris entering the marine environment, plastic debris must be traced back to its origin. Theorized major plastic debris sources include popular tourist destinations, coastal cities, marine traffic highways, and estuarine regions where the watershed and runoff enters the ocean.

2. BACKGROUND: PREVIOUS WORKS

2.1. Estimating Marine Plastic Abundance

The SEA Education Association has a large historic database for plastic samples collected at sea, which has been used in an attempt to determine plastic abundances and abundance trends in the marine environment (Law *et al.*, 2010; Wilcox, Hardesty, and Law, 2020). Initially, calculations into the amount of plastic present in the environment were hard to conduct due to lack of information on both plastic production and on plastic marine pollution. To begin determining plastic marine abundances, studies such as Law *et al.* (2010) were conducted to determine areas of high regional plastic concentration. To do this, Law *et al.* (2010) performed quantitative analyses of samples from 6136 neuston tows conducted by SEA semester cruises between 1986 and 2008 in the Western North Atlantic and Caribbean Sea (Figure 1).

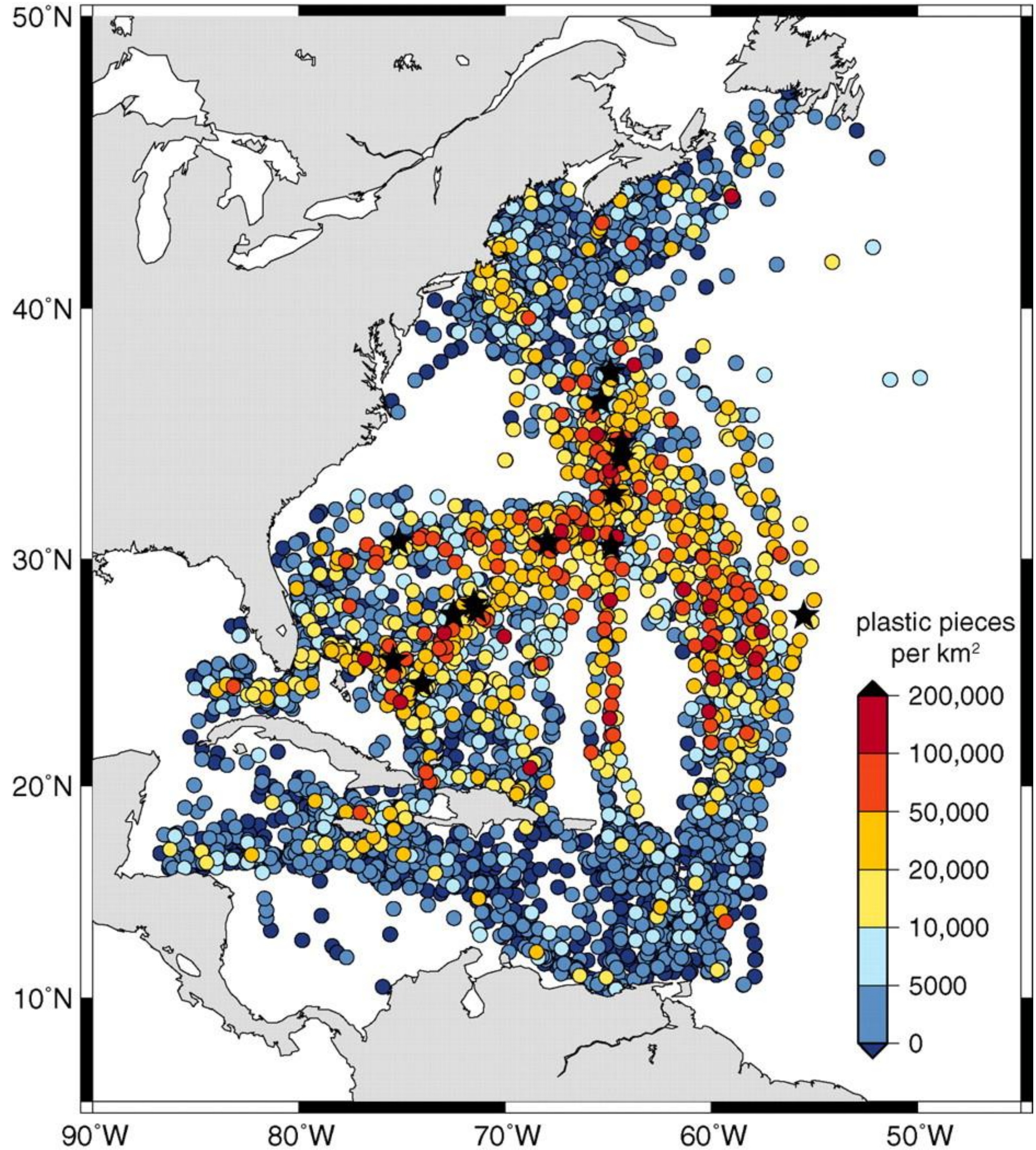

Figure 1: Distribution of plastic marine debris collected in 6136 surface plankton net tows on annually repeated cruise tracks from 1986 to 2008 in the western North Atlantic Ocean and Caribbean Sea. Symbols indicate the location of each net tow; color indicates the measured plastic concentration in pieces km–2. Black stars indicate tows with measured concentration greater than 200,000 pieces km^2. Symbols are layered from low to high concentration; From Law et al. (2010).

Because both the opening of the tow net and the distance of each tow are known, the results are presented as number of pieces per km^2 (Figure 1). This study was used to identify the North Atlantic Gyre as a region of high plastic concentration based on sub-tropical convergence (Law *et al.*, 2010), and illustrates how samples on the East Coast tended to be relatively low in plastic abundance, from 0 to 10,000 pieces per km^2, while higher concentration samples were collected in the Florida Straits, and in the North Atlantic Gyre (Figure 1). The area between Northern Florida and New York has limited data representation in this study (Figure 1). The overall goal of this work was to estimate increases in plastic production of materials and products and suggest an increase in environmental plastic contamination (Law *et al.*, 2010). This hypothesis is supported by Wilcox, Hardesty, and Law (2020), which determines that the plastic abundance at the sea surface in the Western North Atlantic has increased with time, a trend which most strongly correlates to cumulative plastic production. Stronger correlation with cumulative, rather than annual, plastic production indicates that the loss of plastic from the sea surface by biofouling occurs at a slower rate than the input rate, resulting in net accumulation of neustonic plastics (Wilcox, Hardesty, and Law, 2020).

Estimates of the abundances of plastic debris in the environment range from 7-35 thousand tons (Cózar *et al.*, 2014) to 66 thousand metric tons (Eriksen *et al.*, 2014) to 93 to 236 thousand metric tons (van Sebille *et al.*, 2015). This variation emphasizes the lack of understanding of how much plastic is entering the environment annually, its fate once it has entered the marine environment, and spatial differences in the marine environment (van Sebille *et al.*, 2015). While studies have evaluated abundances and distributions of plastic in the marine environment off-shore of China (Shahul Hamid *et al.*, 2018), and in the Pacific (Moore, 2001; 2002), research in the Northern Atlantic is generally sparse and inconclusive (Law *et al.*, 2010), further highlighting the need for more sampling and quantification of marine plastics.

2.2. Studies of Bioaccumulation and Biomagnification Potential

Moore *et al.* (2001) studied the counts and dry weights of plastic debris and zooplankton in samples that they collected in the Central Gyre of the Pacific Ocean. This research was continued in coastal waters off of California (Moore *et al.*, 2002). Using these data, they compared quantities of zooplankton and plastic debris to create abundance ratios. They used this to evaluate the risk of confusion of Neustonic plastics for zooplankton by larger organisms. They found that there was six times as much plastic as zooplankton in the North Pacific gyre by mass, and highlighted the risk for plastic ingestion in that locale as a major concern (Moore *et al.*, 2001). Zooplankton abundance varies from day to night, as many organisms follow a diurnal migration pattern. Diurnal organisms only inhabit and feed at the surface at night. To evaluate the different risk between day-feeders and diurnal organisms, Moore *et al.* (2001) compared the count and dry density ratios for tow samples taken at night and during the day in order to evaluate whether the risk for plastic ingestion is lower at night due to the increased abundance of prey at that time (Figure 2). This study illustrates the importance of time of sampling with respect to the zooplankton to plastics ratio.

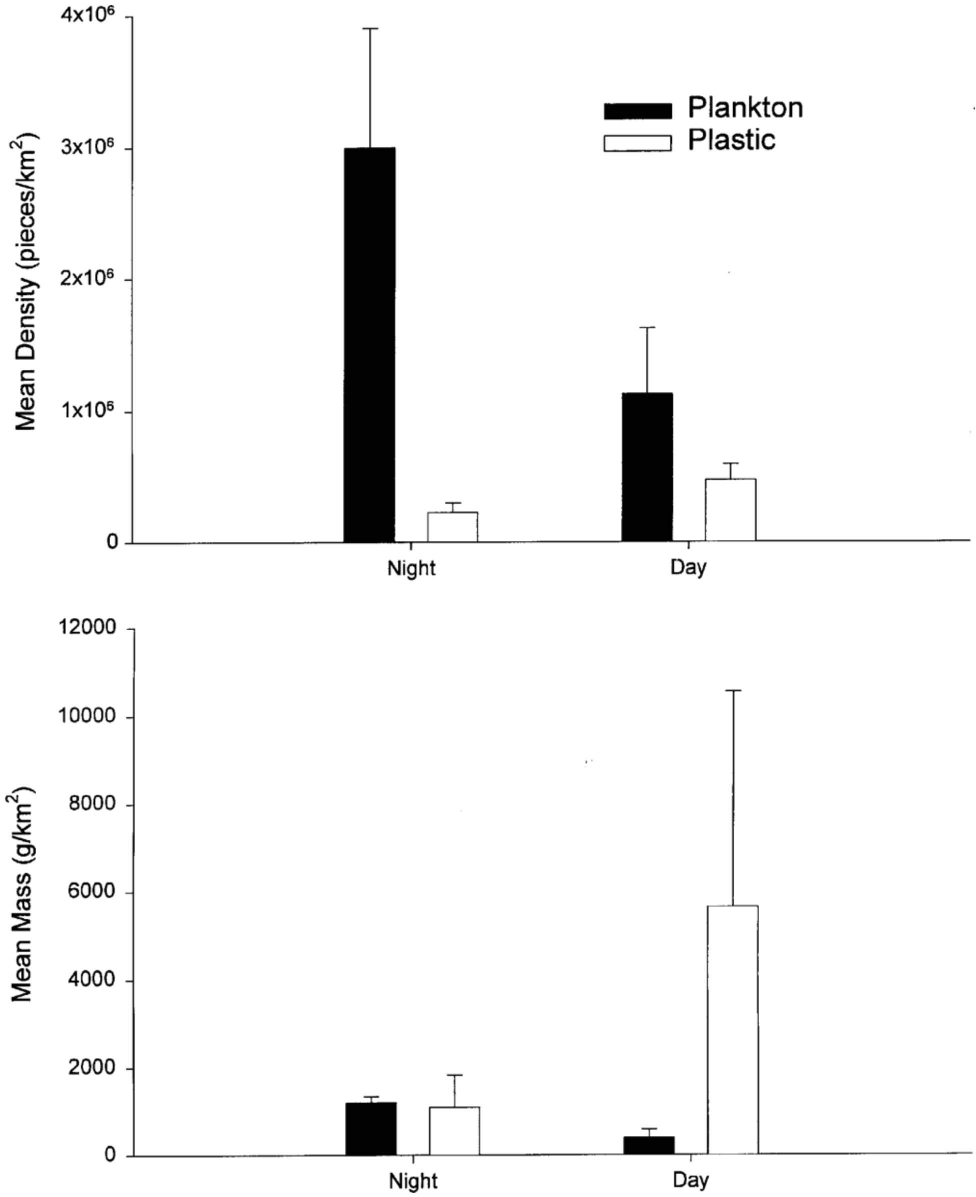

Figure 2. Abundance and mass of plankton and plastic in night versus day samples central gyre of the Pacific Ocean (from Moore et al. (2001)).

Lattin *et al.,* (2004), studied the comparison of zooplankton to plastics at different depths off of the California coast. Lattin *et al.* (2004) found that the mass of plastic debris exceeded that of the zooplankton unless they only weighed neustonic plastics of the same size as the zooplankton, in which case the zooplankton had three times the mass of the plastics collected. In 2012, Collignon *et al.* found a ratio of 0.5 of neustonic plastics to zooplankton weights throughout the

North Western Mediterranean Sea, which they evaluated to pose a potential risk for marine organisms feeding on zooplankton.

Moore *et al.* (2001) used a 333 u, 3.5-meter-long trawl, with a collecting bag of 30 x 10 cm^2, and a transect size of 0.9 x 0.15 m^2 (Moore *et al.*, 2001). Trawls were conducted for random lengths, ranging from 5 to 19km at a speed of approximately 1 m/s (2 knots) (Moore *et al.*, 2001). Moore *et al.* (2002) used the same trawl and transect size, but tows were conducted at 1.5 m/s for between 0.5 and 1km. Collignon *et al.* (2012) used a 333-um mesh with a mouth size of 0.6 x 0.2 m^2 at a speed of 2.5 knots for 20 minutes each.

Similar studies have not been performed in the Atlantic Ocean, or in the Pacific since Collignon *et al.* (2012).

2.3. Impacts of Plastic Debris on Marine Organisms

The impacts of plastic on organisms in the marine and terrestrial environments are still under investigation. As identified in a general metanalysis (See Appendix) of plastic research performed by Rochman *et al.* (2016), most perceived and tested threats and impacts of plastics on organisms have been analyzed on the organism level or below (Figure 1).

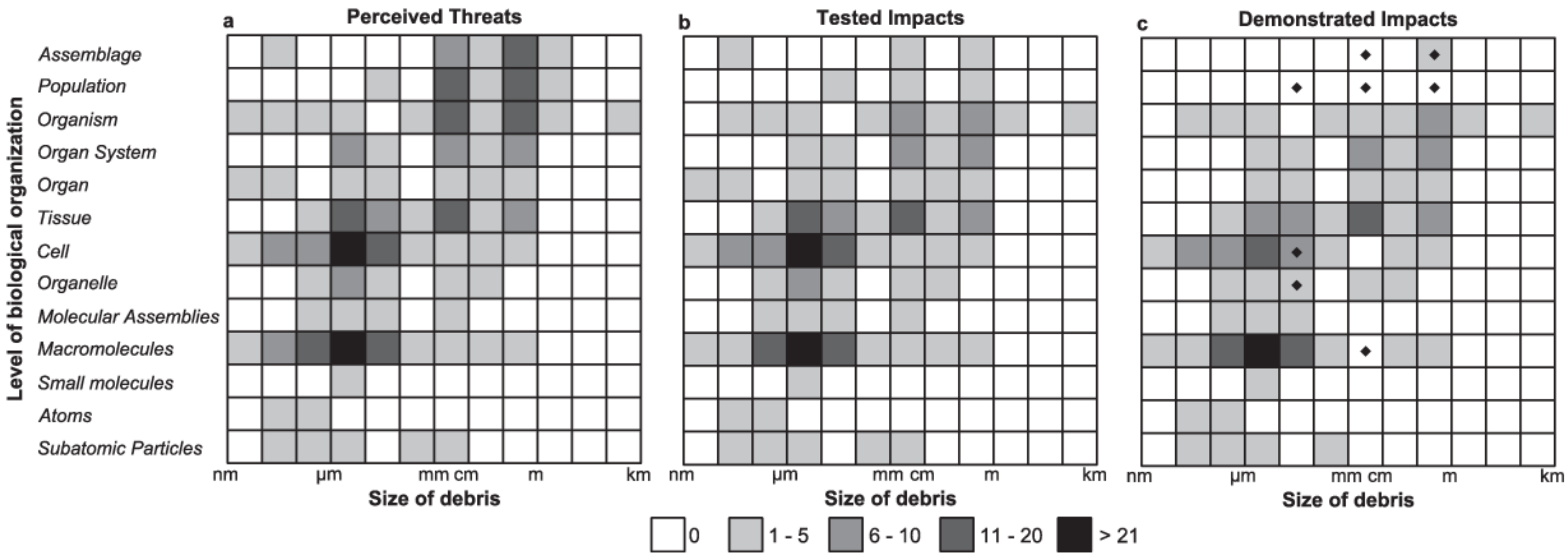

Figure 3. Perceived, tested, and demonstrated impacts of debris. Rows in each matrix represent different levels of biological organization from subatomic particles, atoms, small molecules, macromolecules, molecular assemblies, organelle, cell, tissue, organ, organ system, organism, and population to assemblage. Columns represent order- of-magnitude sizes of debris from smallest (left) to largest (right). Shading in the individual cells of the matrix represent the magnitude of (a) perceived, (b) tested, and (c) demonstrated impacts of debris in peer- reviewed literature identified using the search terms plastic debris and marine debris. Shading represents the number of impacts. Diamonds in the matrix in panel (c) correspond to cells where at least one impact has been demonstrated by correlative evidence. All impacts described at multiple size ranges and levels of biological organization are represented such that there are more impacts than there are papers. Adopted from Rochman et al. (2016).

The lack of representation of studies analyzing community and ecosystem-level plastic impacts is readily apparent in this figure (Figure 3), highlighting the importance of determining the potential for plastic to enter the food web.

Law (2017) categorizes the types of plastic interactions for marine organisms into three groups: entanglement, ingestion, and interaction. Entanglement refers to relatively large debris which traps or constricts an organism (e.g., “ghost fishing,” when abandoned fishing nets and gear entangle and potentially drown megafauna; Law, 2017). Interaction is when an organism comes into contact with debris, which can range from collision events of an organism with a plastic object to the use of plastic as shelter or as a substrate (Law, 2017). Ingestion of plastics has been identified in over 233 marine species, and can be either accidental, intentional, or indirect (through prey that ingested plastic themselves) (Law, 2017). This “indirect” exposure is the focus of the ecologic analyses conducted in this research.

Additives contained in plastics may release toxins into the body of an individual or into the environment during breakdown (Koelmans, 2015; Rochman, 2015) which has been found to have possible endocrine disruption and carcinogenic effects (Godswill and Godspel, 2019). The influences of plastic exerted this way are hard to study and determine, as effects can depend on a number of factors, ranging from length of exposure time, location, polymer type, exposed organism, etc. (Rochman, 2015). To make matters worse, microplastics have been shown to break down into nanoplastics (1-1000nm), which have been found to be capable of travel between cell membranes and may even interact with cell proteins (Holloczki and Gehrke, 2019). The concentrations of plastic in marine fauna, as well as these effects, increase in higher trophic levels. This is especially concerning for humans, with “top-down” fishery structures which preferentially harvest fish from the higher-tier trophic levels. Top predators, which contain the highest concentrations of plastic debris in their bodies, are what we eat. According to the World Wildlife Fund (WWF), around three billion people rely on seafood as their primary source of protein globally (World Wildlife Fund, n.d.). Therefore, it is important to understand the potential health issues attributed to seafood. Recent studies have begun to address the potential sources and impacts of ingested plastics on humans, with carcinogenic impacts being a primary concern (Gruber et al., 2022).

2.4. Movement and Distribution of Marine Plastic Debris

According to Law (2017), "the increasing evidence of the ubiquity of plastics contamination in the marine environment, the continued rapid growth in plastics production, and the evidence—albeit limited—of demonstrated impacts to marine wildlife support immediate implementation of source-reducing measures to decrease the potential risks of plastics in the marine ecosystem." Law (2017) recognized that identification of source areas of plastic debris is important for mitigation of plastic debris, but methodology for such an analysis have not been proposed.

Marine plastic debris can be divided into two basic types: land-based origin and sea-based origin litter (Figure 4).

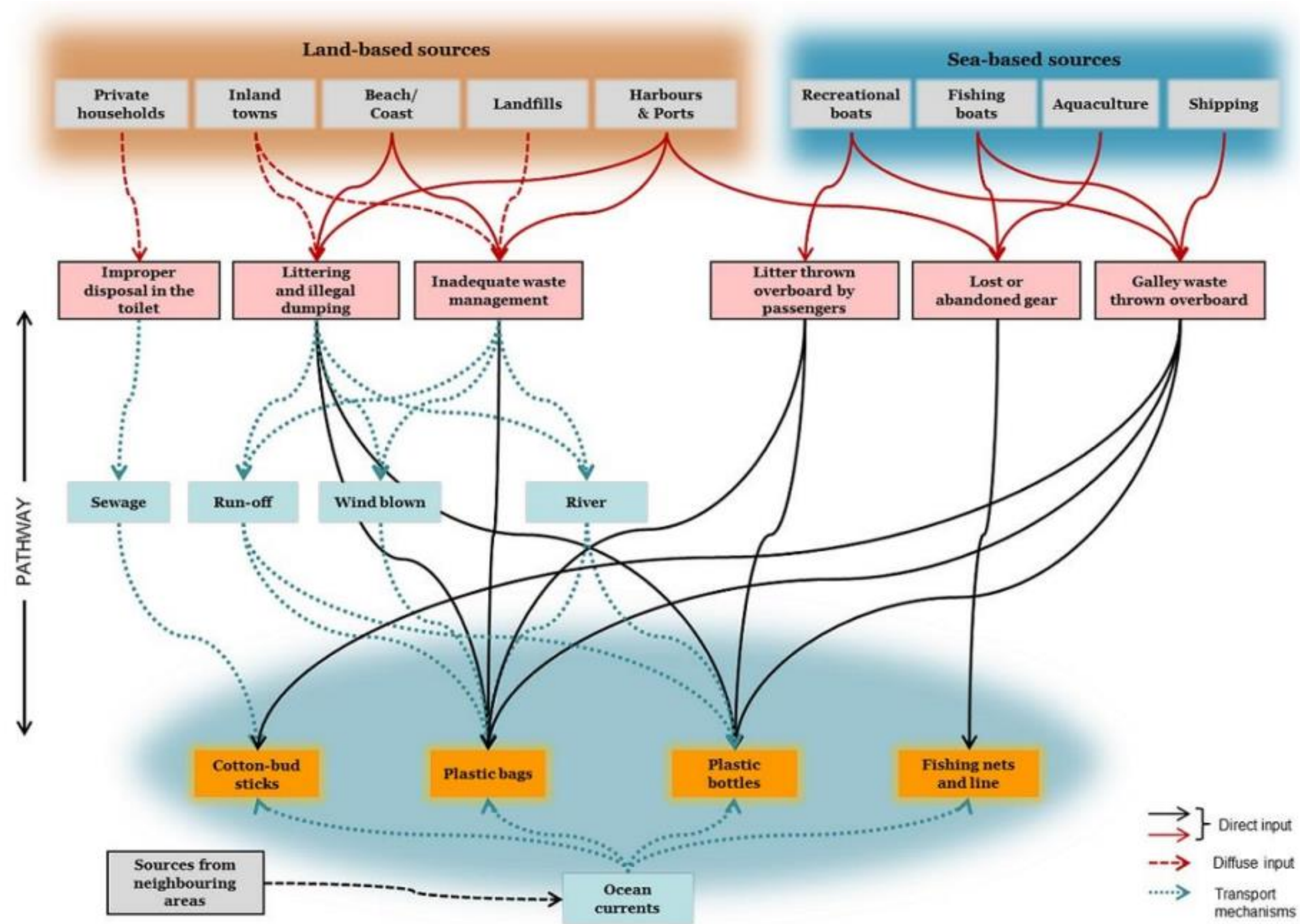

Figure 4.: Multiple sea- and land-based sources (grey boxes) of 4 common items of marine litter and their potential pathways of entrance (blue boxes) into the marine environment. (Note: the size of the boxes does not reflect their relative importance; From Veiga et al. (2016).

Litter may be produced accidentally or deliberatively, but the end result is the same: it enters the marine ecosystem. There are numerous ways in which plastic debris may be introduced to the environment, which is affected by complex production, littering, and environmental variables (Figure 4). This complex nature in how plastics enter the environment makes it difficult to trace the origins of plastic debris (Figure 4).

The movement of plastic through current patterns can be interpreted by remote sensing and *in situ* data, however "the geographic origin of the debris cannot be easily determined from current patterns or from the recovered plastic samples themselves" (Law *et al.* 2010). Law *et al.* (2010) attempted to address this gap in understanding by using satellite-tracked drifting buoys to track pathways of surface mobility, but was unable to estimate source regions of plastic with any precision.

3. OVERVIEW

3.1. Area of Study

Neuston tows (NTs)were performed during SEA Semester Cruise C-297MBC throughout three Large Marine Ecosystems (LMEs) along the Eastern Seaboard: Gulf of Mexico (GOM), Southeast (SE), and Northeast (NE) LMEs. Each of these LMEs is defined by the characteristics of its water mass based on the salinity (and therefore the water density), the sea surface temperature, and the current. The cruise track of C-297MBC included both nearshore and offshore sampling, and accordingly neuston tows include a variety of oceanographic locations such as over continental slope and rise, and in the High Seas (Figure 5).

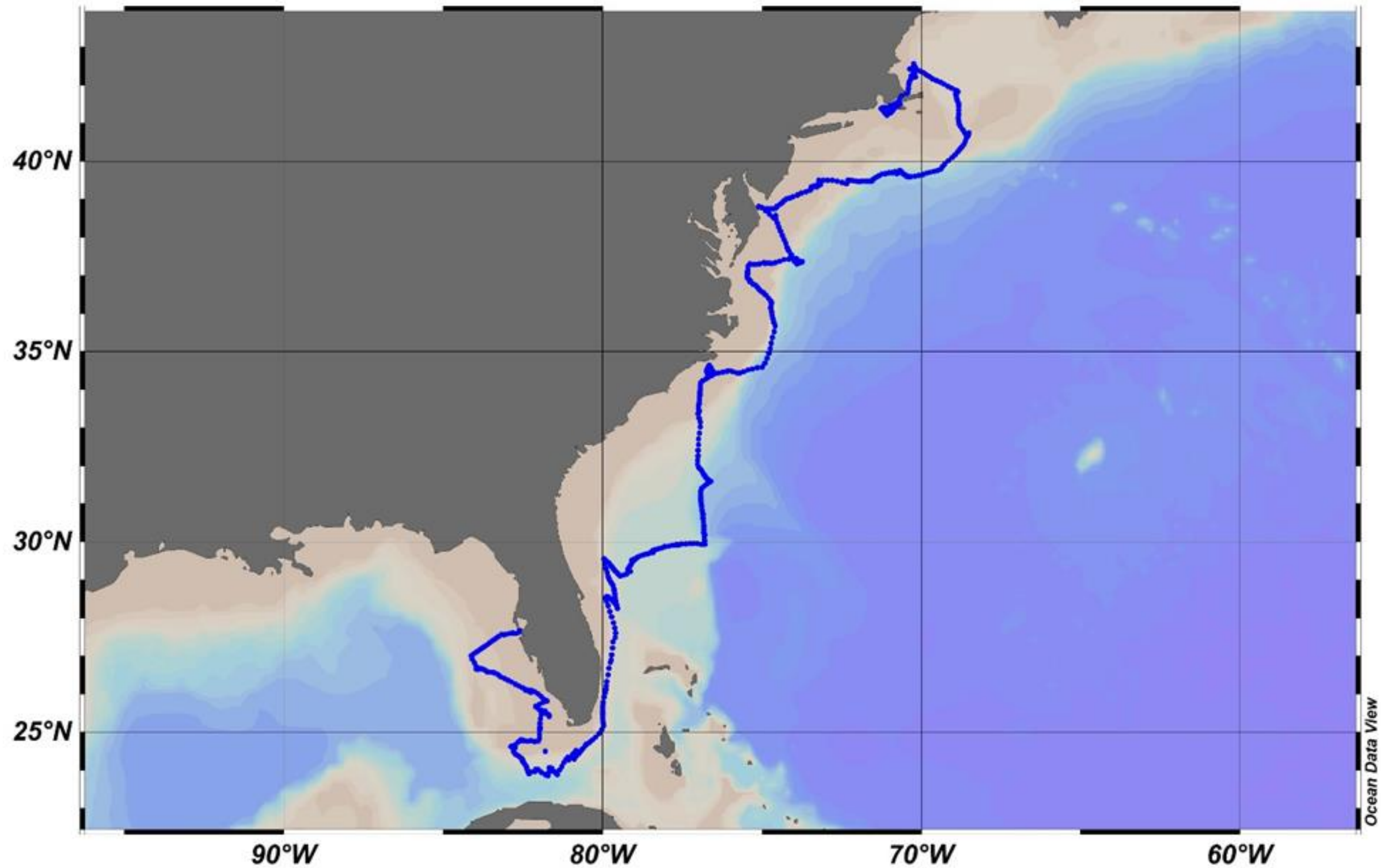

Figure 5. Cruise track from the SEA C-297 Marine Biodiversity and Conservation program, which sailed from St. Petersburg, FL to Woods Hole, MA between April 16, 2021 and May 20, 2021. Neuston tows were performed twice daily during the cruise with weather permitting

The North Atlantic Gyre is not included in this study, rather, the cruise track roughly parallels the East Coast (with varying distances offshore) and crisscrosses the Gulf Stream which advects tropical water from the Gulf of Mexico Northward along the Eastern seaboard. The Gulf Stream commonly produces current anomalies such as warm and cold-core eddies, which adds complexity to the influence of current on the data in this study.

3.2. Hypotheses

3.2.1. Biologic

I anticipated that average plastic abundance in the Atlantic would be higher than that found in the Pacific Ocean by Moore *et al.* (2001), and that the proportion of plastic to zooplankton would be higher than found in previous studies (Collignon *et al.,* 2012; Lattin *et al,* 2004; Moore *et al.*, 2001; Moore *et al.*, 2002). I expected this because of the increase in plastics in the marine environment since this study, based on the estimations by Law *et al*. (2010). I expected that, due to diurnal migration, the ratio of plastic to zooplankton would be lower at night, as observed by Moore *et al.* (2001). I also anticipate that the ratios of count and dry density of plastic to zooplankton would not be similar in each LME (that the ratios for the GOM LME would not be similar to the ratios for the SE LME and the NE LME), due to different physical oceanographic characteristics of each LME.

3.2.2. Modelling

I anticipate that proximity to source, current, salinity, and bathymetry, all potential influences on the plastic abundances at each location, would result in wide ranging ratios of plastic to zooplankton between each LME in this study. By modelling neuston tows with particularly high plastic content, I expect to identify specific sources such as cities or regions where waterways expel riverine and wastewater discharge into the ocean (estuaries). In this study, I model NT 006, 010, 013, 022, 024, 030, 039, 041, and 048, which included plastic pieces, to identify source locations. I predicted that the main influence on plastic abundances sampled in each location are the position relative to the Gulf Stream current and proximity to sources.

4. RESEARCH METHODS

4.1. Field Methods: At Sea

During SEA Semester Cruise C-297MBC, we (the students and staff) collected data both through the use of continuous instrumentation, and through the deployment of oceanographic equipment. For this study, the pertinent data includes salinity, current, depth, temperature, and the samples from the neuston tow deployments.

4.1.1. Continuous Measurements: Salinity, Current, Depth, and Temperature

Cruise C-297MBC recorded hourly measurements of salinity, current, depth, and temperature. The Acoustic Doppler Current Profiler (ADCP), operating at 75kHz, collected information about current magnitude and direction by using sound signals that reflect off of particles within the water current. Changes in the frequency of the signal after the reflection indicate the magnitude and the direction of the current. A thermosalinograph flow-through system continuously recorded sea surface temperature, sea surface salinity, and fluorescence (a proxy for productivity; Figure 6).

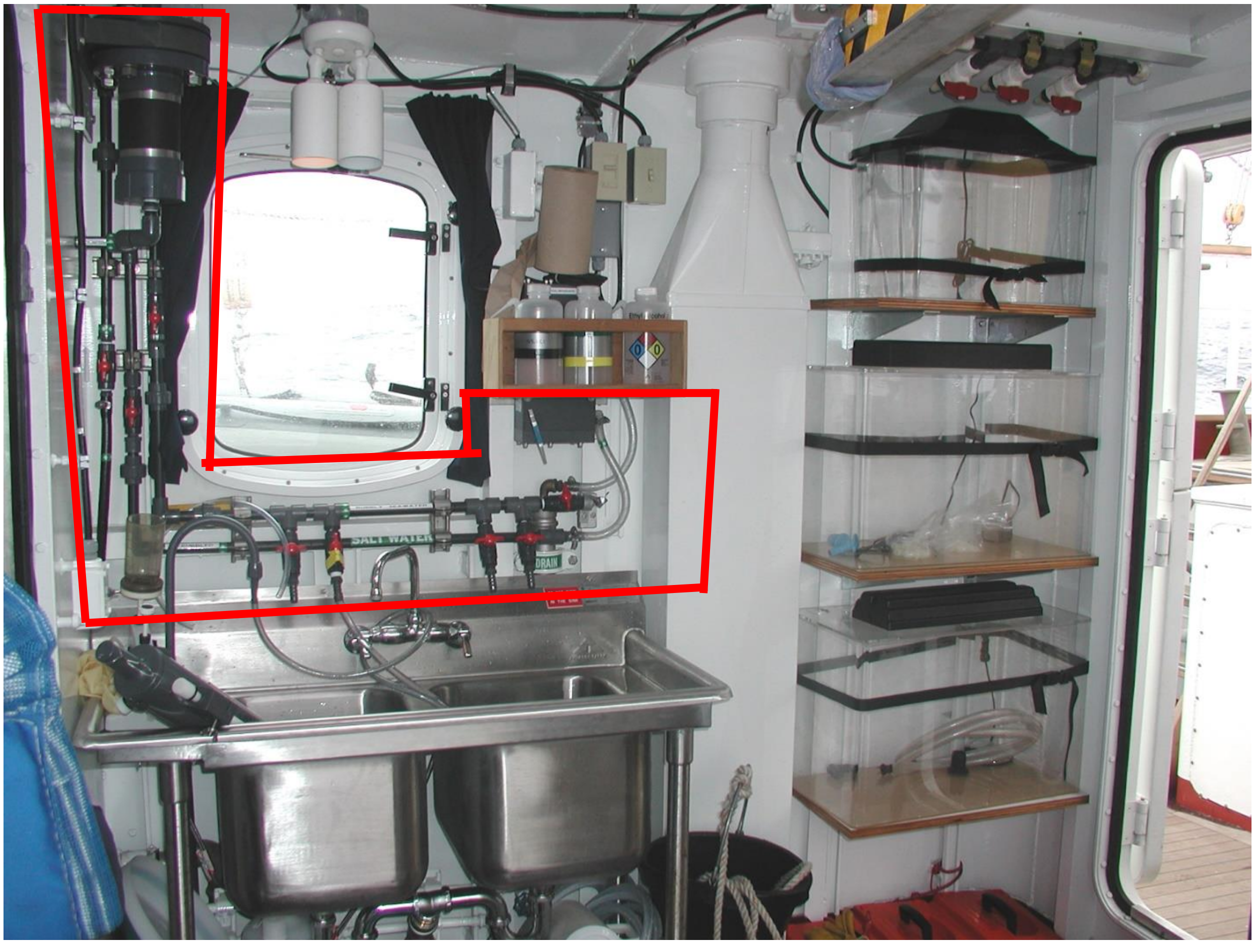

Figure 6. A flow-through thermosalinograph (outlined in red) on board one of the SEA Education Association's vessels, the SSV Robert Seamans.

A chirp echosounder produces a sound which reflects off of the seafloor. The elapsed time between broadcast and subsequent receipt of the echo is used to determine the depth of the seafloor.

4.1.2. Neuston Tow Collection

Neuston tows were deployed at the surface of the water twice a day (around 1200 and 2400 EST), weather permitting. Tows consisted of a net with a one meter-squared mouth size and were conducted at a speed of two knots for 30 minutes, resulting in a transect of 1 nautical mile for each tow. Neuston tows used a 333-micrometer mesh net (Figure 7), similar to those used in Moore *et al.* (2001;2002) and Collignon *et al.* (2012).

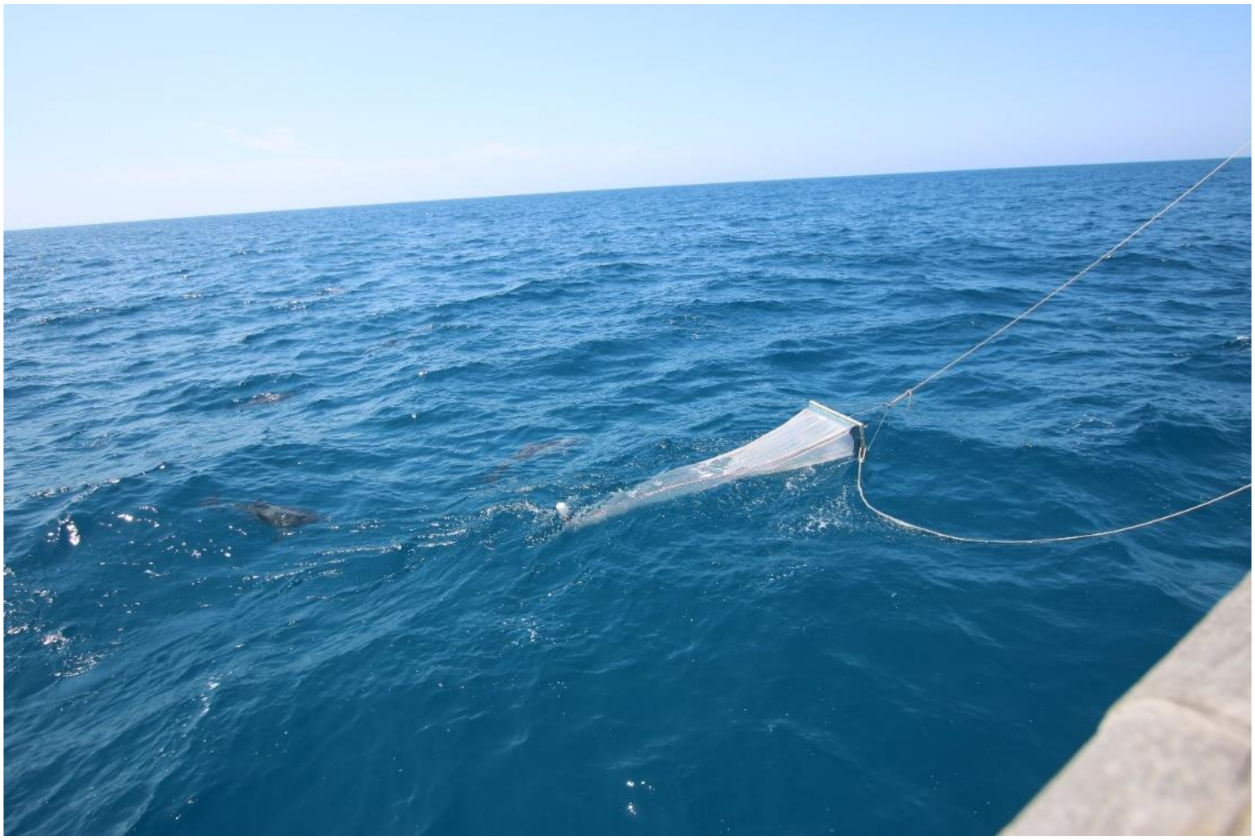

Figure 7. 333 micrometer neuston net towing alongside the SSV Corwith Cramer at approximately 2 knots of speed during cruise C-297MBC.

The neuston net was emptied into a pristine bucket, and then rinsed with saltwater into a rinse bucket. Organisms over 2cm in length, and any plastics, flora, or fish were removed from each bucket by hand using forceps and spoons.

4.1.3. Neuston Tow Sample Processing

Zooplankton: The pristine bucket was poured through a 64-micrometer sieve to isolate biomass from the neuston tow (Figure 8).

Figure 8. Top: Biomass (abundant euphausiids) from a neuston tow in the Hudson Canyon (NE LME), isolated in the sieve. Bottom: neustonic plastic collected from various Neuston Tows on cruise C-297MBC viewed under a dissecting microscope.

Lingering flora, fish, plastics, or large organisms were then removed (Figure 8). A 1mL scoop of pristine biovolume was removed from this biomass and placed onto a petri dish for a 100-count. The 100-count procedure is defined as the species identification of 100 organisms in a 1mL volume scoop from the pristine biovolume sample. This is performed under a dissecting microscope with a 100x objective lens (Figure 9).

Figure 9. C-297MBC student conducting a 100-count

For some samples with less than 100 organisms in the 1mL sample, the 100-count consisted of less than 100 organisms.

After the removal of the 1mL scoop from the pristine bucket biomass, the rest of the rinse bucket was added to the sieve to collect the total biomass.

Utilizing the preceding biomass sample, the crew from C-297MBC took a biovolume measurement for the sample, which was corrected in Microsoft Excel to accommodate tow distance of each transect. Biovolume was determined by adding water to a graduated cylinder, adding the sample, and determining the difference in volume.

From the total sample, the 1mL scoop was observed under a dissecting microscope to analyze the 100-count. We estimated the percentage of the 1mL sample that the 100-count consisted of, which I later used to calculate the total number of zooplankton in the 1mL sample. I further multiplied this by the total biovolume to find the approximate zooplankton count for that tow. The remaining biovolume was stored in scint vials and preserved with ethanol. Tows with large amounts of biovolume only preserved one scint vial worth of biovolume.

Plastics: Plastic particles were separated from the biomass by hand using forceps and a bright headlamp with white and red-light settings. Each particle was counted and recorded before the isolated plastic particles and fibers were placed in a Teflon-lined scint vial, labelled, and stored. If the material was too wet to store, it was left in the engine room or in the lab for 24 hours to dry before storage. Identification of the chemical composition of each sample was beyond the scope of this study and was not completed.

4.2. Laboratory Methods

4.2.1. Sample Processing

Zooplankton: To obtain the dry weight of the zooplankton samples, the stored biovolume samples were sieved to remove the ethanol from the sample using a 64um sieve. The plankton were then rinsed and the biovolume recorded to determine the amount of the original sample stored in each vial. The sample was sieved again to remove the water, the weight of a plastic weighing tray was measured, and the biovolume was poured onto the tray. The samples were allowed to air-dry for 2-4 days (until completely dry) before being weighed to determine the dry weight of the zooplankton. This weight was then multiplied by the total sample sizes to determine the overall dry weight of zooplankton for each tow. In Microsoft Excel, I catalogued counts, tow densities (quantities of zooplankton or plastic per km^2), and dry weights of the zooplankton and plastic from each neuston tow (See Supplementary Materials). I then calculated zooplankton and plastic abundances by volume using the transect and net size for each tow in order to develop plastic to zooplankton quantity ratios for counts and weights (See Supplementary Materials).

Plastics: In the onshore lab, I air-dried the plastics before taking a dry weight for each sample. I pre-weighed the plastic tray for each sample, emptied the scint vial from a tow into the plastic tray, allowed the sample to dry overnight, and re-weighed the total in the morning. This allowed me to measure the dry weight of the plastics collected from a tow by subtracting the weight of the container.

4.3. Data Analyses

4.3.1. Ocean Dataview

Neuston tows were mapped using Ocean Dataview (ODV). Each tow was then sorted into its Large Marine Ecosystem (LME) based on geographic location. Five tows were completed in the Gulf of Mexico LME, sixteen in the Southeast LME, and seventeen in the Northeast LME (Figure 10).

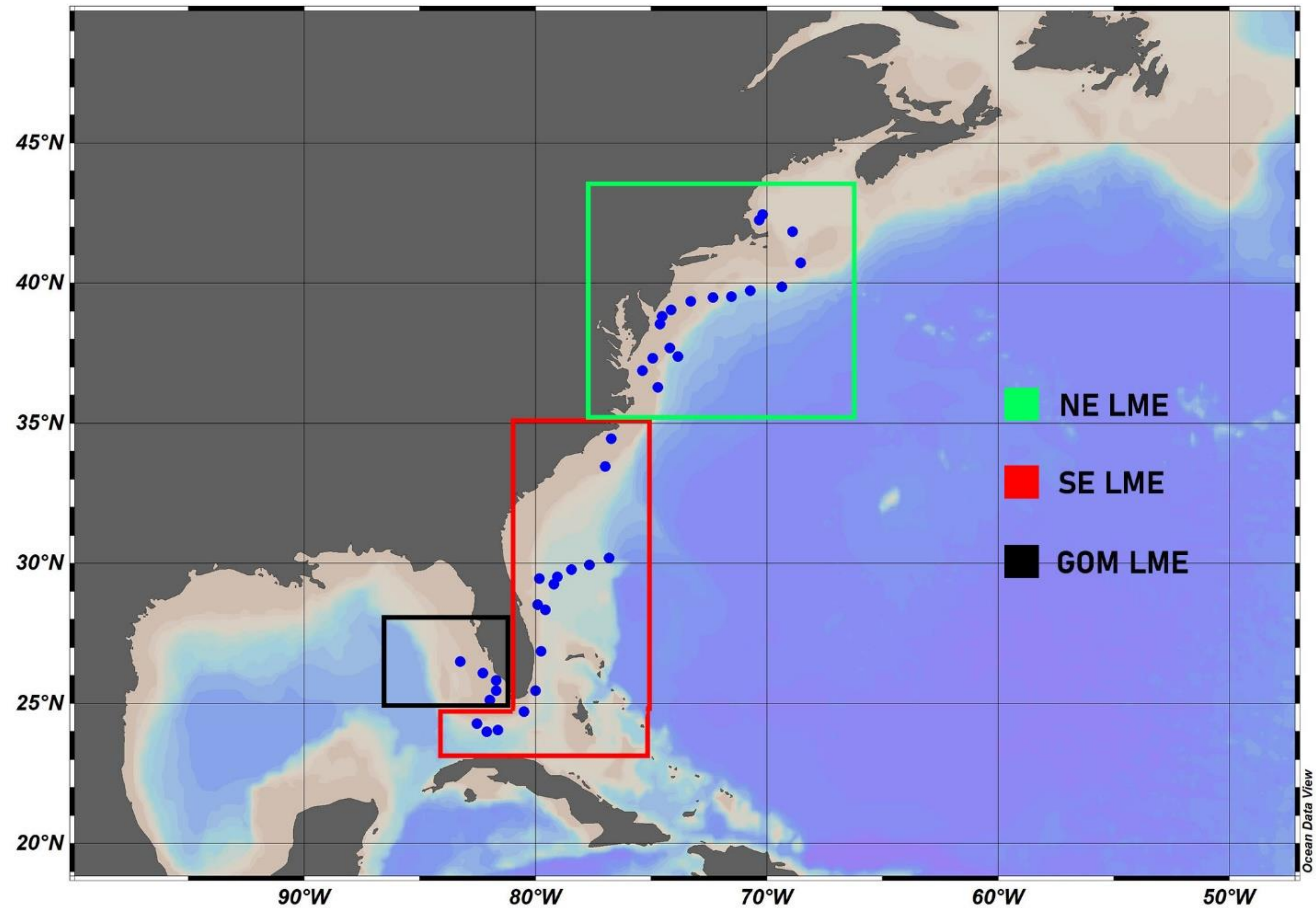

Figure 10. Map illustrating the locations of neuston tows completed by the SEA C-297 cruise. The Gulf of Mexico LME is outlined in black (containing 5 tows), the Southeast LME in red (16 tows), and the Northeast LME in green (17 tows).

ADCP current magnitude and direction was mapped to illustrate which parts of the cruise track encountered the Gulf Stream or current anomalies such as eddies.

4.3.2. Microsoft Excel

I compared the zooplankton and plastic abundances via two ratios: by count per kilometer squared, and by dry weight/density per kilometer squared. To evaluate the different risks for diurnal organisms and day-feeders to ingest plastics, I also performed comparisons of the counts and dry weights per kilometer squared of only the day tows, and of only the night tows.

4.3.3. OpenDrift

Model Verification: OpenDrift Graphical User Interface (GUI) is configured to consult a set group of sources in the order they are listed in the program, as recorded on a GitHub provided by Dagestad (2018). The first sources only consult the Norwegian waters and the Barents Sea which are outside the area used for this study, as a result, OpenDrift would have skipped those first few sources, straight to consultation of these two main databases.

The first source reports wind data from the US National Centers for Environmental Prediction (NCEP) global atmospheric model (Thornton and Otto, n.d.). This Global Forecast System (GFS) is a numerical prediction system which operates globally (Thornton and Otto, n.d.). This system combines the use of a global computer model and variational analysis, which is run by the U.S. National Weather Service (Thornton and Otto, n.d.). The GFS is run four times per day up to 16 days in advance, and uses the FV3 model with ~13 km resolution for forecasting (Thornton and Otto, n.d.). While this is a prediction model, it is run often enough that its records are close to "real-time," for the purposes of this study. The GFS model uses 127 vertical layers for the atmosphere, creating a detailed prediction model (Thornton and Otto, n.d.). This detail of atmospheric breakdown, and the frequency of model runs, indicates that this model has precise wind estimates at the sea surface as needed for this study.

The second source which the OpenDrift GUI relied on heavily is the global HYbrid Coordinate Ocean Model (HYCOM), a multi-institutional consortium sponsored by the Ocean Partnership Project (OPP) through the U.S. Global Ocean Data Assimilation Experiment (GODAE) (Center for Ocean-Atmospheric Prediction Studies (COAPS), n.d.). The purpose of HYCOM is to develop and evaluate a "data-assimilative hybrid isopycnal-sigma-pressure (generalized) coordinate ocean model" (Center for Ocean-Atmospheric Prediction Studies (COAPS), n.d.). This model aims to address the objectives of GODAE, to depict the ocean in a three-dimensional state in real time, provide boundaries for ocean and atmospheric models, and provide conditions for ocean-atmosphere boundary models, such as OpenDrift (Center for Ocean-Atmospheric Prediction Studies (COAPS), n.d.).

These models cumulatively provide detailed real-time data which the GUI uses to calculate possible particle trajectories for the samples in this study, creating a hindcasting simulation for the neuston tows analyzed in this study.

Configuration: OpenDrift provides the ability to simulate the movement of plastics collected by the neuston tows. While OpenDrift does have an explicit plastic drift model (PlastDrift), taking into account statistical depth and turbulence, however, because the plastic samples in this study were restricted to the neuston (the uppermost meter of sea surface), the OceanDrift simulation was determined to be more appropriate as it focuses on the top layer of the ocean (Dagestad and Hope, 2020). This simulation includes direct wind drift (direct effect of wind on the particle), stokes drift (difference in position over time, based on Eulerian or Lagrangian particle trajectories), advection (horizontal transfer of matter), and turbulence that would have affected the plastic particles observed in this study (Dagestad and Hope, 2020).

I began each sample with a run using 1,000 particles cast backwards in time from the collection point for 730 hours (one month). Because each neuston tow contained 100 particles or less on average, this represented a tenfold increase in the number of particles to aid in the stochastic hindcast. I set the coastline action to "stranding," so that once particles encounter land (i.e., their potential origin location), the model run terminated. If a model did not encounter an origin location over the 730-hour run, I re-ran the model for 1008 hours (6 weeks). If this was still inconclusive, I then ran the model for 1460 hours (2 months). Time steps were set to 15.0 minutes, and 30.0 minutes, respectively, for the timestep output. All other configurations were left at default, and the advection scheme was left set to Eulerian.

Plastic may not have originated at the "stranding" location if it was introduced directly into the marine environment (such as in the case of plastic litter off of a ship). However, because the plastic collected in this study includes microfibers and other small, degraded plastics, it is more likely that these samples have been breaking down in the environment over time. Thus, it is probable that these plastics originated closer to their "stranding" locations as calculated by this model, due to the longer time the samples had in the environment to break into smaller pieces.

Because OpenDrift is based on Lagrangian (moving with the flow, total derivative) particle trajectory modelling, rather than Eulerian volume-based modelling, larger quantities of particles result in a more reliable simulation output (Dagestad and Hope, 2020). Accordingly, to confirm the reliability of the models, I ran a few models with 5,000 particles.

Hindcasting Models: Neuston Tows: OpenDrift GUI required GPS coordinates in latitude and longitude of each neuston tow, as well as a sampling radius of 10 meters to isolate the sample location (Figure 11).

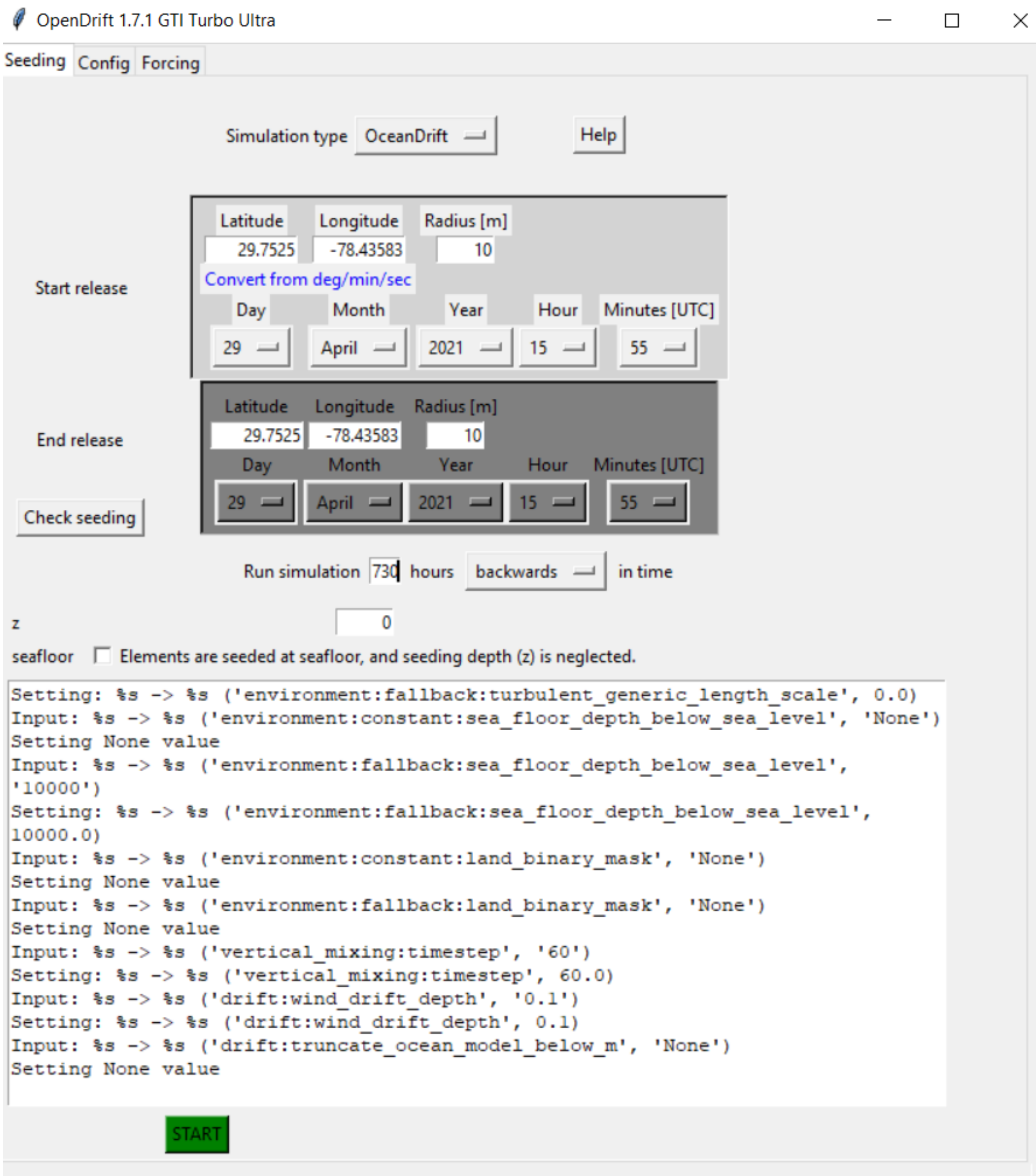

Figure 11. OpenDrift GUI, set to hindcast NT 22 with 5000 plastic particles to identify the source region for the plastic sampled in this tow.

Model outputs include figures illustrating the probabilistic paths that plastic particles may have taken to reach their collection point, as well as animations simulating the movement of the particles over time.

5. RESULTS

5.1. Plastic to Zooplankton Ratios

In order to determine the proportion of plastics relative to the number of zooplankton in the surface waters of the Eastern seaboard, ratios of plastic to plankton were developed for both total count and by dry weight. Plastic to zooplankton count ratios for samples which included plastic arranged from a low of 0 to a maximum of 0.1541 plastic pieces to zooplankton per meter squared (NT 039). Other ratios, such as of plastic to zooplankton in tows 002 and 004, read a ratio of 0 plastic to each zooplankton (determined to four significant figures). In order to evaluate the ratios, I put the plastic samples on a logarithmic scale (See Supplementary Materials) to highlight any trends in the data (Figure 12).

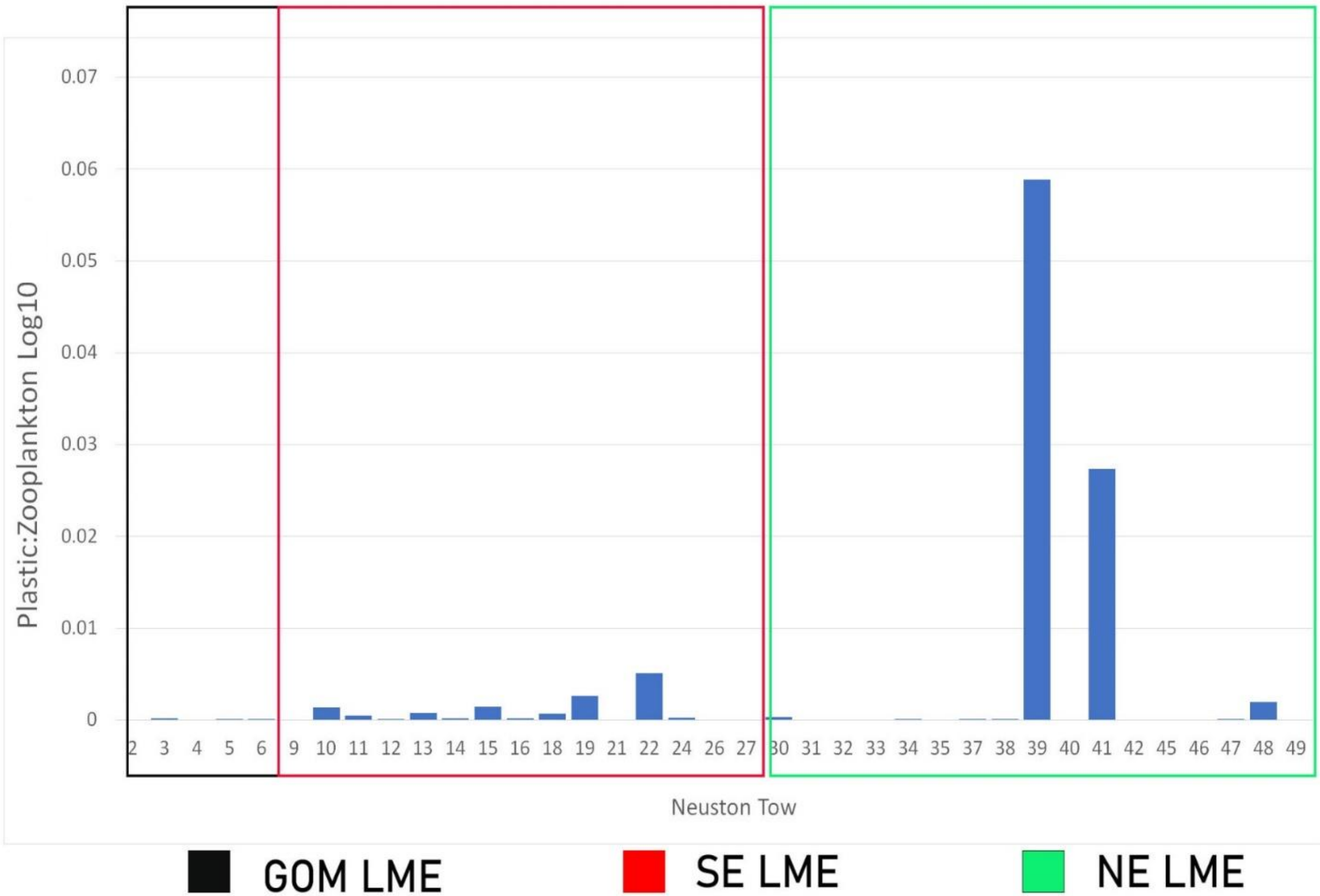

Figure 12. Plastic count (#/tow) to zooplankton count (#/tow) ratio for each tow. Datapoints have been corrected to a logarithmic scale to account for some variability, and 1 was added to each station to correct to positive (See: Supplementary Materials). Tows are sorted by LME: GOM LME tows are located in the black box, SE LME tows in the red box, and NE LME tows in green.

Neuston tows in which no plastic particles were collected were not included in this study. The GOM LME, overall, has negligible plastic count to zooplankton count ratios throughout all neuston tows; The SE LME had low ratios of plastic to zooplankton by count, which were similar across most neuston tows in the region, and the NE LME tows had higher variability, with a few tows (NT-039 and NT-41) having high plastic to zooplankton count ratios (0.0588 and 0.0273, respectively), while the rest of the tows had little to no significant ratio values (Figure 12).

Trends seen in the LMEs are consistent between the count ratio and the density ratios (Figure 12, 13).

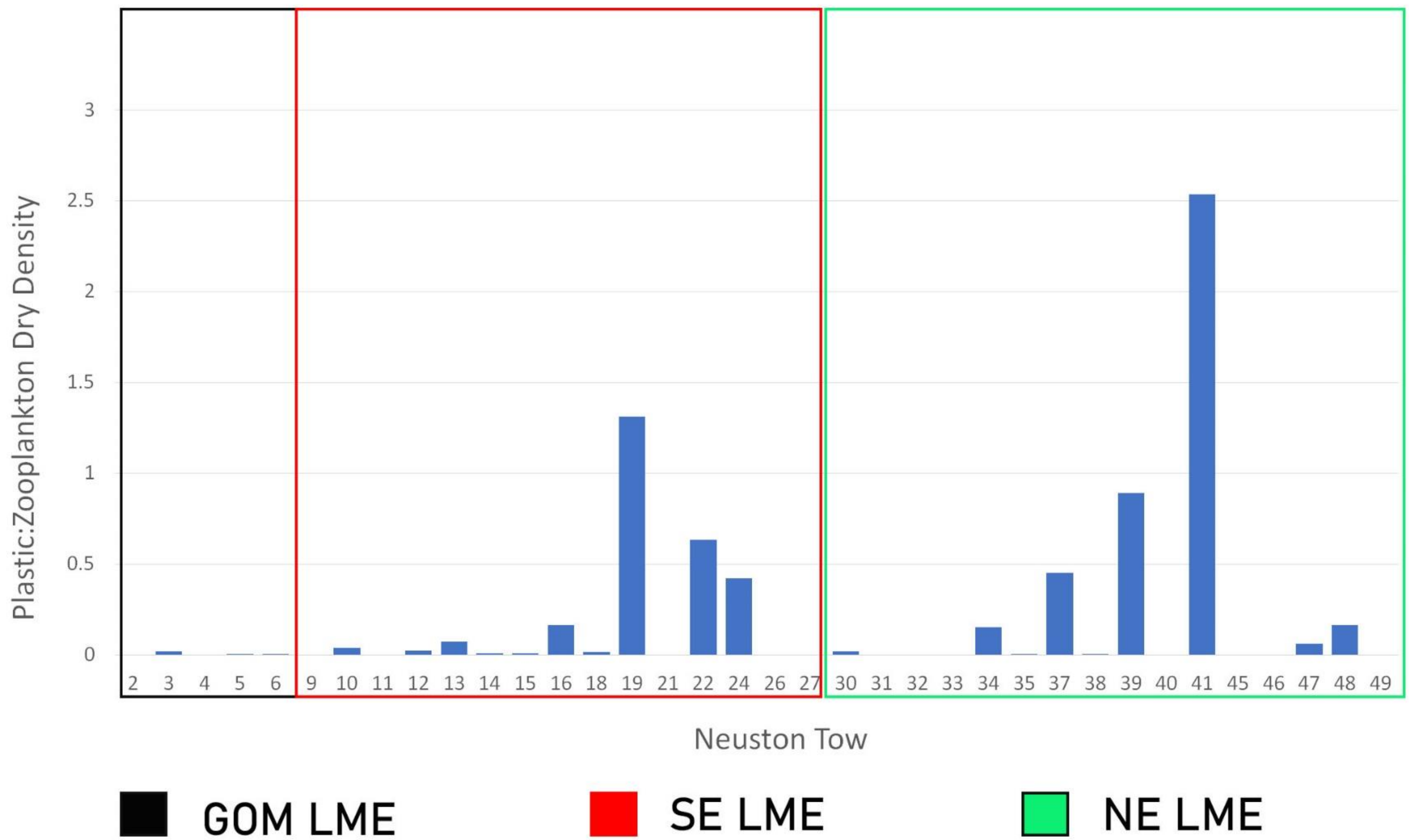

Figure 13. Plastic mass (g/tow) to zooplankton mass (g/tow) ratio for each tow (See Supplementary Materials). Tows are sorted by LME: GOM LME tows are located in the black box, SE LME tows in the red box, and NE LME tows in green.

The GOM LME shows a negligible plastic to zooplankton ratio based on the density as well as on the counts, while the SE LME continues to have low to medium value ratios with low variability (Figure 12, 13). The NE LME also is consistent between the count and dry weight ratios, with some high and some low-ratio tows and high variability in both cases (Figure 12,13).

5.1.1. Diurnal Variation

The tows performed during the day, around 1200 EST, show varying plastic to zooplankton count ratios. These are negligible in the GOM LME, consistently around 0.005 in the SE LME, and highly variable with scattered high-value ratios in the NE LME (0.028-0.068) (Figure 14).

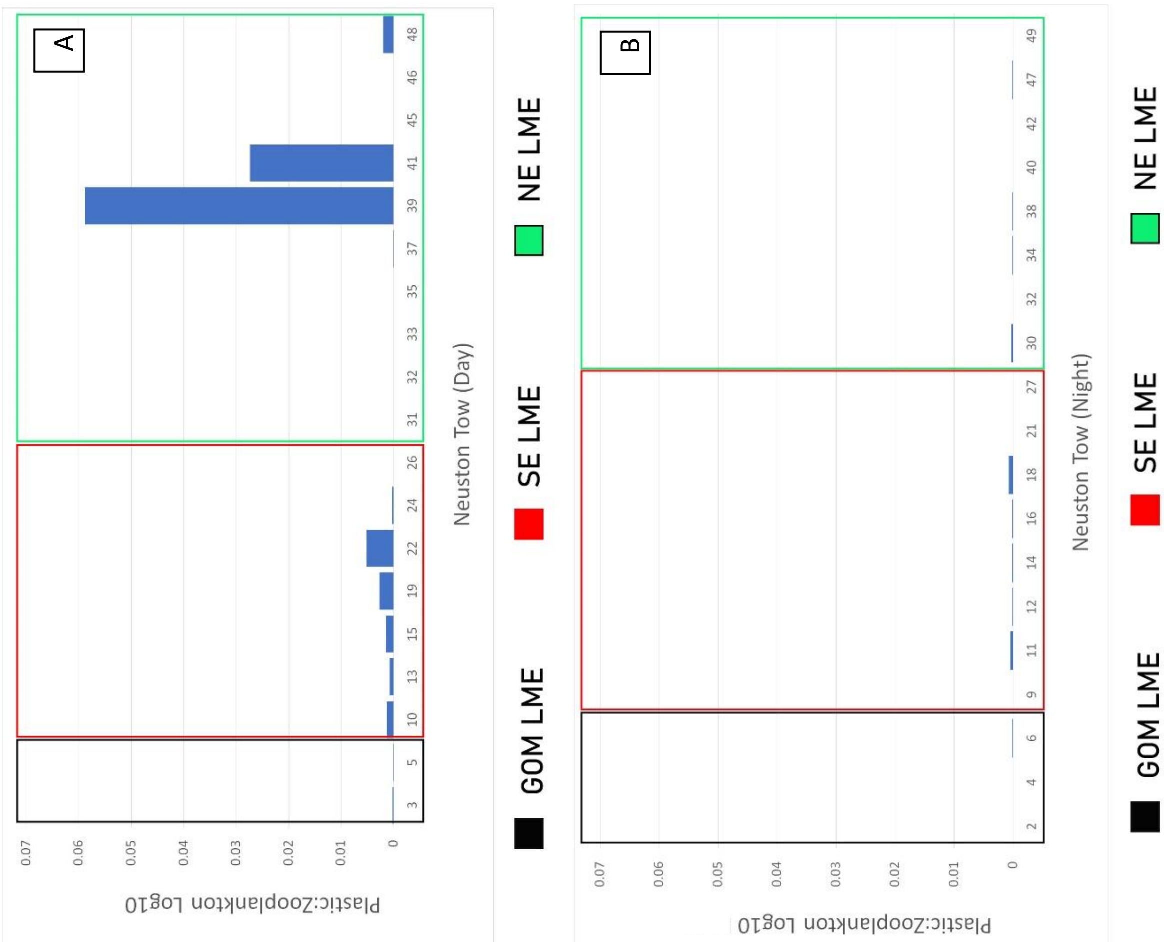

Figure 14. Plastic (#/tow) to zooplankton count (#/tow) ratios on a logarithmic scale for each tow, corrected to positive (See Supplementary Materials). Day tows (left) were collected between 1100 and 1400 EST. Night tows (right) were collected between 2100 and 0200 EST. Tows are sorted by LME; GOM outlined in black, SE in red, and NE in green. A and B are shown on the same scale.

The night tows, presented on the same scale as the day tows, likewise, show negligible plastic to zooplankton ratios throughout all LMEs (Figure 14). The dry weights continue to show this clear difference (Figure 15).

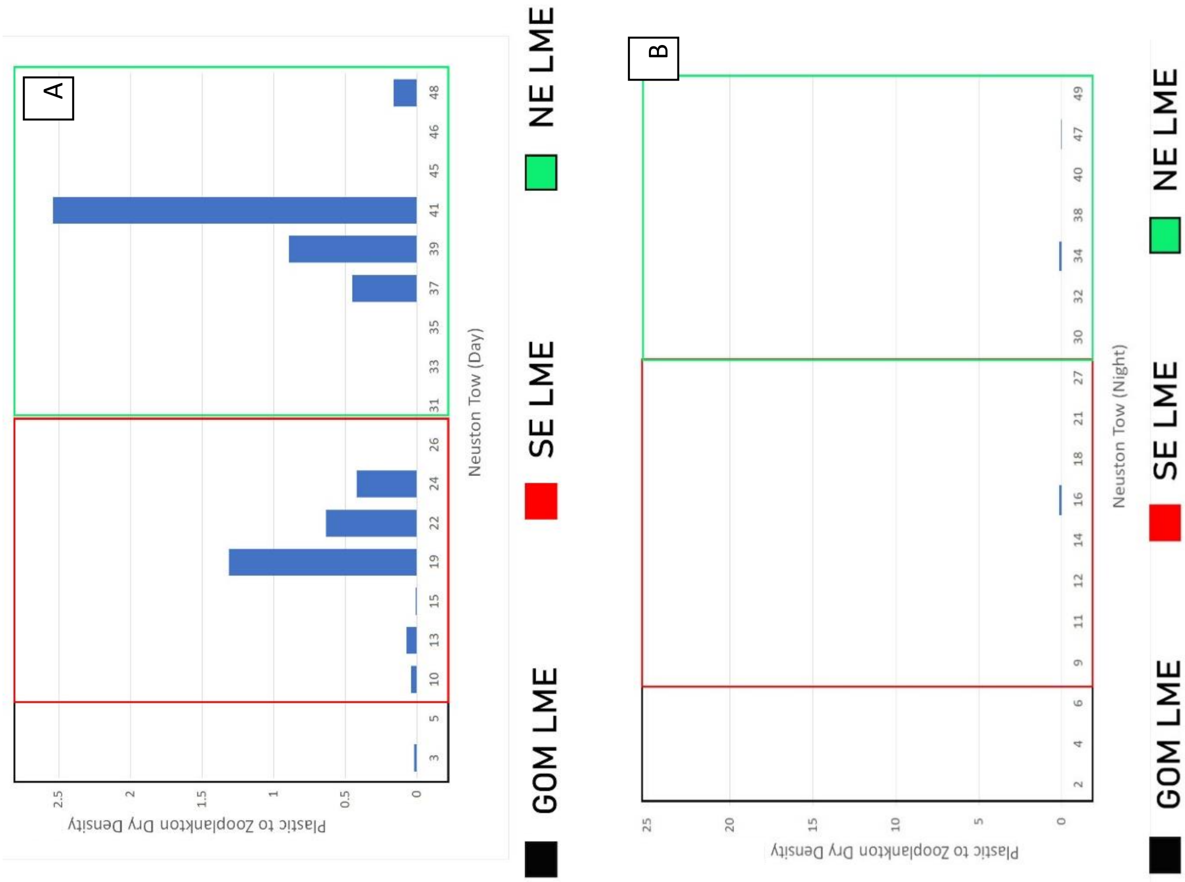

Figure 15. Plastic dry density (g/tow) to zooplankton dry density (g/tow mL) ratios for each tow (See Supplementary Materials). Day tows (A) collected between 1100 and 1400 EST. Night tows (B) were collected between 2100 and 0200 EST. Tows are sorted by LME; GOM outlined in black, SE in red, and NE in green.

The Gulf of Mexico LME exhibits negligible ratios of plastic to zooplankton dry densities during both the day and the night (Figure 15). The SE LME shows a marked difference in ratios between the day samples and night tows (Figure 15). The NE LME also shows this trend clearly, with high-ratio tows collected during the day and low-density tows collected at night (Figure 15).

5.2. Investigation of Physical Oceanographic Influences

5.2.1. Physical Oceanographic Data: Salinity, Temperature, Depth, Current

I used physical oceanographic data including salinity, temperature, and depth to define the borders between the large marine ecosystems in this study. Salinity, measured by the flow-through thermosalinograph, is one component of defining the water masses within each LME. The GOM LME has high salinity of around 36-37 psu coastally, while the SE LME has around 36 psu and the NE LME has less than 35psu (Figure 16) (CATDS Salinity Expert Center, n.d.).

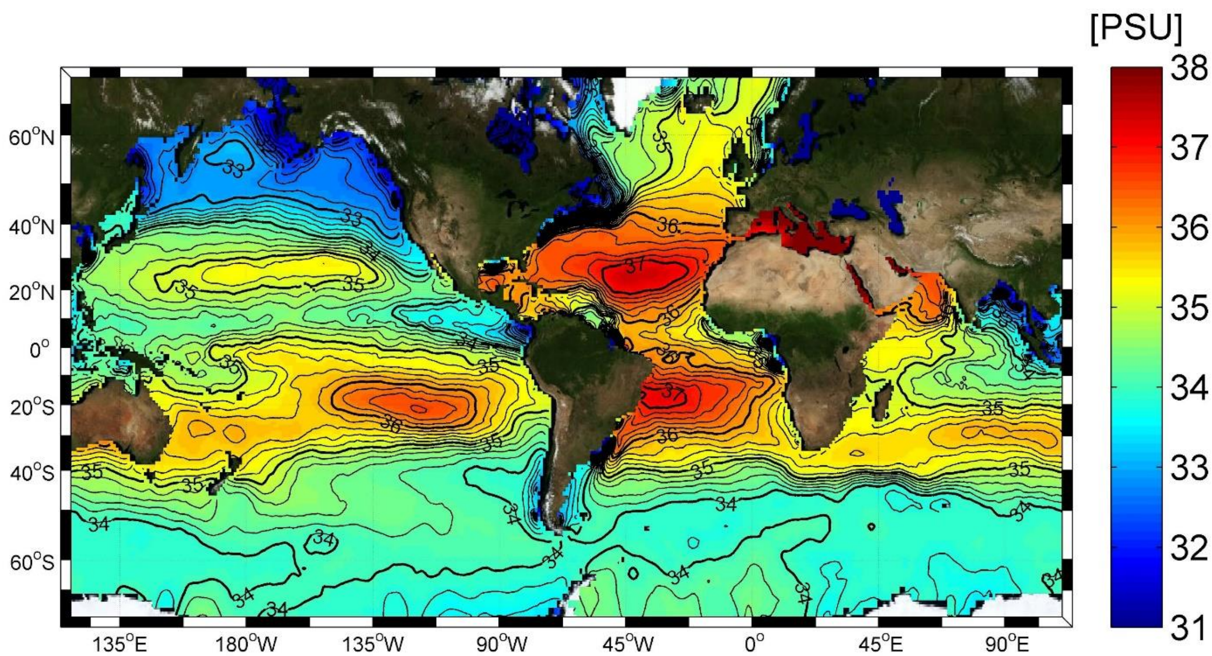

Figure 16. From the CATDS Salinity Expert Center: Annual mean of the sea surface salinity distribution based on the 2005 World Ocean Atlas.

Sea surface temperature was also used to define these boundaries. The GOM LME ranges from 22-26 degrees Celsius (Office of Satellite and Product Operations, n.d.; Figure 17).

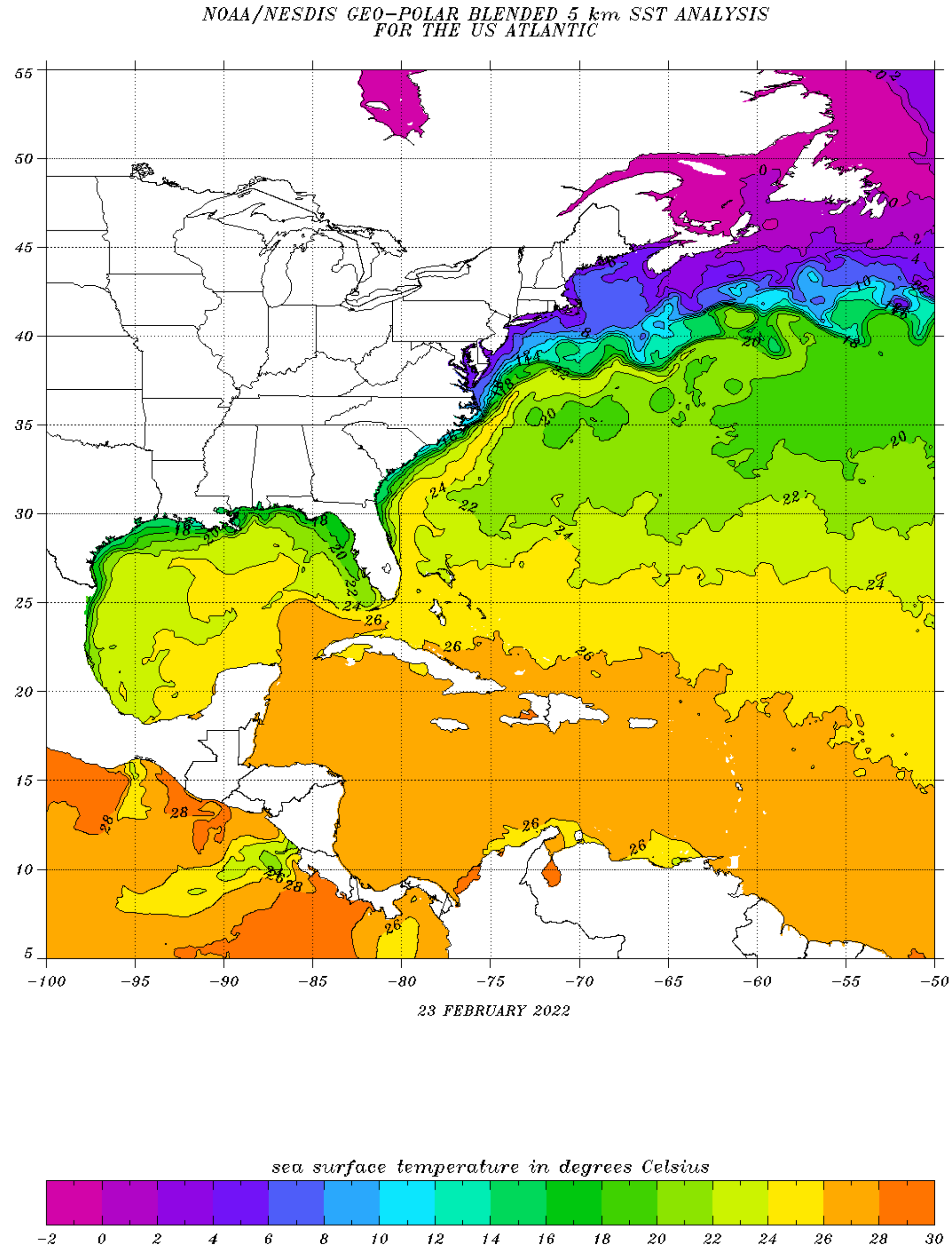

Figure 17. From the Office of Satellite and Product Operations: NOAA blended 5km sea surface temperature analysis for the Eastern Seaboard, February 23 2022.The Gulf Stream can be seen where the warmer waters from the Caribbean (orange and yellow) are pulled up into the colder Northern waters (blue, purple), providing a warm-water tail indicative of the Gulf Stream.

The SE LME ranges from 20-22 degrees coastally, and 24 degrees where the Gulf Stream pulls warmer waters up from the Gulf of Mexico (Figure 17). The NE LME consists of 4-8 degrees Celsius coastally, and up to 14 degrees offshore (Figure 17). Warmer waters flow North, and then Eastwards off of Massachusetts with the Gulf Stream via North Atlantic Drift.

The general bathymetry of the seafloor along our cruise track shows that C-297MBC neuston tows were conducted over the continental slope and rise, as well as over Blake's Plateau, Hudson Canyon, and similar features. The cruise did not sample over the abyssal ocean, and never approached the center of the North Atlantic Gyre.

Current, measured by the ADCP, indicated when the ship encountered the Gulf Stream, illustrated by long red lines on the cruise track (Figure 18).

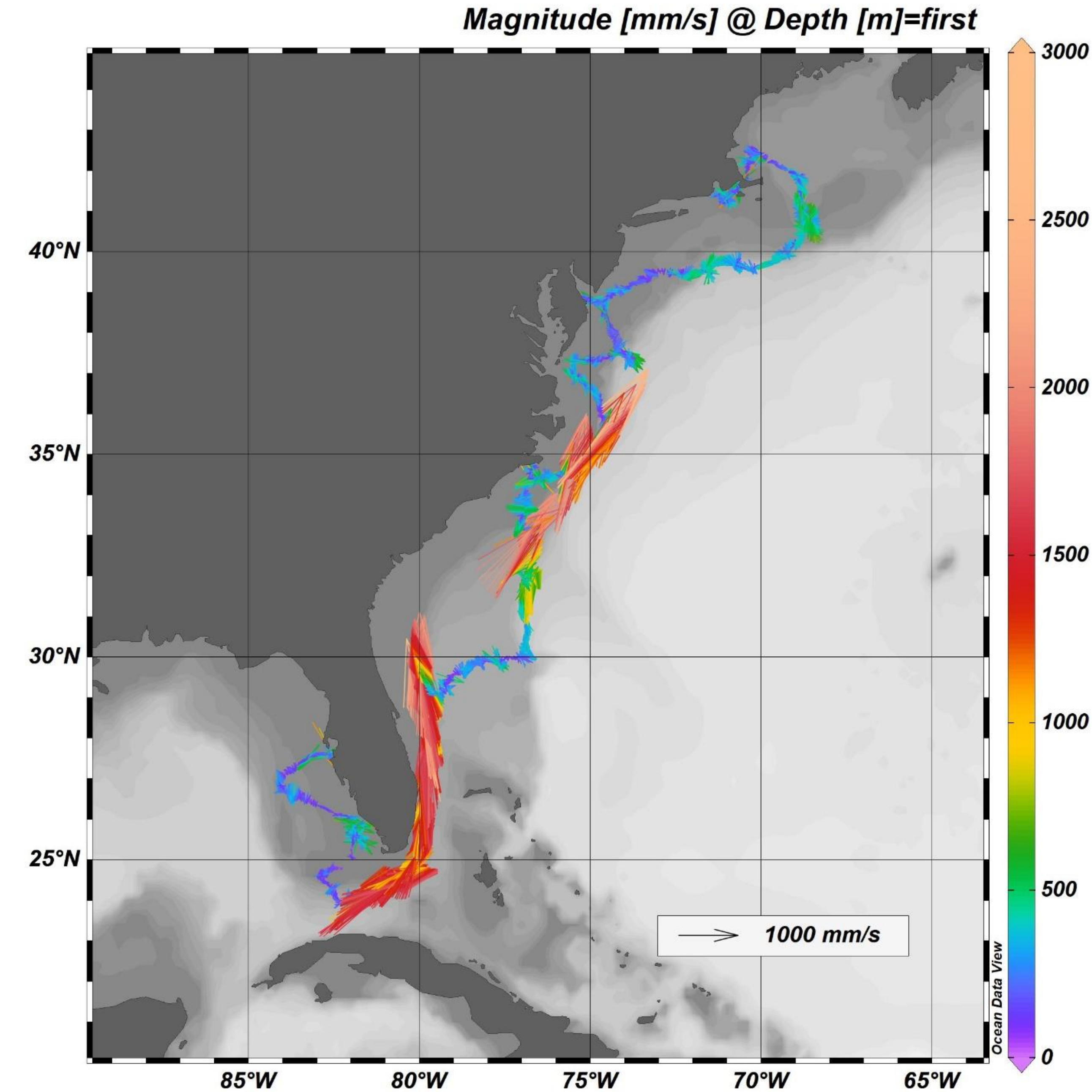

Figure 18. ODV map illustrating the current measured by the SSV Corwith Cramer along the cruise tract for SEA Semester C-297MBC. Current, measured via ADCP at a depth of 0-10m, is illustrated with an arrow pointing in the direction of current from the point of collection, and magnitude illustrated by line length and color (see: legends).

5.2.2. OpenDrift Models

Physical Oceanography: OpenDrift model outputs illustrate theoretical particle trajectories for each neuston tow in each LME. Animations produced by OpenDrift illustrate the projected particle trajectories of each model in time steps which show the speed, and therefore the movement, of the sample.

Source Region Identification: Each neuston tow (containing plastic) modelled in this study were hindcast to a potential source location. These points at which the particles "stranded" in OpenDrift are considered potential source locations for the plastic, unless the particles entered the water at some other point on the trajectory path by direct deposition into the ocean via a marine source. I mapped neuston tows 006, 010, 013, 022, 024, 039, 041, and 048, which contained greater than five pieces of plastic, using OpenDrift to identify potential source regions. When all 1000 or 5000 (depending on the calculation) particles in a sample stayed on the same projected path, it has a low projected variability and thus a high reliability (Dagestad and Hope, 2020). When a projected path splits into numerous projected pathways for particles, the potential source region is predicted with high potential variability and low reliability (Dagestad and Hope 2020). NT 006, for example, was collected at 25.1175° N, 81.96806° W and traced back with very high confidence to approximately 24.55° N, 81.72° W (Figure 19).

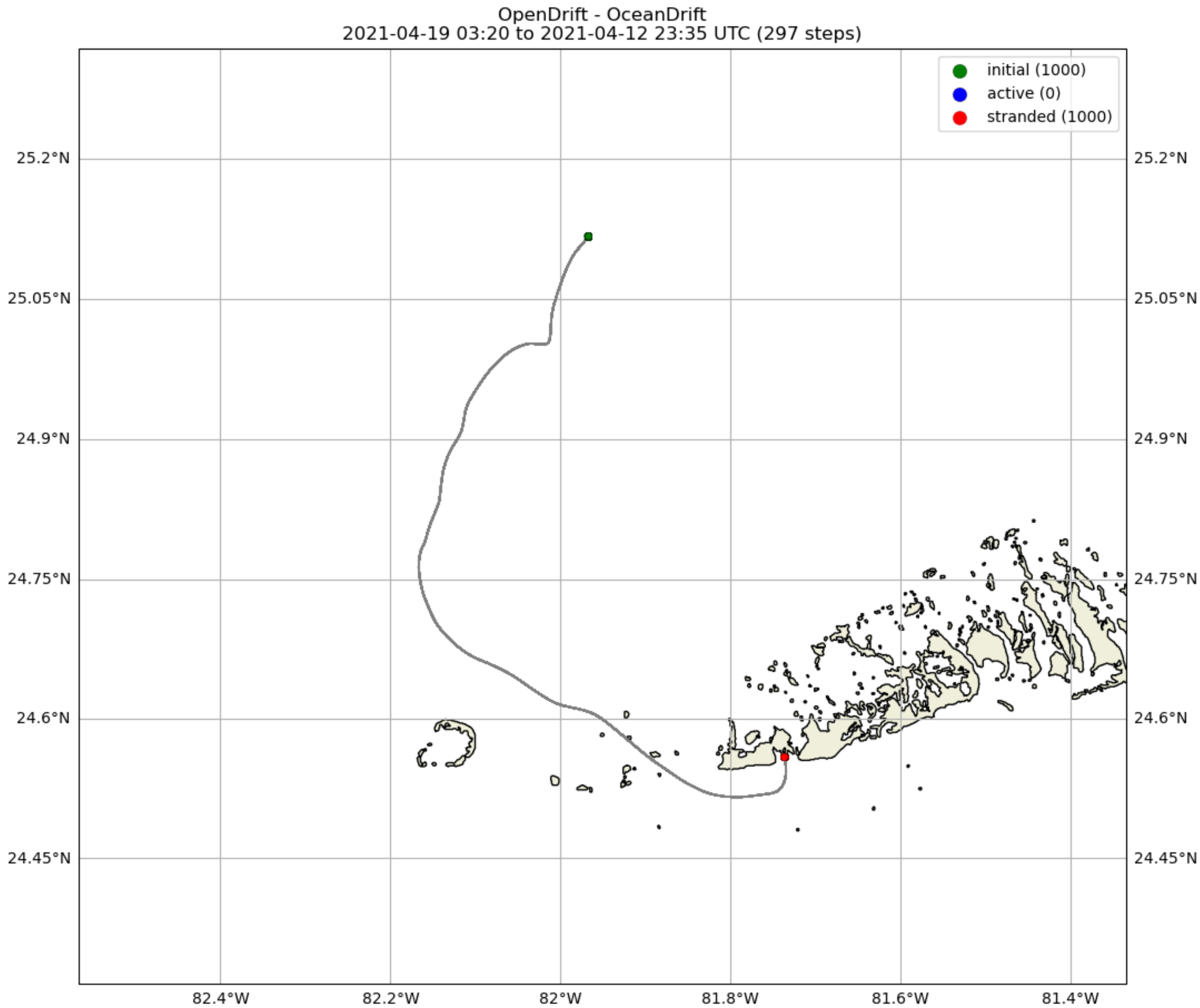

Figure 19. Hindcasting of C-297MBC NT 006, collected at 25.1175° N, 81.96806° W (green dot) at 03:20UTC on 4/19/2021 and calculated using 1000 particles for Lagrangian reliability. All particles were calculated to "strand" at 24.55° N, 81.72° W (red dot) by 4/12/2021, identifying this as the source for plastics collected by NT 006. Grey path between the NT location and stranding location shows the probable path taken by the plastics: thin path indicates little variability in calculated plastic motion.

NT 006 was released into the environment and was caught in currents which rapidly pulled the sample North to the point of collection in the Gulf of Mexico (Figure 19). OpenDrift calculated that the date of release (stranding) was approximately one week before the date of sample collection (Figure 19). The coordinates of the "stranding point," or origin, of NT 006 correspond to Key West, Florida (Figure 20, 21, 22).

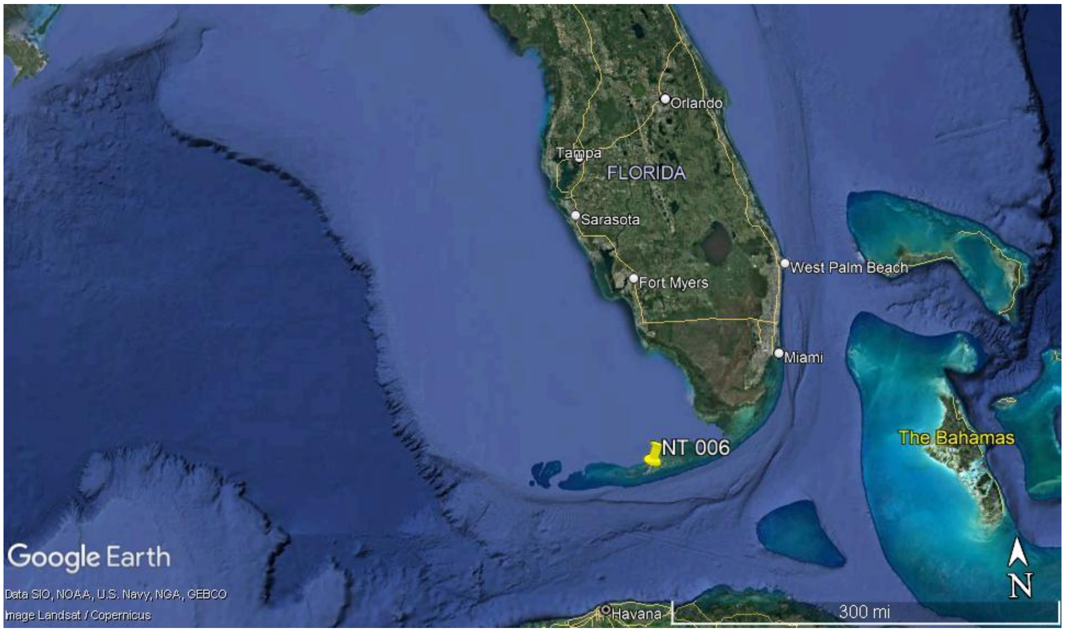

Figure 20. Location of 24.55° N, 81.72° W, the stranding location of NT 006 calculated by OpenDrift, zoomed out for scale with Florida on Google Earth Pro.

Figure 21. Location of 24.55° N, 81.72° W, the stranding location of NT 006 calculated by OpenDrift, zoomed in for location identification and for scale with Florida on Google Earth Pro. Coordinates correspond to Key West, FL.

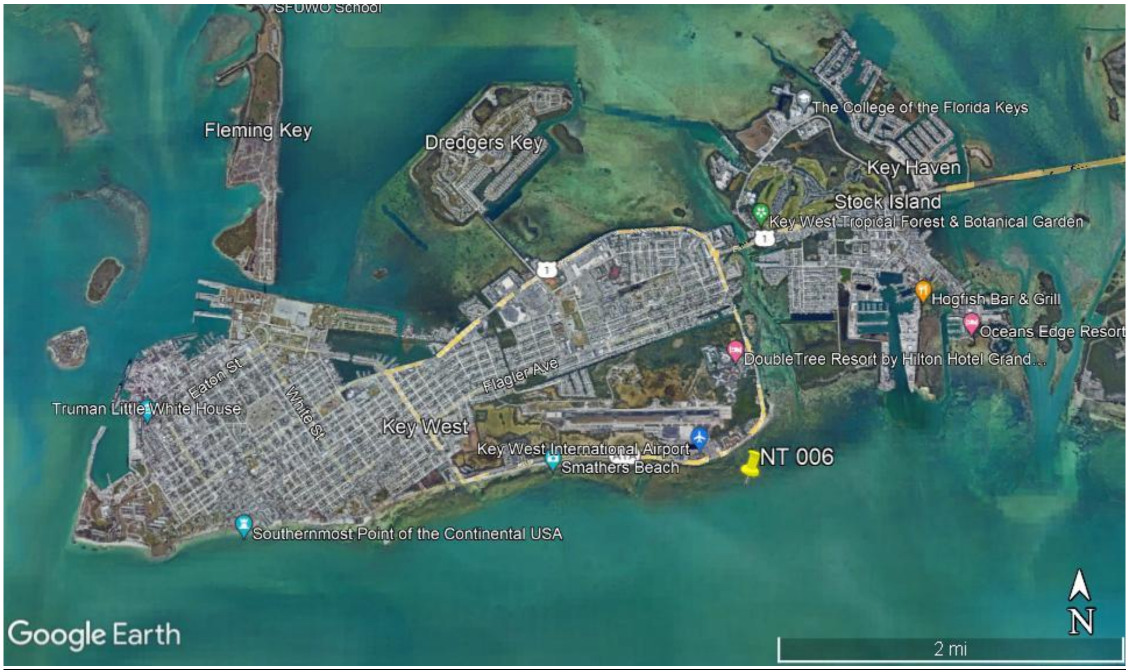

Figure 22. Location of 24.55° N, 81.72° W, the stranding location of NT 006 calculated by OpenDrift, showing local urbanization of Key West on Google Earth Pro.

NT 010, collected at 23.985° N, 82.10111° W, hindcast with strong confidence to approximately 22.4° N, 84.4° W (Figure 23).

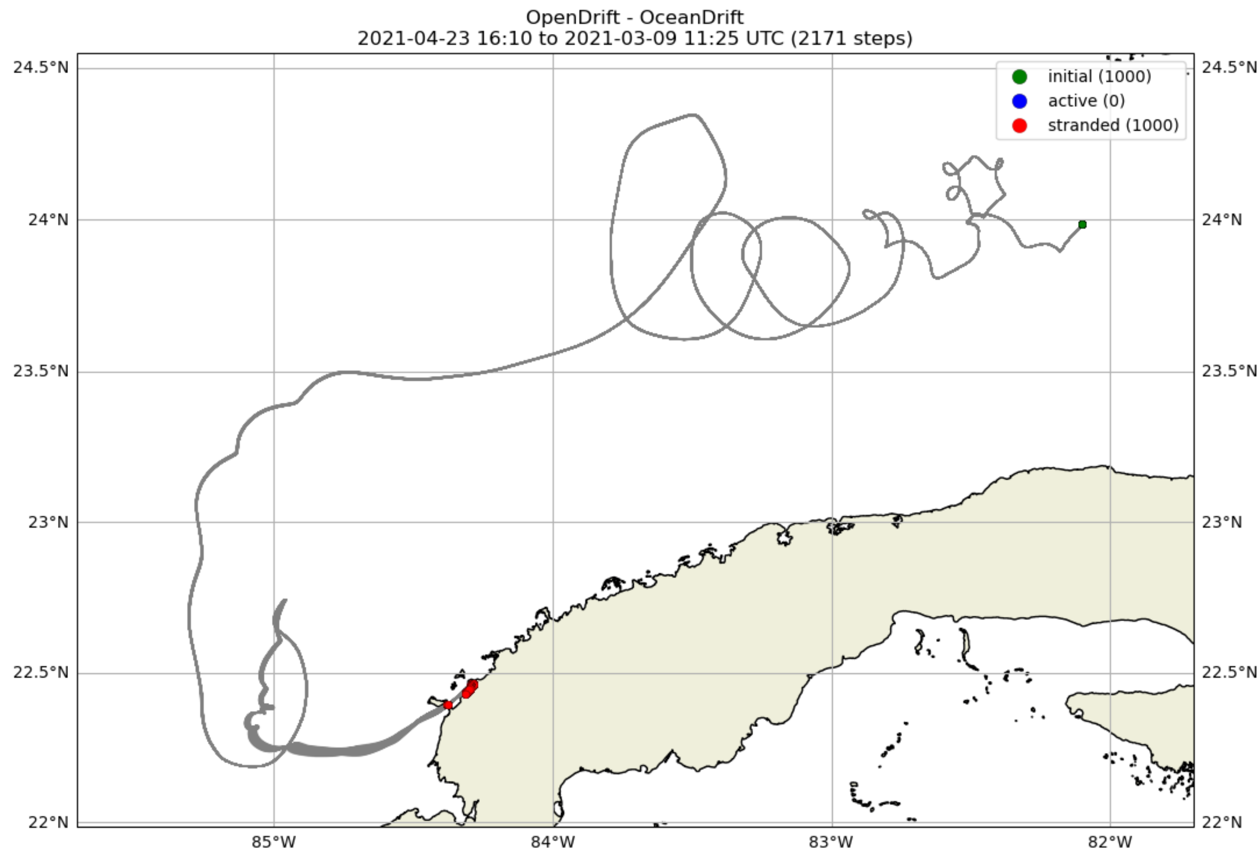

Figure 23. Hindcasting of C-297MBC NT 010, collected at 23.985° N, 82.10111° W (green dot) at 16:10 UTC on 4/23/2021 and calculated using 1000 particles for Lagrangian reliability. All particles were calculated to "strand" at around 22.4° N, 84.4° W (red dots) by 3/9/2021, identifying this as the source for plastics collected by NT 010. Grey path between the NT location and stranding location shows the probable path taken by the plastic: thicker path indicates more possible variability in plastic movement.

OpenDrift predicted that this sample originated (stranded) at the Northwestern end of Cuba (Figure 23), from which point it was pulled North, made a loop, and then continued North before being caught in a spiraling motion before the point of collection (Figure 23). The coordinates of the stranding point of NT 010 correspond to Northwestern Cuba, in an island inlet (Figure 24, 25).

Figure 24. Location of 22.4° N, 84.4° W, the stranding location of NT 010 calculated by OpenDrift, zoomed in for location identification and for scale with Florida on Google Earth Pro. Coordinates correspond to Northwestern corner of Cuba.

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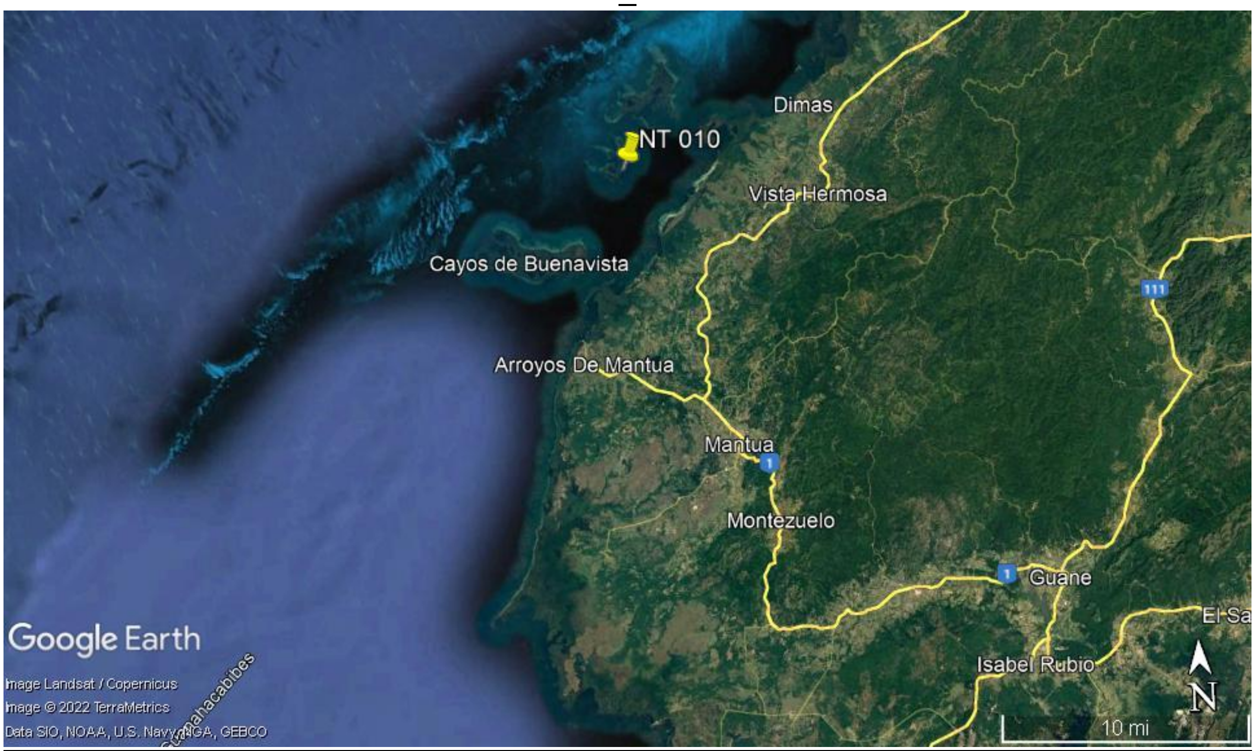


Figure 25. Location of 22.4° N, 84.4° W, the stranding location of NT 010 calculated by OpenDrift, zoomed in for location analysis on Google Earth Pro. Image indicates coordinates correspond to a coastal inlet.

NT 013, collected at 25.43556° N, 79.98556° W, hindcast with high variability to Western Cuba, waters South of Cuba, or a Loop Current-related anticyclonic eddy Northwest of Cuba (Communications to Physical Oceanography 2021) (Figure 26).

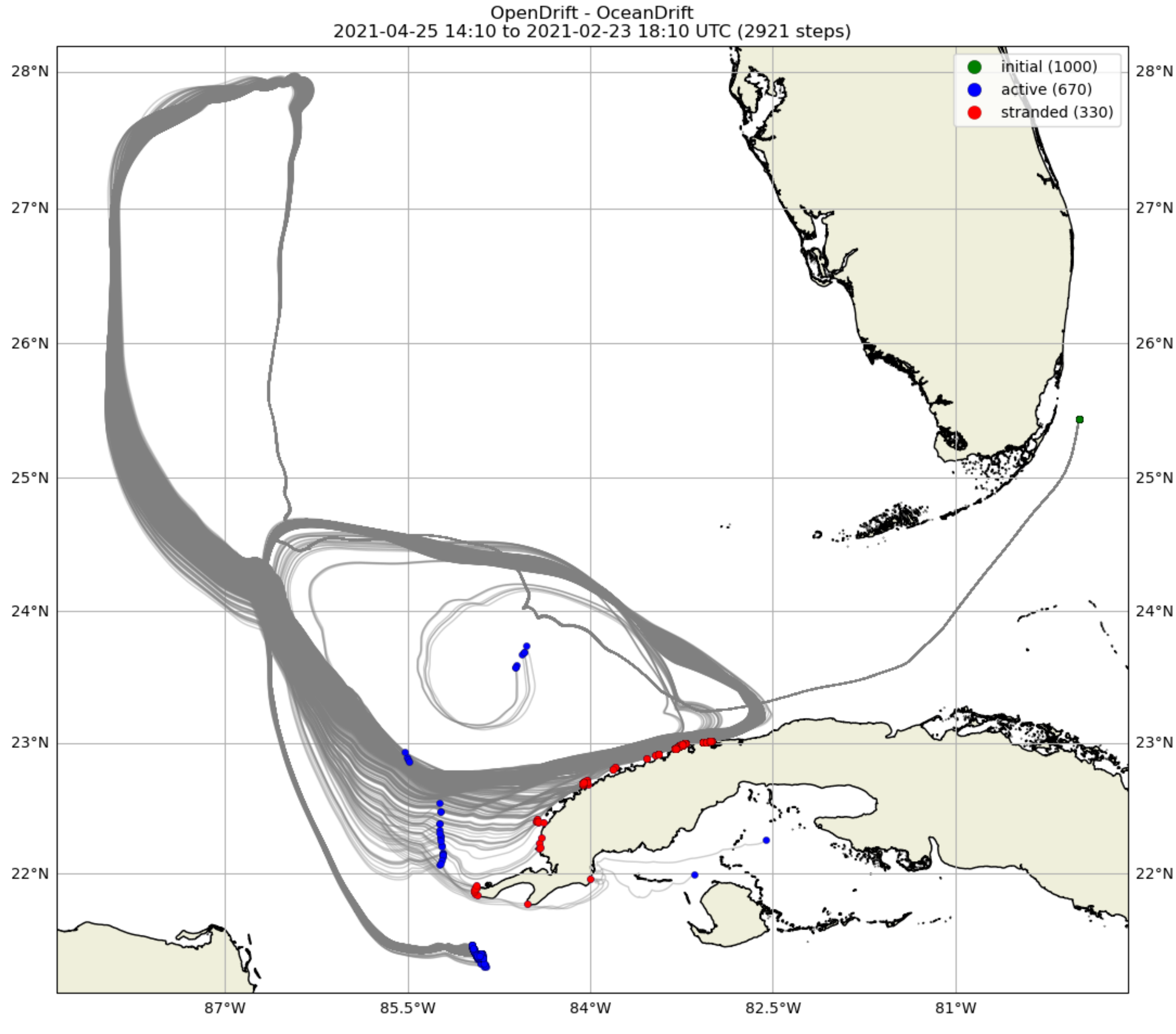


Figure 26. Hindcasting of C-297MBC NT 013, collection point marked by the green dot at 14:10 UTC on 4/25/2021 and calculated using 1000 particles for Lagrangian reliability. Particle trajectory paths traced reliably to above 27 degrees latitude, but the potential pathways branched after that point. Grey path between the NT location and stranding location shows the probable path taken by the plastic: a wider path indicates more possible variability in plastic movement.

The branching potential trajectories of this model indicate varying potential origin pathways for the plastics found in NT 013, and indicate that this sample had high variability and therefore the specific origin can only be narrowed to a region, rather than specific coordinates, due to this variability (Figure 26). The Northernmost hindcast stranding point is in Cuba, just West of Havana, while the Southernmost is off of the Southwestern tip of Cuba (Figure 27).

Figure 27. Location of the Northernmost and Southernmost stranding locations of NT 013 plastics, as calculated by OpenDrift in Figure 26, Image is zoomed in for location analysis on Google Earth Pro.

NT 022, collected at 29.7525° N, 78.43583° W, hindcast to maintain its overall geographic location over two months on Blake’s Plateau (Figure 28).

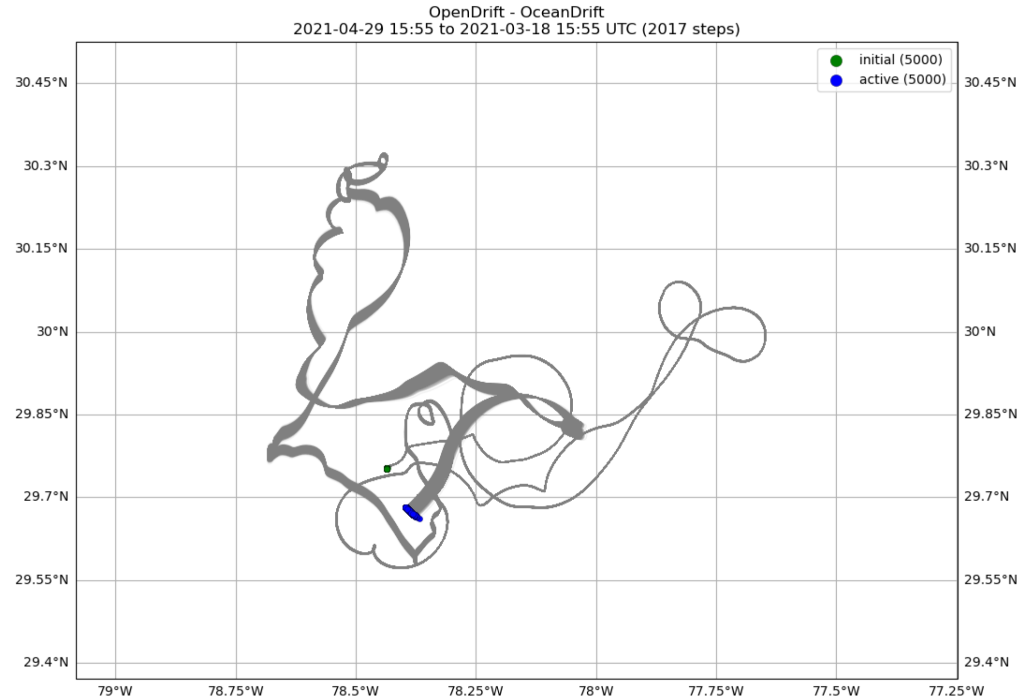


Figure 28. Hindcasting of C-297MBC NT 022 shows the plastic meandering offshore near the collection point between 03/18/2021 and the sample date of 04/29/2021. Unless this debris was deposited here by ships, this time frame for OpenDrift calculations were unable to identify a source region.

The model indicates that six weeks prior to sample collection, the plastics in NT 022 were located at 29.65° N, 78.35° W. This model illustrates a meandering spiral pathway for NT 022, while generally staying in the same location overall over marine plateau off of Eastern Florida (Figure 29).

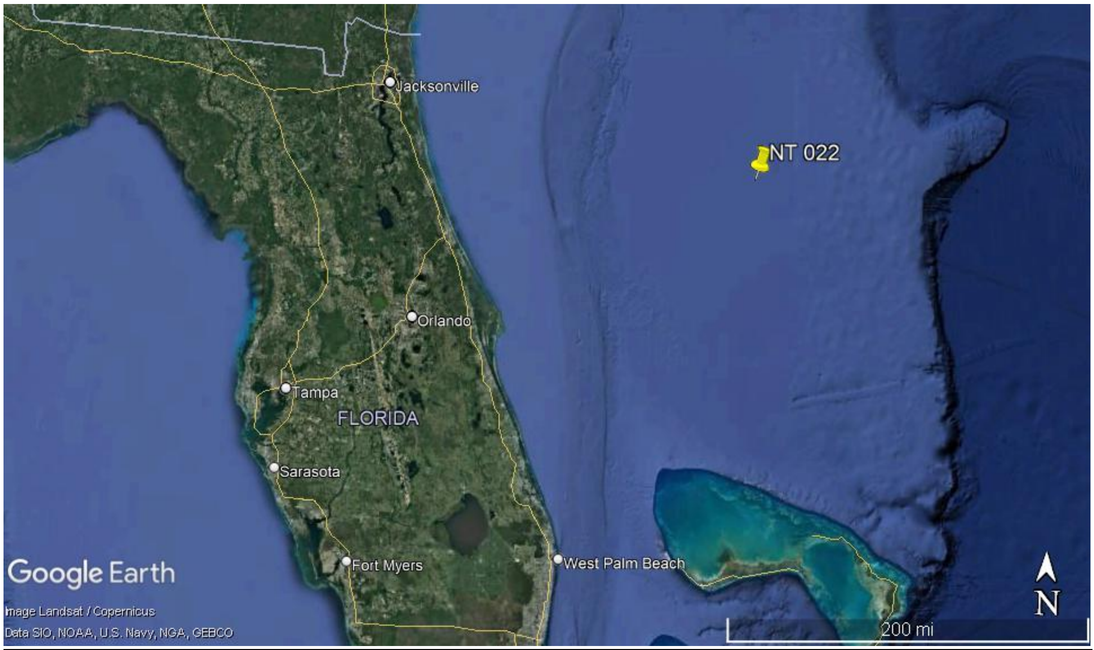


Figure 29. Location of final calculated location of NT 022 at 29.65° N, 78.4 ° W.

NT 024, collected at 30.18333° N, 76.80111° W, streamlined through the Florida Straights via the Gulf Stream (Figure 30).

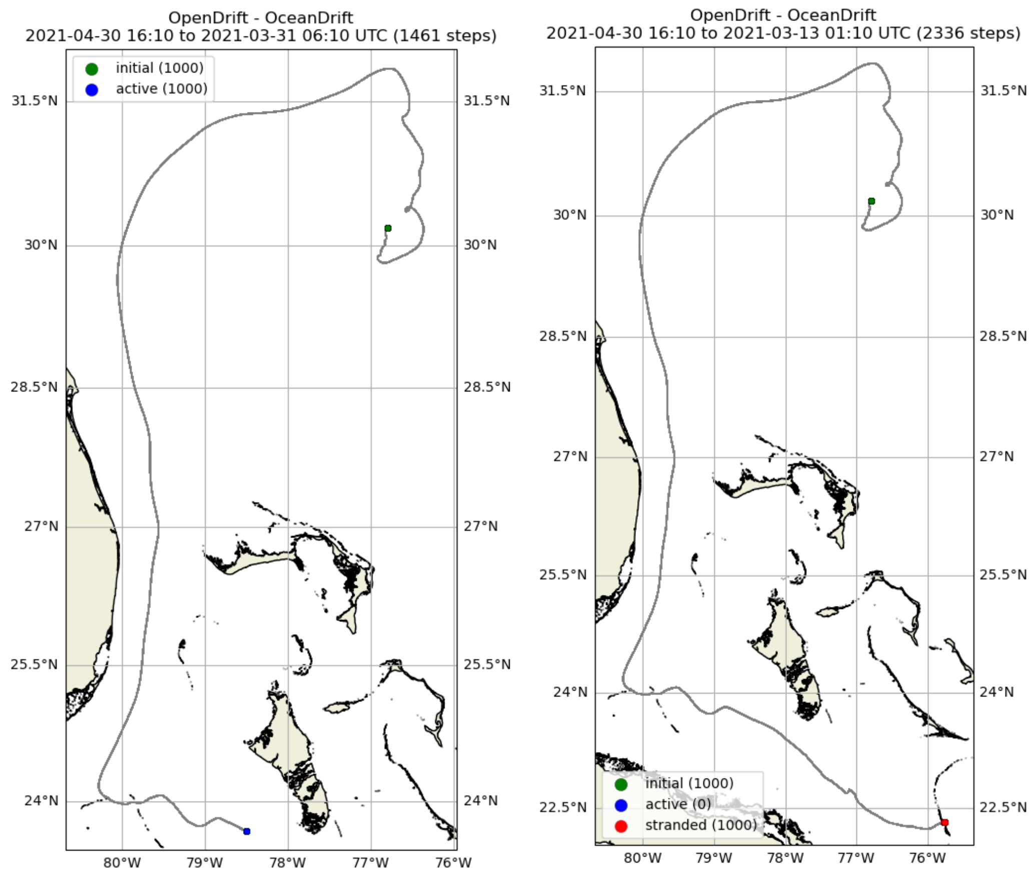


Figure 30. Hindcasting of C-297MBC NT 024, collection point marked by the green dot from 16:10 UTC on 4/30/2021 and calculated using 1000 particles for Lagrangian reliability. Initial calculation (left), calculated for one month of hindcasting, with no stranding. A longer hindcasting period (right), calculated for two months, had the particles stranding on a small island South of the Bahamas. Grey path between the NT location and stranding location shows the probable path taken by the plastics: thin path indicates little variability in calculated plastic motion.

The sample moved North from its origin location, before being caught in the Florida Straits and the Gulf Stream, which rapidly carried the sample Northward along the coast (Figure 30). The sample moved further offshore up the coast, exiting the Gulf Stream where it drifted slowly before the sample was collected (Figure 30). The stranding point of NT 024 was a small island South of the Bahamas, with high reliability (Figure 30, 31).

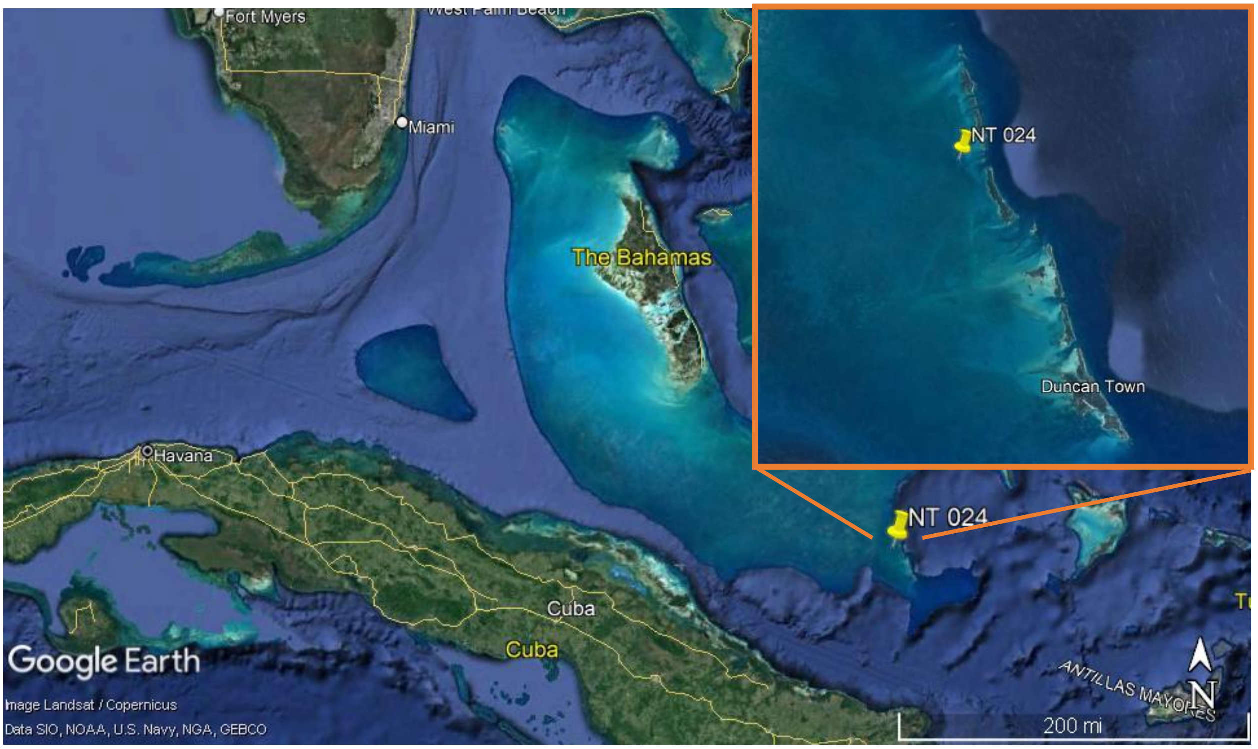


Figure 31. Location of the stranding location of NT 024 calculated by OpenDrift, zoomed in for location analysis on Google Earth Pro. Image indicates coordinates correspond to small island south of the Bahamas.

NT 030, collected at 36.26861°N, 74.70083° W, stranded at approximately 35.69° N, 75.49° W with very high confidence (Figure 32).

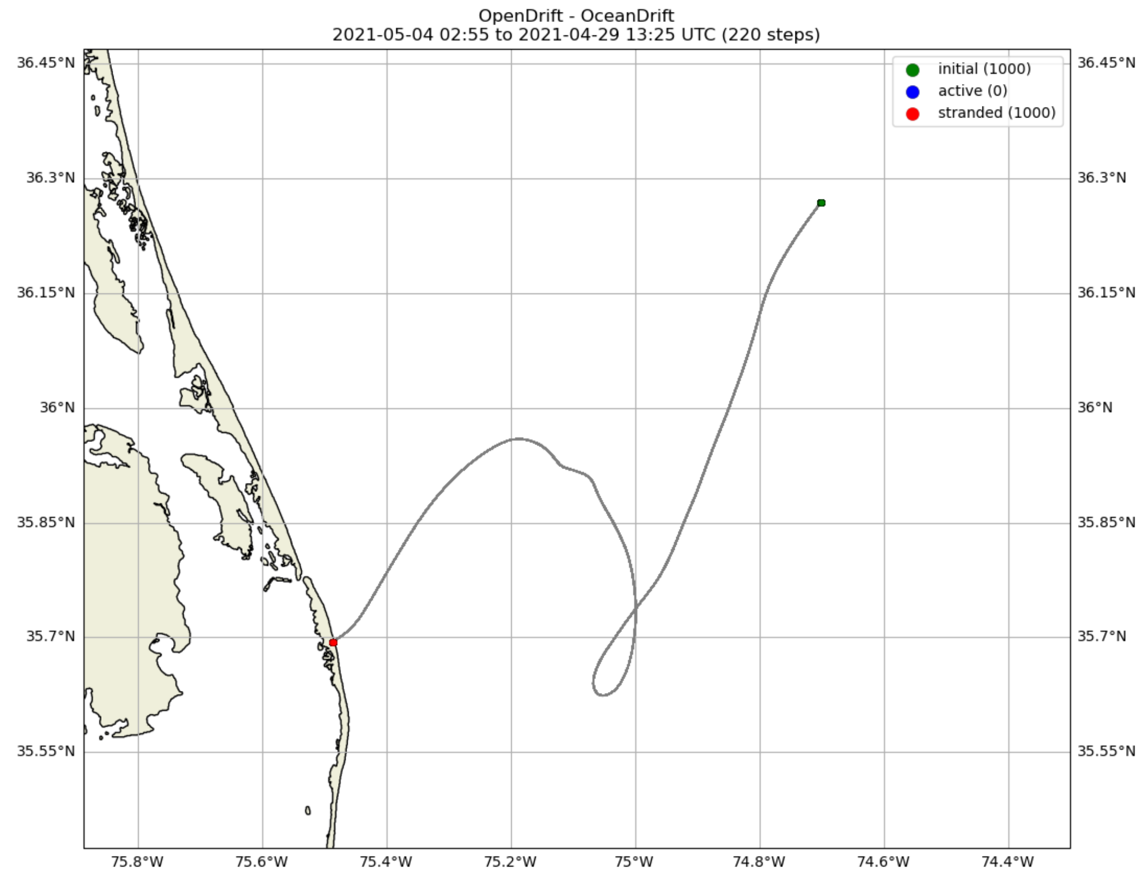


Figure 32. Hindcasting of C-297MBC NT 030, collected at 36.26861°N, 74.70083° W (green dot) at 02:55UTC on 05/04/2021 and calculated using 1000 particles for Lagrangian reliability. All particles were calculated to "strand" at 35.69° N, 75.49° W (red dot) by 04/29/2021, identifying this as the source for plastics collected by NT 030. Grey path between the NT location and stranding location shows the probable path taken by the plastics: thin path indicates little variability in calculated plastic motion.

OpenDrift suggests that this sample had a somewhat direct path from origin to collection location, moving generally Northeast, with only one loop in the path (Figure 32). These coordinates correspond to a barrier island off North Carolina, between the Atlantic Ocean and the Pamlico and Albemarle Sounds (Figure 33).

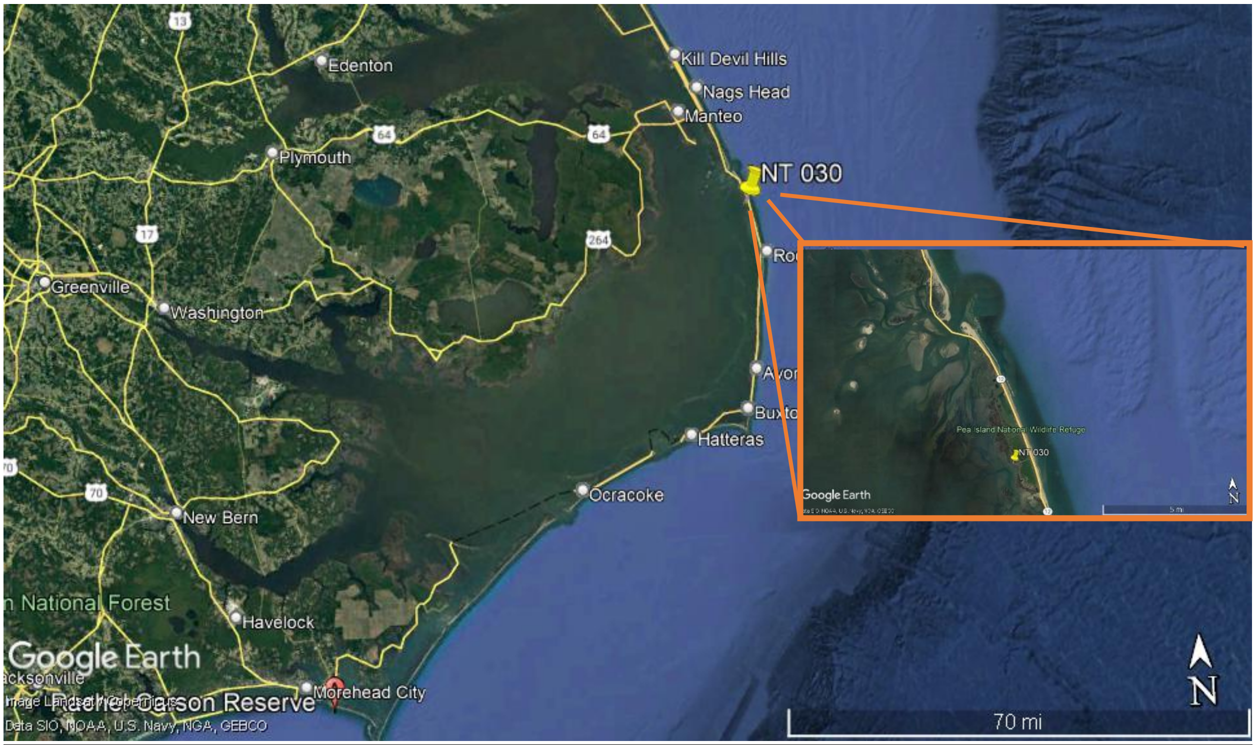


Figure 33. Location of the stranding location of NT 030 calculated by OpenDrift, zoomed in for location analysis on Google Earth Pro. Orange box shows magnified view of the "stranding" location, which appears to be a barrier to an estuarine environment.

NT 039, collected at 39.33389° N, 73.26861° W, stranded at approximately 39.35° N, 74.47° W with very high confidence (Figure 34).

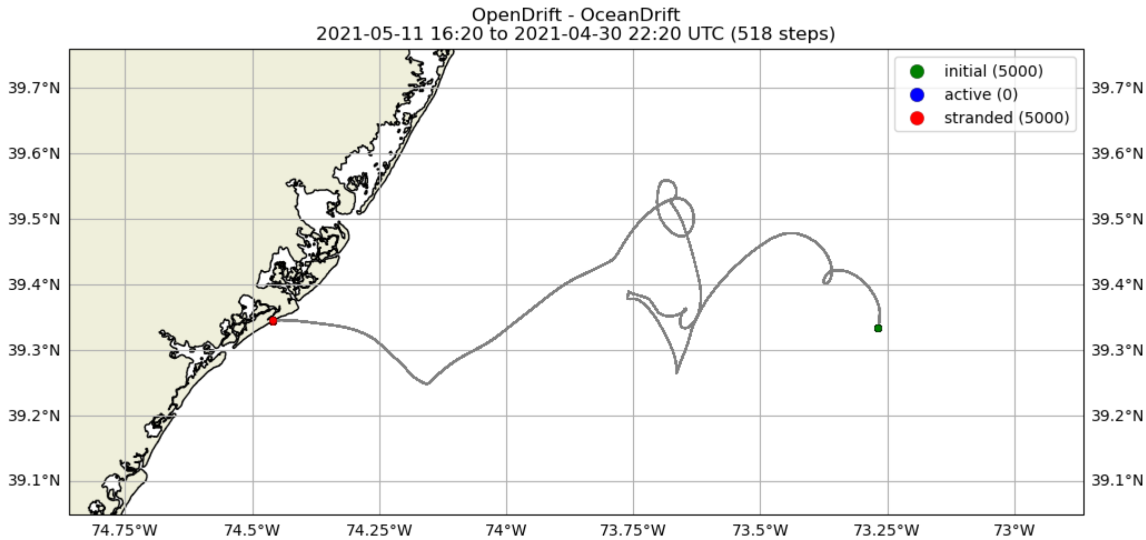


Figure 34. Hindcasting of C-297MBC NT 039, collected at 39.33389° N, 73.26861° W (green dot) at 16:20UTC on 05/11/2021 and calculated using 5000 particles for Lagrangian reliability. All particles were calculated to "strand" at 39.35° N, 74.47° W (red dot) by 04/30/2021, identifying this as the source for plastics collected by NT 039. Grey path between the NT location and stranding location shows the probable path taken by the plastics: thin path indicates little variability in calculated plastic motion.

This stranding point corresponds with Atlantic City, NJ (Figure 35) and had an erratic, yet low-variability, projected pathway (Figure 34).

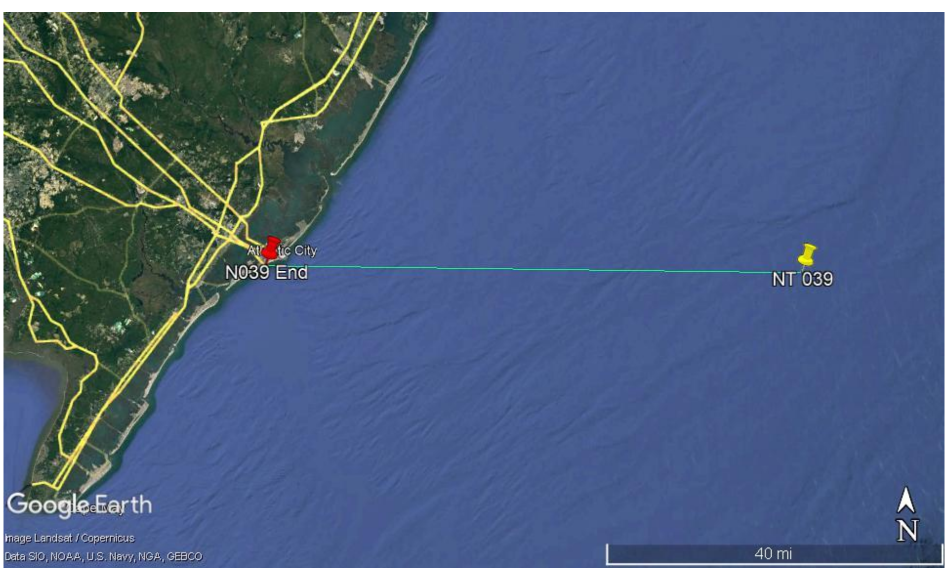


Figure 35. Location of the stranding location of NT 035 calculated by OpenDrift, zoomed in for location analysis on Google Earth Pro. Image indicates coordinates corresponds to Atlantic City, NJ.

NT 041, collected at 39.50222° N, 71.51917° W, stranded at 40.05° N, 74.1° W with high reliability.

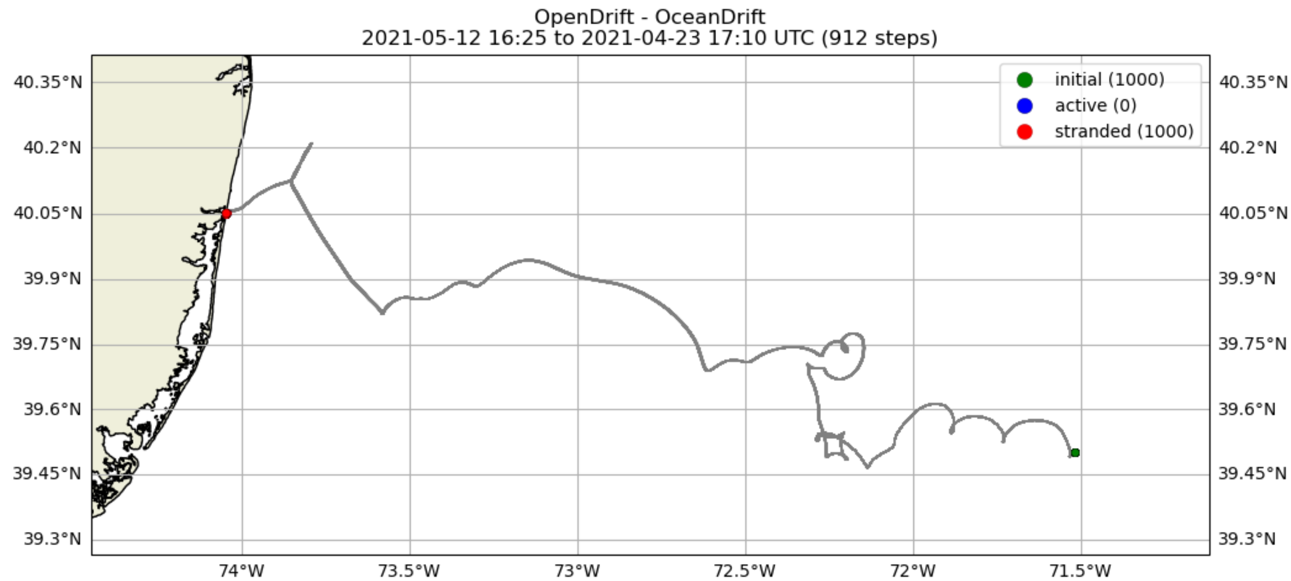


Figure 36. Hindcasting of C-297MBC NT 041, collected at 39.50222° N, 71.51917° W (green dot) at 16:25UTC on 05/12/2021 and calculated using 1000 particles for Lagrangian reliability. All particles were calculated to "strand" at 40.05° N, 74.1° W (red dot) by 04/23/2021, identifying this as the source for plastics collected by NT 041. Grey path between the NT location and stranding location shows the probable path taken by the plastics: thin path indicates little variability in calculated plastic motion.

While the Lagrangian particle trajectory has little variation, this path has many different changes in direction, and exhibits a spiral-like path further offshore (Figure 36). The origin ("stranding") location indicated by OpenDrift corresponds to a highly urbanized barrier island along the New Jersey coastline (Figure 37,38).

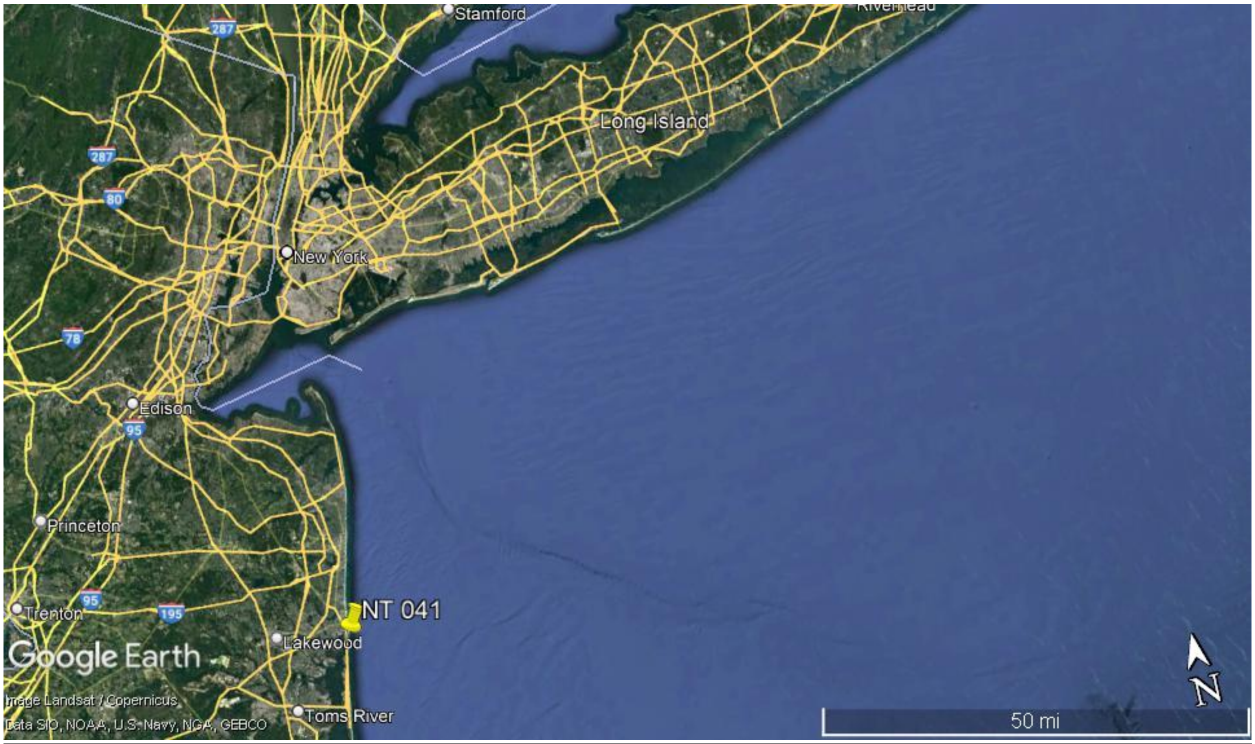


Figure 37. Location of 40.05° N, 74.1° W, the stranding location of NT 041 calculated by OpenDrift, zoomed out for scale with Long Island, NY on Google Earth Pro.

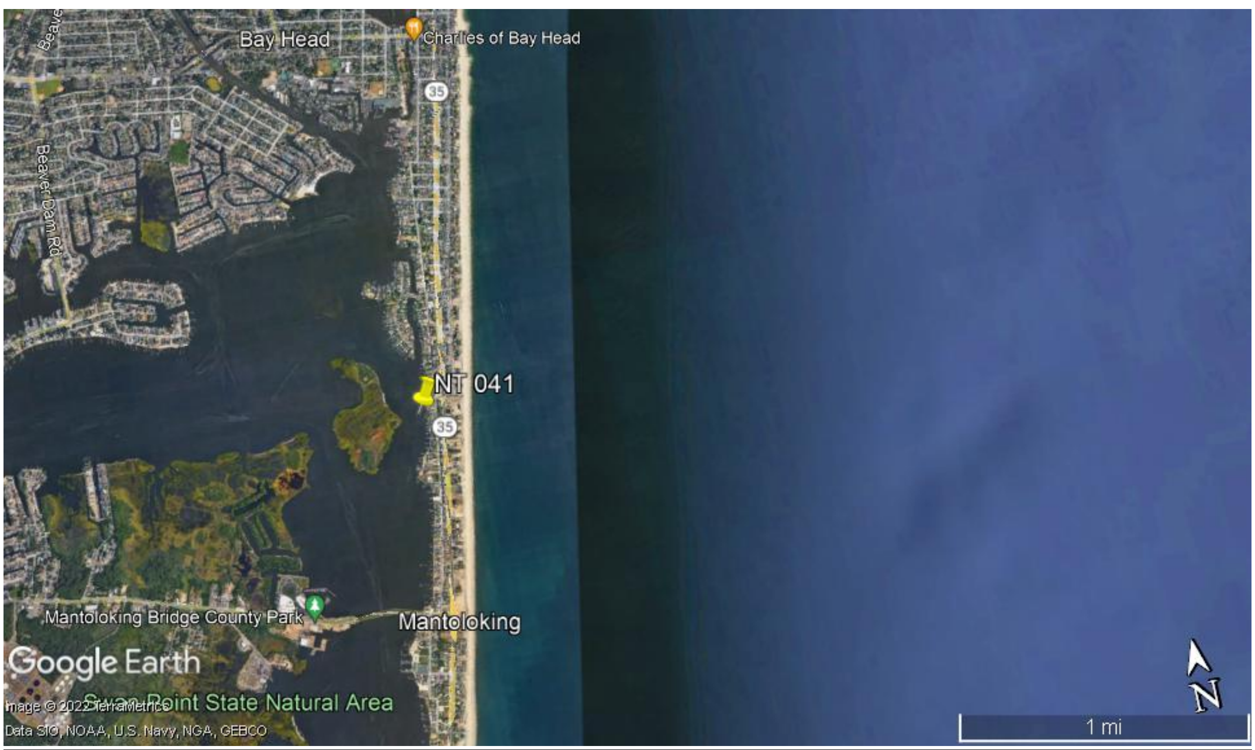


Figure 38. Location of 40.05° N, 74.1° W, the stranding location of NT 041 calculated by OpenDrift, for identification of this area as a highly developed barrier island on Google Earth Pro.

NT 048, collected at 42.43417° N, 70.16917° W, hindcast to approximately 42.64° N, 70.625° W with very high confidence (Figure 39).

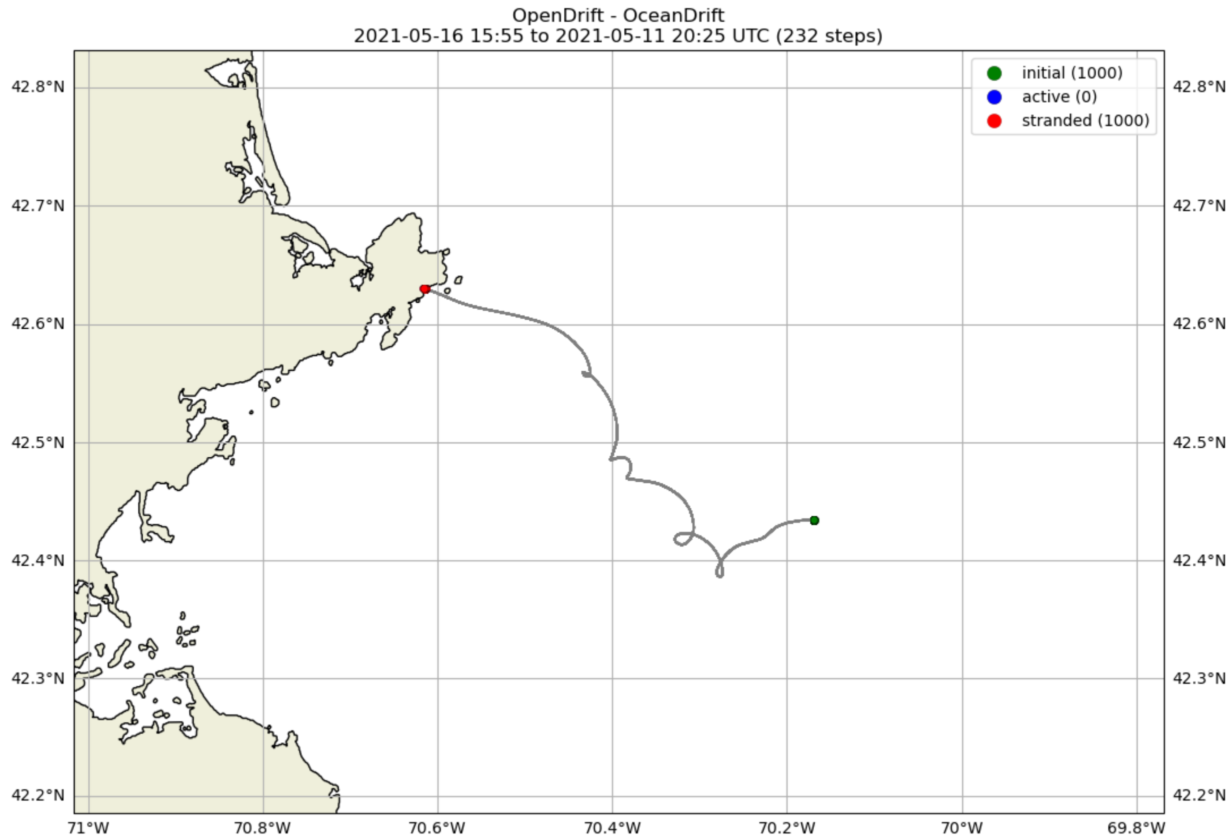


Figure 39. Hindcasting of C-297MBC NT 048, collected at 42.43417° N, 70.16917° W (green dot) at 15:55UTC on 05/16/2021 and calculated using 1000 particles for Lagrangian reliability. All particles were calculated to "strand" at 42.64° N, 70.625° W (red dot) by 05/11/2021, identifying this as the source for plastics collected by NT 048. Grey path between the NT location and stranding location shows the probable path taken by the plastics: thin path indicates little variability in calculated plastic motion.

The model indicates that this sample was not in the marine environment long, with the model "stranding" after 4.8 days (Figure 39). The path was mostly direct from source to location, with only some slight looping (Figure 39). These coordinates correspond to somewhere between Gloucester and Rockport, MA (Figure 40).

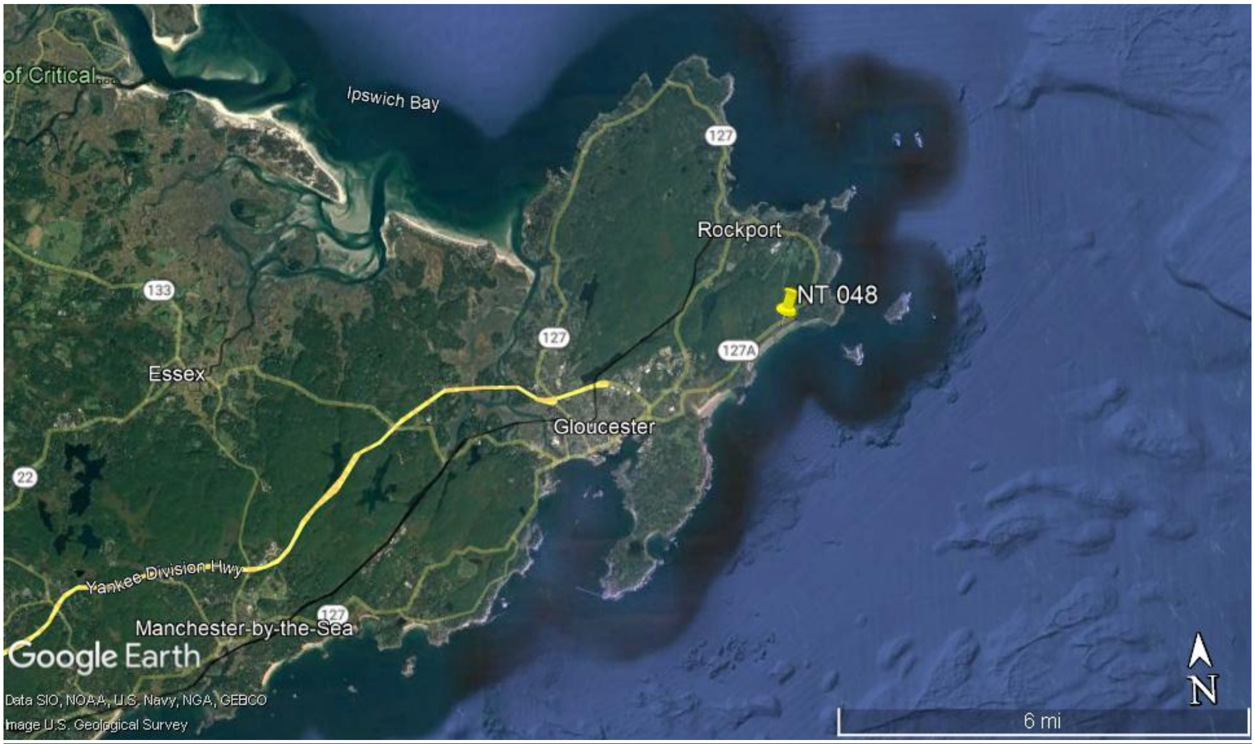


Figure 40. Location of 42.64° N, 70.625° W, the stranding location of NT 048 calculated by OpenDrift, for identification of this area as being located between Gloucester and Rockport, MA on Google Earth Pro.

6. INTERPRETATIONS

6.1. Ecological: Plastic to Zooplankton Ratios

The Gulf of Mexico, Southeast, and Northeast LMEs each have differences in the amount and trends in their plastic to zooplankton ratios, likely reflecting variations regarding oceanographic conditions, location relative to the Gulf Stream, and proximity to source areas. The Gulf of Mexico LME showed negligible ratios in every sample taken, while the SE LME consistently had ratios of around 0.005 plastic to zooplankton. The NE had the highest variability, with two tows (NT-039 and 041) having unusually high plastic compared to plankton count ratios. When comparing weights, these trends persisted, but with increased variability. The GOM LME had negligible ratios, and the SE LME had low but noticeable ratios while the NE LME showed increased variability. The data collected by this study indicate that the Gulf of Mexico LME has little to no risk of bioaccumulation and biomagnification of plastics, which directly contradicts the research of Di Mauro *et al.* (2017). More research is needed to pursue this discrepancy.

The SE LME, on the other hand, had a consistently low risk of bioaccumulation and biomagnification throughout the LME. The NE LME has the highest risk, and had the highest variability. It is unclear why these trends are present: Diurnal migration may account for some of the variation, but other variables including current strength and direction, eddy locations, location to source, and other oceanographic conditions may be influential factors. Further analysis and studies are needed to determine what causes the differences between each LME and between variation between the count and weight ratios.

Zooplankton is more abundant at night, decreasing risk of ingestion for diurnal organisms at night compared to during the day. The data indicate that plankton are more abundant by count than plastic, but that plastic is more abundant by mass.

6.2. Oceanographic: Plastic Movement and Regional Sources

The hindcasting of each plastic-containing neuston tow indicates that, while origin regions for plastics can be identified, there is no one dominant source type (cities, estuaries), making it more difficult to target conservation efforts. NT006 and NT048 trace back to tourism locations of Key West, FL, and Gloucester, MA (respectively). NT 010, 013, 022, and 024 indicate that plastic is migrating from the South from Cuba and the Bahamas up to the Eastern Seaboard of the US. NT030 traces back to a barrier island protecting an estuarine output region. NT039 and NT041 both hindcasted to highly urbanized areas along the New Jersey coastline; Atlantic City, and a residentially-developed barrier island. Although the source locations of the plastic are diverse, this study indicates that tourism locations, coastal urbanized areas, and estuarine locations are probably sources of plastic along the Eastern seaboard.

7. DISCUSSION

7.1. Ecological: Plastic to Zooplankton Ratios

The Gulf of Mexico LME (GOM LME) had very little plastic compared to zooplankton with little variability, both by count and by dry weight (Figure 12, 13; See Supplementary Materials). The Southeast LME (SE LME) had low to medium plastic to plankton content with little variability (Figure 12,13). The Northeast LME (NE LME) had high variability with some samples having very little plastic to plankton content, and others having particularly high plastic to plankton content (Figure 12, 13). This supports my initial hypothesis, that each LME would have different plastic to zooplankton ratios due to their differing oceanographic characteristics.

Moore *et al* (2001) compared the zooplankton to plastic amounts in terms of the night and day differences between mean counts and mean masses, and showed that zooplankton was more abundant during the night than during the day in comparison to plastic, consistent with the effects of diurnal migration (Figure 2). A similar relationship exists in my data, as indicated by a marked increase of plankton during the night compared to the day. This supports the effects of diurnal migration on plastic to zooplankton ratios. Moore *et al.* (2001) showed that plankton had higher counts of zooplankton than plastic during both day and night, but plastic generally weighed more during day and night tows. Accordingly, at night there is decreased risk of plastic ingestion for diurnal organisms. This trend supports my hypothesis that the effects of diurnal migration would be evident in the plastic to zooplankton ratios.

Overall, the ratio of plastic count to zooplankton count was 1:5 in Moore *et al.*'s findings (2001) and approximately 1:18000 in the tows of this study. The weights were 6:1 plastic to zooplankton in Moore *et al.*'s findings (2001), 2:1 in Collignon *et al.*'s (2012) findings, and 1:94 in this study. Moore *et al.* (2001) analyzed samples that were collected in the middle of the Pacific Gyre, while this study analyzed samples taken from the coastal Western Atlantic. This may account for this discrepancy in ratios, as oceanic gyres, where currents congregate from the whole basin, accumulate plastics. Coastal areas, such as those analyzed in this study, have marine debris moved along by currents, rather than accumulating it in place (e.g., in the center of a gyre). This oceanographic accumulation would have been included Moore *et al.* (2001), but not in this study. This difference could have driven the difference in ratios seen between these studies.

If this study were to be completed in the center of the Atlantic Gyre, it may be a more direct source of comparison for Moore *et al.* (2001), although the temporal difference would still be a factor for variation. However, the usefulness of this study would be negated: as discussed in previous studies, the origins of plastics cannot be isolated easily from gyre samples, when it is difficult to tell how long a plastic particle has been in that location (Law *et al.*, 2010; Law, 2017, Veiga, 2016). By sampling coastally, the origin of the plastic can be readily identified by the methodology established in this study. To determine locations to focus on for plastic debris mitigation, coastal sampling is more practical than gyre sampling. Accordingly, another way to compare the Pacific and Atlantic Oceans would be to repeat this study in the coastal Pacific to provide a more direct comparison for this data.

The findings from this investigation supports some, but not all, of the conclusions from Moore *et al* (2001) and Collignon *et al.* (2012). The data from this study support their conclusions that zooplankton is more abundant by count than plastic, but does not support their results that plastic is more abundant by mass. Due to the lack of data from the North Atlantic Ocean prior to this study, and due to the differences in sample locations 20-year gap between Moore *et al.* (2001;2002) and this research, the risk level for ingestion of plastic in the North Western Atlantic is difficult to compare.

Overall, zooplankton were more abundant than plastic when analyzed by count, with a ratio of 1 plastic particle to 17,858 zooplankton individuals. Moore *et al.* (2001) found a ratio of 1 plastic to 5 zooplankton, a dramatic difference. This difference is likely due to the oceanographic conditions of the sample site as well as temporal difference; Moore *et al.* (2001) sampled in the North Pacific central gyre: a location with little upwelling and, accordingly, lower productivity than most coastal locations. The samples used in this study included both inshore and offshore transects, incorporating upwelling-driven productive locations that would exhibit higher biomass than samples taken in a gyre.

When analyzed by mass, Moore et al found a ratio of 6g per km^2 plastic to 1g per km^2 zooplankton, and Collignon *et al.* (2012) found a ratio of 2 g per km^2 plastic to every 1g per km^2 zooplankton. In this study, I found a ratio of 94g per km^2 plankton to every 1g per km^2 plastic (See Supplementary Materials). While there is a difference between this study and previous studies, the variation is likely due to differences in the sampling tow distances, as well as the effect of coastal upwelling on productivity of the sample sites.

This presents a possible avenue for research for how plastics may enter the food chain from the environment, food web dynamics which have been absent from previous research (Rochman, 2016). Due to the potential carcinogenic and endocrine disruptive effects of plastic as well as the possible influences of micro- and nano-plastics on proteins and the human body, understanding how humans may be exposed to plastic is an important topic for research (Godswill and Godspel, 2019; Holloczki and Gehrke, 2019; Koelmans, 2015; Rochman, 2015; Gruber *et al.*, 2022). This study makes the first step in this direction, by presenting methodology for identifying the potential for ingestion of plastics compared to zooplankton in the marine environment.

7.2. Oceanographic: Plastic Movement and Regional Sources

While the approach this study takes to identify source regions of plastic is new, it successfully identifies tourist-heavy, traffic-laden, urbanized, or estuarine regions as plastic debris origins and provides targets for future study. Existing remediation approaches of marine plastics focuses mostly on the clean-up of beaches and the marine environment, while the actual sources of plastic are not mitigated. The identification of regional source area types provides targets for future research and mitigation. This study also indicates that plastic originates from Cuba and the surrounding water in the Gulf of Mexico, which implicates Cuba as a large source of plastic debris, or that plastic is often dumped by ships into the Gulf.

8. LIMITATIONS OF STUDY

This study was limited by the mesh size of the neuston net (333 micrometers), and the methods of processing used in this study. By processing these samples in saltwater by hand, rather than using methodology described by Moore *et al.* (2001), plastics could have been missed, and plastics smaller than the eye can see (microplastics) would not have been counted in the plastic counts. Moore *et al.* (2001) treated the samples with 5% formalin before being soaked in freshwater and transferred to 50% isopropyl alcohol. Then, the samples were strained and put back in seawater, at which point the plastic materials floated while living material stayed at the bottom (Moore *et al.*, 2001). This methodology would have provided a more accurate means for the isolation of plastics in this study rather than attempting to pick out samples by hand, mixed in with the living material.

Another limitation of this study was seasonal: sampling occurred in Spring 2021, whereas the Eastern Seaboard experiences varying degrees of productivity based on the season. Accordingly, the proportion of plastic to zooplankton likely varies with the season, an effect which is outside the scope of this study.

This study was further limited by the datasets used in OpenDrift, as for these calculations, only global models were used. The models could be made more accurate with the addition of more local datasets for the model runs. The most limiting factor on this study is the lack of previous work. This study is the first of its kind to use hindcast modelling methodology, and the ecologic analyses have not been performed in the Atlantic, or since 2012 in general (Moore *et al.* 2001, Moore *et al.* 2002, Collignon *et al.* 2012). This lack of information and background data has limited the conclusions of this study to be mostly speculative, rather than comparisons to previous trends.

9. FUTURE WORK

This study developed a baseline for plastic to zooplankton ratios in the North Western Atlantic Ocean. Future research should repeat this study to confirm that the relative abundances of plastic to zooplankton observed are characteristic for each LME sampled. Additionally, future research should utilize the methods used by Moore *et al.* (2001;2002) to develop plastic to zooplankton ratios for the North Atlantic Gyre and Sargasso Sea. Studies should be conducted approximately every two years (and in different seasons) in order to determine whether plastic abundances relative to zooplankton abundances is changing over time.

In order to continue evaluating the potential for ingestion of plastics along the Eastern seaboard, research should be conducted in each of the four seasons (Spring, Summer, Fall, and Winter) to evaluate seasonal variability in plastic to zooplankton ratios, and to determine annual averages for each LME of plastic to zooplankton abundances.

In addition to continuing the plastic to zooplankton ecological analyses, future studies need to continue to analyze the effects of plastic on marine organisms, and on humans. Understanding the effects of plastic and plastic additives on organisms is an important step in plastics mitigation.

Furthermore, OpenDrift should be used to trace more plastic samples back to possible origin points. To do so, samples should be collected inside of the Gulf Stream to limit variability and refine the hindcasting methodology for origin identification. This will help to further establish what coastal regimes (tourism, urbanized areas, estuarine output regions) are at the highest risk factor for the input of plastics into the marine environment. By better understanding where plastic is coming from, plastics can be better mitigated for the sake of conservation.

Plastics are still a new avenue of research, and while this study was unable to make definitive conclusions about the state of plastic abundances along the Eastern seaboard, it provides baseline work for future studies to develop a more comprehensive understanding of how much plastic is in each area (compared to the number of zooplankton), and where that plastic is coming from.

10. CONCLUSIONS

Each LME analyzed in this study has slightly different potentials for plastic ingestion and, accordingly, different risks for bioaccumulation and biomagnification. This, in turn, indicates that seafood from these regions may have varied plastic content liable for human ingestion. More studies are needed to further analyze these trends and their potential impacts, as significance of ratios of plastic to zooplankton in the Atlantic are not yet established, bioaccumulation and biomagnification of plastics in the marine environment are not yet confirmed, and the effects of plastic ingestion on humans is not fully understood. When compared to Moore *et al.* (2001), the ratios of plastic to zooplankton found in this study are low, and may not initially appear concerning. This conclusion, however, cannot be confirmed, due to the lack of information on coastal ratios and of the Atlantic Gyre: more research is needed to determine the level of significance for potential plastic ingestion as interpreted by this study.

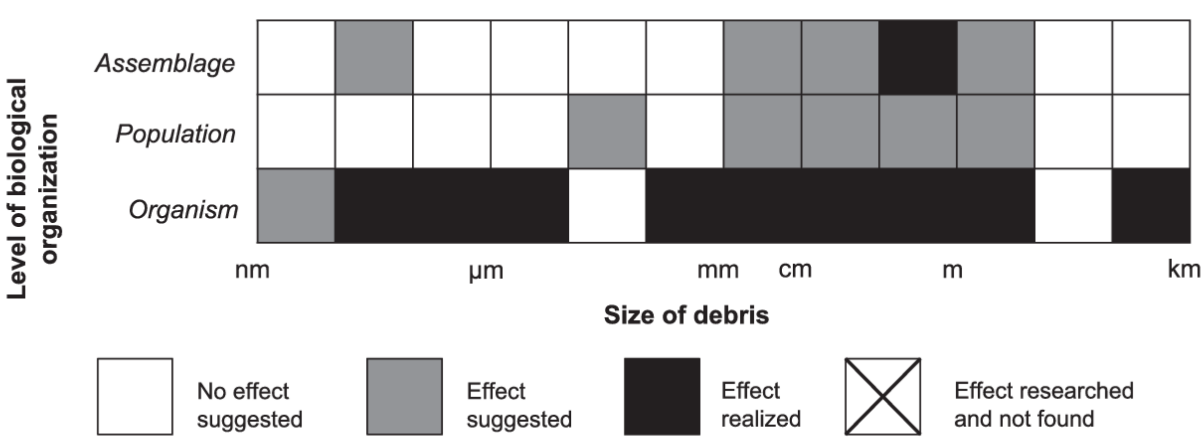
This study also shows that there is not one dominant source type for the origin of marine plastic debris; that is to say, one source type (urbanized areas, tourism areas, estuarine regions) is not the predominant source for plastic debris, as shown by this study. Accordingly, any conservation efforts must be multi-pronged to address different sources. Hindcasting models such as those in this study allow for a future avenue of identification of plastic origins for conservation and remediation priorities. This study identified tourist-heavy, traffic-laden, urbanized, and estuarine regions as plastic debris origins, and also identified Cuba and surrounding waters as a major source of plastic debris.

The conclusions of this study, in summary, are first, that plastic was found in neuston tow samples collected along the Eastern Seaboard between March and May, 2021. Second, that the plastic samples found are similar in size to zooplankton, and can thus may be mistaken as food by other organisms and ingested. Third, that there are many oceanographic factors (temperature, salinity, depth, current, and more) which cause source tracing complexity. This potentially explains some of the variability seen between samples in this study. Fourth, there are various sources of marine plastic debris on the Eastern seaboard, including (but not limited to) the OpenDrift-identified tourist-heavy, traffic-laden, urbanized, and estuarine regions named in this study. And finally, that hindcasting modelling appears to be a viable approach for tracking marine plastic debris, and while this methodology can be improved upon, it is an exciting avenue for future work.

11. APPENDIX

Table 1. Table from Rochman (2016) illustrating the level of biological organization previous plastic-related studies analyzed (a) and the names of the studies and their classified level, size range analyzed, and causes of impact (b).

a



b

Reference Cited	Level of Organization	Size Range	Cause of Impact
Beck and Barros *Mar. Pollut. Bull.* **1991**, *22*, 508-510.	Organism	100 mm – 10 m	ingestion
Bjorndal et. al. *Mar. Pollut. Bull.* **1994**, *28*, 154-158.	Organism	1 mm – 1 m	ingestion
Brandao et al. *Mar. Pollut. Bull.* **2011**, *62*, 2246-2249.	Organism	10 mm – 1 m	ingestion
Browne et al. *Curr. Biol.* **2013**, *23*, 2388-2392.	Organism	100 µm – 1 mm	ingestion
Bugoni et al. *Mar. Pollut. Bull.* **2001**, *42*, 1330-1334.	Organism	10 mm – 100 mm	ingestion
de Stephanis et al. *Mar. Pollut. Bull.* **2013**, *69*, 206-214.	Organism	100 mm – 1 m	ingestion
Fowler et al. *Mar. Pollut. Bull.* **1987**, *18*, 326-335.	Organism	1 mm – 1 m	entanglement
Gilardi et al. *Mar. Pollut. Bull.* **2009**, *60*, 376-382.	Organism	1 m – 10 m	entanglement
Good et al. *Mar. Pollut. Bull.* **2010**, *60*, 39-50.	Organism	100 m – 1 km	entanglement
Jacobsen et al. *Mar. Pollut. Bull.* **2010**, *60*, 765-767.	Organism	1 mm – 1 m	ingestion
Lee et al. *Environ. Sci. Technol.* **2013**, *47*, 11278-11283.	Organism	10 nm – 10 µm	ingestion
Moore et al. *Mar. Pollut. Bull.* **2009**, *58*, 1045-1051.	Organism	1 mm – 1 m	entanglement
Udyawer et al. *Mar. Pollut. Bull.* **2013**, *73*, 336-338.	Organism	10 mm – 100 mm	entanglement
Uhrin and Schellinger *Mar. Pollut. Bull.* **2011**, *62*, 2605-2610.	Organism	100 mm –1 m	smothering
Vélez-Rubio et al. *Mar. Biol.* **2013**, *160*, 2797-2811.	Organism	10 mm – 100 mm	ingestion
Katsanevakis et al. *Mar. Pollut. Bull.* **2007**, *54*, 771-778.	Assemblage	100 mm – 1 m	addition of habitat
Lewis et al. *New Zeal J. Mar. Fresh.* **2009**, *43*, 271-282.	Assemblage	100 mm – 1 m	smothering

Table 2. OpenDrift model inputs and outputs for each NT analyzed in this study.

Neuston Tow	Collection Latitude (degrees North)	Collection Longitude (degrees West)	Stranding Latitude (degrees North)	Stranding Longitude (degrees West)	Model start (date time UTC)	Model End (date time UTC)	Lagrangian particle quantity	Duration at Sea (days)
6	25.1175	81.96806	24.55	81.72	4/19/2021 03:20	4/12/2021 23:35	1000	7.8438
10	23.985	82.10111	22.4	84.4	4/23/2021 16:10	3/9/2021 11:25	1000	45.1979
13	25.43556	79.98556	~27	variable	4/25/2021 14:10	2/23/2021 18:10	1000	60.8333
22	29.7525	78.43583	29.65	78.35	4/29/2021 15:55	3/18/2021 15:55	5000	42
24	30.18333	76.80111	22	76.5	4/30/2021 16:10	3/13/2021 01:10	1000	48.625
30	36.26861	74.70083	35.69	75.49	5/4/2021 02:55	4/29/2021 13:25	1000	5.4375
39	39.33389	73.26861	39.35	74.47	5/11/2021 16:20	4/30/2021 22:20	5000	10.75
41	39.50222	71.51917	40.05	74.1	5/12/2021 16:25	4/23/2021 17:10	1000	18.9688
48	42.43417	70.16917	42.64	70.625	5/16/2021 15:55	5/11/2021 20:25	1000	4.8125

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