Polar Pollution: Modeling Potential Origins and Sinking of Plastic in the Arctic Ocean

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Plain Language Summary:

This study evaluates the delivery of microplastics to the Arctic Sea. Microplastics are defined as pieces of plastic less than 5 millimeters long. I used a wind-driven model called Adrift to first look at some locations where I thought these plastics could be coming from. The Adrift Model assumes all plastics float, but in reality, plastic distributions in the ocean are the result of a complex relationship between sinking and floating. Therefore, I added a sinking factor to model output to have a more accurate idea of where microplastics could be at any given time in the Arctic Ocean. I first decided on three locations of origin: The North Sea, the west coast of Iceland by Reykjavik, and the water by Greenland's largest town, Nuuk. These locations were chosen based on their proximity to Arctic-bound currents and higher populations near coastline. I modeled the plastics as if they all floated by coding several python animations using the raw data I downloaded from the Adrift site. I then did a literature search to procure microplastic sinking rates from several papers. I picked the slowest rate to start with, 0.001m/s. I assumed every particle sank and applied the sinking rate to figure out what depth the particles would be at, and then tested each sinking rate. I then let the particles float, adding on increments of two months to figure out how long the microplastics would have to float before they would make it into the Arctic. I found that particles from Iceland and Greenland would have to float for two months to travel to the Arctic, and particles from the North Sea would have to float for minimum six months. After 12 months of floating, Iceland had a 0.256 probability, Greenland had a 0.298 probability, and the North Sea had a 0.424 probability.

Abstract:

Increasing levels of plastic are being found in remote Arctic areas. Movement, sinking rates, and origins of plastic particles in the Arctic Ocean were evaluated using a modeling approach. The Adrift Model which moves particles through the ocean via modeling average currents and winds, was implemented and enhanced to add components that originally were not accounted for. With no

methods to remove plastics and the land being so remote, the Arctic is extremely vulnerable to plastic pollution. I determined the most likely sources (locations and countries) of the plastics being found in areas that have little or no human interaction. The Adrift Model only predicts particle movement in a single 15m cell at the surface of the ocean and does not account for particle sinking. Data was evaluated and visualized using Google Colab after computations on model output have been applied via Microsoft Excel to overcome these limitations. Based on the North Sea containing a large northbound current into the Arctic as well as it being the location for several major cities, I predicted that the primary source of plastic was near the North Sea. Iceland had a probability of 0.017 in Arctic after two months and 0.256 after one year, which is approximately 250 metric tons of plastic. Greenland had a 0.005 probability after two months and 0.298 after one year, which translates to 46 metric tons. Finally, the North Sea had a 0.00 probability after two months and 0.424 after one year, which translates to around 279,000 metric tons. The three chosen locations had plastic particles that traveled into the Arctic, with plastics from Iceland and Greenland having to float for two months, and plastics particles from the North Sea having to float for a minimum of six months to be carried into the Arctic.

Introduction:

Plastics are being found in increasingly remote locations of the Earth over the last fifteen years (Cózar et al., 2017). Since the introduction of plastics in the 1950's, global production rates have continued to grow and show no signs of waning (Cózar et al., 2014). Plastic was not viewed as an environmental threat for many years, especially in marine environments. (Moore, 2008). When the first articles of plastic pollution surfaced in the 1970s, they were met with little heed from the scientific community (Andrady, 2011). Now it is hypothesized that about four percent of all plastic waste generated around the world ends up in the ocean (Kvale et al., 2020). Despite the increasing levels of plastic in marine environments, the distribution and abundance of the debris is relatively unknown, although evidence points towards a rapid spread of plastics throughout the global ocean (Barnes et al., 2009). In the past, the scientific world turned most of its focus on subtropical gyres for plastic research due to these marine areas having high levels of accumulated debris(Cózar et al., 2017). Other areas such as the Polar and Antarctic regions were not prioritized due to the fact that there were no near sources of pollution (Cózar et al., 2017). However, with high concentrations of floating plastics being reported in these remote locations, there is cause for concern. It is now recognized that plastic originates from not only terrestrial sites, but from vessels as well which can lead to plastic items being found in very remote locations (Eriksson & Burton, 2003). One study conducted on several species of seabirds (Fulmar, Kittiwake, Murres, and Guillemots) in the Canadian territory of Nunavut concluded that over 72% of sampled Fulmars and 15% of Kittiwakes had consumed plastic (Baak, Provencher, & Mallory, 2020). In the Antarctic, one hundred and sixty four plastic particles were recovered in Fur Seal scat, most likely from eating pelagic fish who had previously consumed the plastic (Eriksson & Burton, 2003). These studies and others show us that plastics are infiltrating remote ecosystems and are working their way up the trophic levels. The polar/subpolar regions are especially vulnerable to this type of pollution. Many more-developed countries have implemented measures/policies to aid in the prevention of plastic pollution. In the Arctic, there are no methods of plastic prevention and no one to collect/monitor changes, making the far north a virtually unstoppable area of plastic accumulation.

The Adrift Model

The Adrift Model, created by Erik van Sebille in 2012, uses drifter data from the Global Drifter Program in combination with surface drifter buoys which in turn provides langrangian data (Van Sebille et al. 2012). The information from both sources is combined to show the possible outcomes of where this plastic will end up or in the case of using a reverse model, it will show the source of the plastic. Each drifter route is translated into a transition matrix which is representative of the global ocean. The time increments on the model are two months due account for seasonality and an appropriate number of diagonal crossings. This model does have a few constraints, first being that the model only shows plastic in the first 15m of water and assumes that the probability of the ocean's surface will always add up to one. This is due to the influence of wind and currents. The model also does not account for sinking or particles being removed by washing up onshore.

Modeling Plastic Sinking Rates

My research sought to add the component of depth into my model. Plastic sinking rates not only depend on size, fluid density and particle density, but also on the shape of the plastic, which leads to deviations from the theoretical values (Kowalski, Reichardt, & Waniek, 2016a). Due to the vast array of plastics, there are also huge discrepancies between sinking rates. Particles can range anywhere from 1-43x10^{-3} ms^{-1} (Kukulka, Proskurowski, Morét-Ferguson, Meyer, & Law, 2012) to 0.004-0.18 ms^{-1} (Chubarenko, Bagaev, Zobkov, & Esiukova, 2016). Chubarenko's values are extremely fast implying that a particle could sink 15km per day, so Kukulka's values will be applied to the model. The slower values were chosen to since the faster rates prevented the particles entering the Arctic. These values were calculated using the Dietrich formula (1982):

$$Theor\ V_s=((\rho_s-\rho_f)/\rho_f)g\nu\omega_*)^{1/3}$$

Where ρ_s=particle density, ρ_f =fluid density, g=gravity of earth, ν= kinematic velocity, and ω_*=dimensionless sinking velocity (Kowalski, Reichardt, Kukulka, and Chubarenko 2016).

I hypothesized that the main source of plastic will be the North Sea and countries surrounding, primarily England and the Netherlands. The North Sea is a small sea in between the UK and Norway/Sweden. The North Atlantic Current and the Norwegian Current both sit slightly outside the sea, transporting water northward (Hansen & Østerhus, 2000) . If particles were released at this point, they could be swept into the Norwegian Current, where they then travel North (Figure 1). These particles could then become part of the North Cape Current which becomes the Murman Current and would continue to cycle through the East and West Spitsbergen Currents (Figure 1). There is also the possibility the plastic is swept into the East Greenland Current and then travels around the country of Greenland into the Arctic Archipelago. I hypothesize that London and Rotterdam could be large sources of plastic, especially Rotterdam since it is the largest port in Europe with heavy ship traffic. There is also the possibility of Nuuk, the largest city in Greenland, being a source of pollution. This will be compared against the null hypothesis that Arctic plastic sources are completely diffuse. Although this project is focused on the North Sea/Arctic Ocean and surrounding bodies of water, this method could be extended to regions beyond for further investigation.

Overview of Plastic Composition:

The North Sea is mainly composed of polyethylene, around 75%, with mixed polymers and other plastics making up the remainder. Most particles found were less than 75um in length (Bergmann et al., 2017). Iceland/Reykjavik is around 70% polyethylene with styrene and mixed polymers making up the remainder (Svavarsson et al., 2012). Information about the plastic composition was not found for this research, so it was assumed that the percentages are roughly the same for the sake of calculations.

The sinking rates of plastics will be seasonally dependent due to UV degradation (Song et al., 2017). In the Arctic Ocean light is very seasonal, with only a short window of sunlight to break down the plastics. During this window of sunlight in the summer however, there is almost constant daylight. Due to this, I hypothesized that plastics in the Arctic have high degradation rates in the summer, but overall will degrade slower than plastics at lower latitudes. This will keep the particles from sinking and therefore slowing their sinking rate. This will be compared against the null hypothesis that all sinking rates will be the same. The major limitation of this project is that information is unknown about where plastics go in the ocean. Currently, 99% of plastic is unaccounted for once it is in the ocean (Cózar et al., 2014). There is virtually no information on where microplastics are in the Arctic, or how long it takes for them to travel there. Sinking rates of microplastics are also extremely variable, and there has been no research on how fast microplastics sink, specifically in the Arctic Ocean.

Methods:

The data I used was from the Adrift Model (http://plasticadrift.org). The model was run through at the selected three origin points to observe if plastic is traveling upward into the Arctic. The Arctic included the Greenland, Barents, and Kara Seas, and the main Arctic Ocean. These were all areas within the Arctic with confirmed microplastics. Each origin point's data was downloaded directly from the model into a CSV file. One of the main limitations of the Adrift Model visualization tool for this project is that the visualization cuts off the Arctic circle, so the plastics went out of view after a high enough latitude. The data file however still reported particle positions from Arctic latitudes (>66°), so another visualization needed to be created.

Using Google Colab, the data was modeled over a ten-year period through MATLAB animation, with the particles being spatially mapped using a probability gradient. This code was run through each origin point to create three models for the three locations where particles were released. These models assumed that all particles would float similar to the Adrift Model. It was then assumed that for the purpose of the model, all the particles would sink once they entered the three origin points. The data was recorded in increments of two months, which were converted to days. For the sinking model, the average depth of the Arctic Ocean was 1205m. Everything that sank to or beyond this depth was considered not moving anymore and was excluded from the model. The (Kukulka 2012) sinking rate, 0.001m/s, was used first and was multiplied by the amount of time passed since release to get the current depth. After (Kukulka 2012) was used, each of the other three sinking rates were substituted in to see if any particles would make it into the Arctic (Table 1). Since it is known that there is a mix of floating and sinking plastic, the next step was letting the plastics float for a fixed period of time before allowing them to sink. Plastics particles were allowed to sink after two-month increments starting from 2 months up to one year. Only the probability at 66 degrees north and upward was included to insure they were within Arctic waters. The probabilities for each increment were summed up and compared in tables two and three. To find the approximate amount of plastic in metric tons that is reflective of the probabilities, data was taken from https://ourworldindata.org/plastic-pollution. For the countries surrounding the chosen locations, the amount of plastic was summed up and multiplied by 4%, which is the approximate percentage of plastic that ends up in the ocean each year. This value was then applied to the probabilities to get the amount of plastic at the given times.

Results:

If assuming all particles float and are wind driven, all three locations have particles that reach the Arctic Ocean (Figure 2). The North Sea and Iceland locations had the highest probability of particles being in the Arctic, and most of the particles remained in the Arctic Latitudes for the entire ten years. Some of the particles from the Greenland release point made it into the Arctic, but most were carried into and remained in the North Atlantic Gyre (Figure 2). When all the particles were assumed to have a uniform sinking rate of 0.001m/s (Kukulka 2012), the particles would hit the sediment of the seafloor at 1205m and stop moving around two weeks. When the other three sinking weights were applied, the particles sank to the bottom within two and a half to three days, with (Kowalski 2016) being the fastest rate (Figure 3). This signified that if all plastic particles were to sink upon entering the ocean, none would make it up into the Arctic (Figure 4).

Plastics Floating for Increments of Two Months:

Plastics were allowed to float for two months before sinking. At timestamp year zero month two there was a probability of zero for plastics from the North Sea being in Arctic waters (above 66°). There was a probability of 0.0173 for plastics from Reykjavik to be in the Arctic and 0.00524 for

Greenland/Nuuk (Table 3). When the plastics floated for four months before sinking there was still zero probability for the North Sea, Iceland had a probability of 0.293 and Greenland/Nuuk was 0.0611 (Table 3). When the plastic particles floated for six months before sinking, the North Sea had a 0.00158 probability. Iceland had a probability of 0.348 and Greenland/Nuuk had a probability of 0.0611 (Table 3). If the plastics floated for eight months there was a 0.476 probability for Iceland, 0.279 for Greenland/Nuuk, and 0.0683 for the North Sea (Table 3). Plastics floating for ten months from Iceland had a 0.332 probability to be in the Arctic, a 0.324 probability from Greenland/Nuuk, and 0.244 probability from the North Sea (Table 3). Finally, if plastics float for one year before sinking there is a 0.256 probability for the Iceland plastics to be in the Arctic, a 0.298 probability for Greenland/Nuuk, and 0.424 for the North Sea (Table 3).

Discussion:

This study provides a better analysis of how plastics are getting into the Arctic, where they are originating from, and where they may be situated in the water column. The plastics from the North Sea remain in the sea itself for several months before traveling up the Norwegian Current. Once the plastics were above Finland, they either traveled through the Pechora Current or higher up the Murman Current (Hansen et al., 2000), where it seemed most of the particles would circulate throughout. The plastics that were carried into the East Spitsbergen Current traveled under Svalbard into the West Spitsbergen Current where they circulated in the Norwegian Seas. Some plastics traveled with the Pechora Current into the Yamal Current and Kara Sea, where they remained until year ten. Implementing all the sinking rates to all the particles, no particles in the visualization made it out of the sea (Table 2). In actuality there is a mixture of particles that sink immediately and those that continue to float (Kvale et al., 2020). If I let the particles float for two months and then applied the 0.001m/s sinking rate, no particles made it past the 66° into the Arctic. There was still zero probability at year zero and four months, and finally there was a small probability of 0.002 at six months. The Adrift model started in January and went in two-month increments, so the plastics finally made it into the Arctic from the North Sea in July of the first year. Once the plastics from the North Sea made it into the Arctic, the concentration went up rapidly from ~1300 metric tons of plastic at six months to ~27900 tons circulating around the Arctic in the first year. In (Cózar 2017) it was hypothesized that the Arctic seafloor is a significant sink for plastic since there was little plastic in surface waters (Cózar et al., 2017). My research affirms this statement, as the approximated amount of plastic does not reflect what we are currently finding on the surface. The plastics from the west coast of Iceland first traveled through the Irminger Current on the Northwestern tip of Iceland as well as moving into the East Greenland Current. The particles then traveled around the southern tip of Greenland, Cape Farewell, where they circulated through the Labrador Current. The particles traveling east had a similar path to those released from the North Sea, traveling through the Norwegian and North Cape Currents. As time passes the high spatial probability shifts towards the east, and eventually a high probability of particles is traveling through the Kara Sea. When the sinking rates were applied, particles were located above 66° in the Arctic at year zero month two. Plastics released from Greenland/Nuuk start in the West Greenland Current and Labrador Currents. Some of them travel up to the Baffin Island Current and remain for the totality of the project. Around year two the plastic particles traveling east through the North Atlantic Current where they are carried through the North Atlantic Current taking again the same path as the other two release points. Overall, the majority of the particles although traveling through parts of the Arctic, end up end in the North Atlantic Current and get caught in currents of the North Atlantic Gyre.

The Adrift Model is a solid foundation to better understand where plastics are traveling in our seas, but ultimately, it is a model. Until there is concrete evidence of how fast microplastics sink and what effects their degradation, we cannot know where they will truly be. When sinking rates were added to the model, they were applied to every particle being released. To make a more accurate model, the sinking rate needs to be applied to the correct proportion of plastics based on the composition of microplastics in the release areas. With the addition of UV degradation rates that reflect The Arctic environment, we should be able to see where these particles are in the Arctic and how they are contributing to the microplastic sink (Kvale et al., 2020).

Using the UV degradation rate, I determined that the rate I used from (Chamas et al., 2020) would not have a significant effect on the plastics. The average size of a particle found in the North Sea was around 70 µm and composed of polyethylene. The mean rate for this type of particle is 9.5 µm/year, or 1.58 µm every two months. Based on these parameters I determined that the particles released most likely would not be heavily impacted by degradation in the first year, but further research is needed to fully prove this. The model output demonstrates that these three locations are active sources of Arctic plastic contributing to the plastic debris found in the open waters of the Arctic (Cózar et al., 2014). The North Sea is the largest contributor by far with 279,000 metric tons, over 1000% of the other locations within the first year.

For further research, the effects of UV degradation on plastics specifically in the Arctic should be studied further. Since the UV degradation rates were not taken from an Arctic environment, they do not reflect the extreme phases of the Arctic sunlight, and its effects on the plastics. Both the Adrift Model and the created visualization tool indicates that large probability of the plastics end up entrapped in the Kara Sea. Another suggestion for further research would be to further look into the processes within the Kara Sea that cause plastic to accumulate there and what impacts this might have on the local environment.

Conclusion:

From this project I conclude that the North Sea, the west coast of Iceland, and Greenland/Nuuk are all origin points of microplastics in the Arctic, with the North Sea contributing the most with ~279,000 tons of plastic reaching above Arctic latitudes in one year. The particles from each origin point have to float for a minimum of two months before making it into the Arctic latitudes. Hopefully with this research and further knowledge we can begin to understand more about where microplastics will be located and how long it takes for these microplastics to degrade and sink in these northern environments. Further research might add the impact of UV degradation on the productions and sinking of microplastics in the Arctic.

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Tables:

Table 1. Plastic particle sinking rates from 2012-2017.

Sinking Rates:
1-43mms^{-1} (Kukulka 2012)
6 to 91x10^{-3}ms^{-1}: (Kowalski 2016)
0.004-0.18 ms^{-1}: (Chubarenko 2016)
5-12mms^{-1} (Khatmullina 2017)

Table 2. Plastic proportions in the arctic if plastic sinks immediately after release.

Release Points	**% of Plastic in Arctic if all plastic sinks**
A: Iceland/Reykjavik	0
B: Greenland/Nuuk	0
C: North Sea	0

Table 3. Plastic Proportions in the Arctic if plastic is allowed to float for two-month increments.

Release Points	**% of Plastic in Arctic if all plastic sinks after:**					
	2 months	4 months	6 months	8 months	10 months	12 months
Iceland/Reykjavik	0.017	0.293	0.347	0.476	0.332	0.256
Greenland/Nuuk	0.005	0.012	0.061	0.279	0.324	0.298
North Sea	0	0	0.002	0.068	0.244	0.424

Table 4. Amount of Plastic in the Arctic in metric tons if plastics are allowed to float for two-month increments.

Release Points	**Plastic in Arctic (in metric tons) if all plastic sinks after:**					
	2 months	4 months	6 months	8 months	10 months	12 months
Iceland/Reykjavik	16.626	286.554	339.366	465.528	324.696	250.368
Greenland/Nuuk	0.785	1.884	9.577	43.803	50.868	46.786
North Sea	0	0	1316.2	44570.8	160576.4	279034.4

Figures:

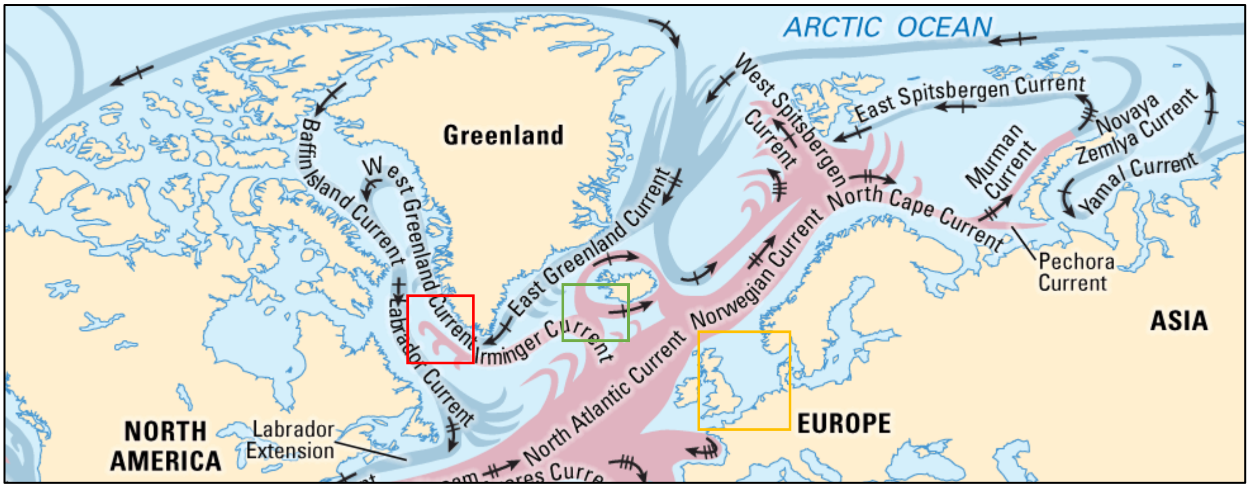

Figure 1. Map of Global currents in Northern Hemisphere. Currents of interest are the systems located next to the east of Greenland and above Asia. The orange box represents the North Sea release. The red box is the Greenland/Nuuk release point, and the green box is the Iceland/Reykjavik release point. (Encyclopædia Britannica)

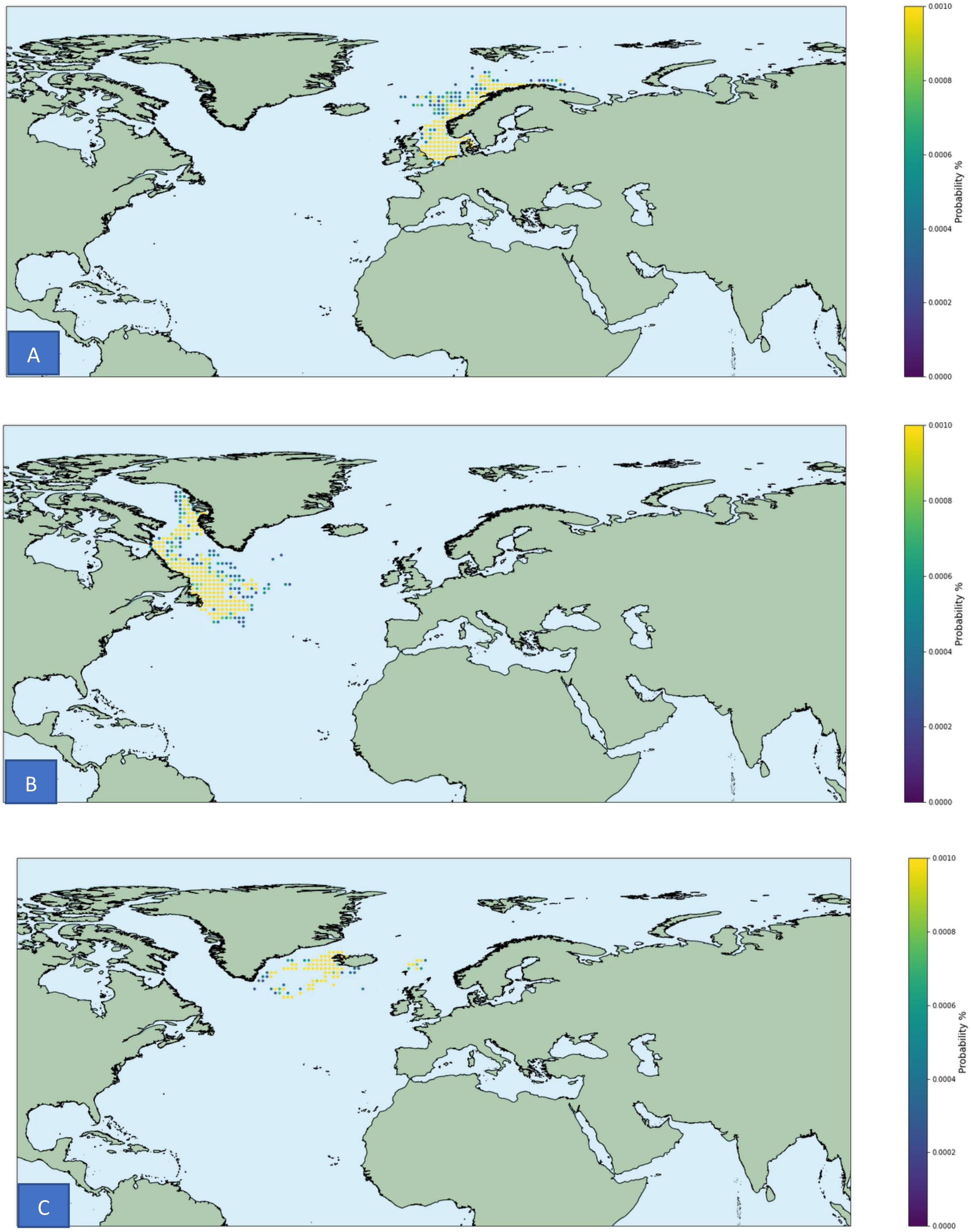

Figure 2. Microplastic Concentrations at Year 1. Panel A represents the North Sea. Panel B is Greenland/Nuuk. Panel C is Iceland. The probability is shown through a color gradient on the right ranging from 0.000 to 0.0010.

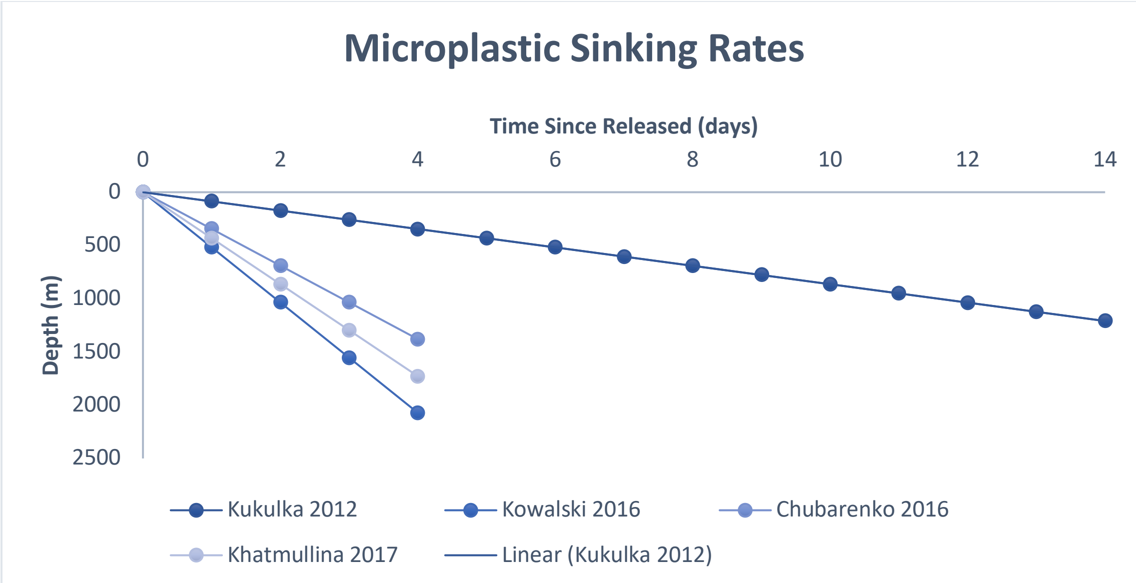

Figure 3. Microplastic Sinking Rates. Time since released is on the x-axis in days and depth in meters is displayed on the y-axis.

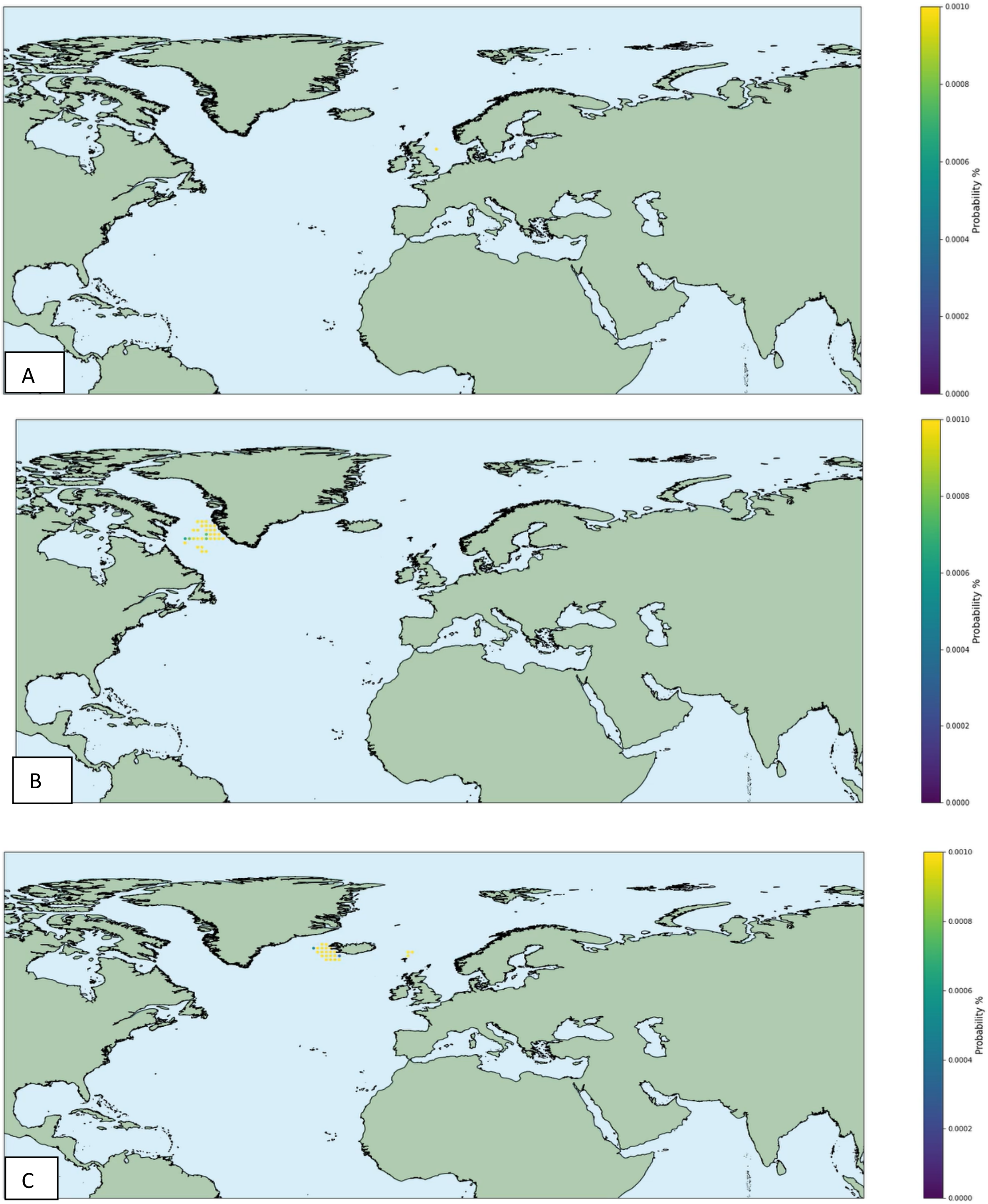

Figure 4. Microplastic Concentrations at year 0 month 2. The North Sea is panel A, Greenland/Nuuk is panel B, and Iceland is panel C. All panels display origin of plastic before it has sunk. The North Sea has not moved from its origin point and is represented by the singular dot. The probability is shown through a color bar gradient on the right from 0.000 to 0.0010.