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Abundance of Floating Plastic Particles Is Increasing in the Western North Atlantic Ocean

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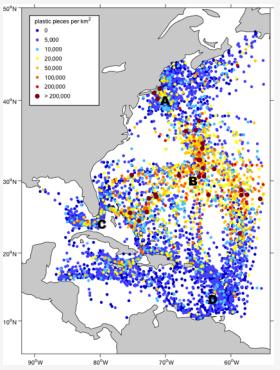
Supporting Information

ABSTRACT: Since the start of commercial plastics production in the 1940s, global production has rapidly accelerated, doubling approximately every 11 years. Despite this increase and clear evidence of plastics loss into the oceans, including a substantial standing stock, previous research has not detected a temporal trend in plastic particle concentration in the surface ocean. Using a generalized additive statistical model, we examined the longest data set on floating plastic debris available globally, collected using plankton nets in the western North Atlantic from 1986 to 2015. There was a significant increasing temporal trend in plastic particle concentration that tracked cumulative global plastics production. We estimated an increase of 506,000 tons of floating plastic in the ocean in 2010 alone or 0.2% of global production. Our results suggest that, while loss of plastic particles from the surface ocean undoubtedly occurs, the input exceeds the collective losses.



INTRODUCTION

Plastic pollution in the ocean is of widespread concern, spurring a number of recent studies that attempted to estimate the extent of contamination at the sea surface. The first global estimation of the mass of floating plastic particles found 6350−32,000 tons,[1] a surprisingly low amount compared to the estimated input of plastic waste from land into the ocean of 4.8−12.7 million tons (Mt) in 2010 alone.[2] This raised a question originally posed a decade earlier when the first time series of ocean plastic particle abundance showed a significant increase from the 1960s and 1970s to the 1980s and 1990s but no clear increase between the latter two decades:[3] where is all the plastic? Similarly, no temporal trend in surface plastic abundance could be detected in a 22 year data set (1986−2008) from the subtropical gyre of the western North Atlantic Ocean, where floating plastics accumulate,[4] or in an expanded analysis to 2012.[5] The lack of increased floating plastic particle abundance over time is puzzling since global plastics production increased by 562% between 1976 and 2014,[6] similar to the increase in the amount of plastics discarded in the United States municipal waste stream.[7] Moreover, the rate of plastic production is accelerating, with a doubling time in the order of 11 years,[6] implying that changes should be easier to detect with the passage of time. In addition, two recent global modeling analyses of ingestion rates by marine species have detected increases in ingestion rates over time,[8,9] although a regional long-term monitoring study of a single seabird species did not.[5]

It could be that plastics are removed from the sea surface at a rate that compensates for the increased input. Floating plastic particles may be removed by ingestion by marine organisms, buoyancy decrease and sinking, coastal deposition, or fragmentation to sizes smaller than the plankton nets typically used to collect them.[4] Evidence from a variety of laboratory and field studies supports the occurrence of each of these removal mechanisms,[10,11] but the removal rate in the ocean has not been satisfactorily quantified for any of these potential mechanisms. Unless removal rates collectively equal or exceed the input rate, one would expect to measure an increase in the abundance of floating plastics over time in the subtropical ocean gyres, where floating debris accumulates.

A second possible explanation for the lack of observed increase in abundance in time is the difficulty in separating the confounding effects of spatial and temporal variation in the observations. Previous studies have described large spatiotemporal variability in the amount of floating plastic debris collected using surface plankton nets,[12,13] even in the subtropical ocean gyres. Surface winds cause vertical mixing of particles[14,15] and appear to have other nonlinear effects on surface concentration with increasing wind speed.[16,17] Variability due to wind mixing, small-scale circulation features, variable input or removal, and other factors is difficult to quantify because evaluations of temporal trends to date have not been made using data sets from longitudinal studies at fixed locations. This implies that spatial variation in sampling over time will add further variance into the observations, making a time trend more difficult to detect.[11]

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The goal of this work was to evaluate whether there is evidence of a time trend in floating surface plastic particles in the western Atlantic Ocean.

METHODS

We reanalyzed the Sea Education Association's North Atlantic data set, including nearly 8000 plankton net measurements collected from 1986 to 2015 along annually repeated cruise tracks using consistent sampling and analysis methods (Figure 1A).

Although the surface-towed plankton net will capture items larger than the net mesh (0.335 mm) and smaller than the net mouth (1.0 × 0.5 m), the majority of plastic particles collected are less than 10 mm in size,[17] though some items are substantially larger. For this reason, we refer to plastic collected in plankton nets as plastic particles or fragments. Note that particles commonly referred to as "microfibers" were not counted during net processing and therefore were not included in the data set.

We used a generalized additive model to investigate potential sources of statistical variability in the data set, with the primary goal to evaluate evidence for a temporal trend in the data.[18] After removing variability that can be explained by sampling conditions (associated with wind speed during the net tow, tow length, and time of day), we assessed whether there was evidence of a temporal trend in the measured surface plastic concentration. After identifying a trend, we evaluated three possible explanations: a linear increase with time, an increase in proportion to annual production of plastics, and an increase in proportion to the cumulative production of plastics since 1950. We obtained global plastics production data from plastics industry estimates.[6] We used a linear interpolation to fill in missing observations for the production data, creating a data set on production that matched our observations of plastic fragments at sea (Figure 1B). We used these annual production data and estimates to calculate an estimate of cumulative plastic production (Figure 1B).

The presence of a trend, and its proportionality with those three covariates, allowed us to evaluate the net plastic particle accumulation (inputs minus removal) at the ocean surface over time (see further detail of methods in the Supporting Information).

RESULTS

The best base model to remove variability not associated with a temporal trend, as determined by the Akaike information criterion (AIC),[18] included a 2D spline to account for spatial location and first-order linear terms for wind speed and tow length (Table S1). It also contained a smooth term for time of day, removing a daytime bias toward higher concentrations. The best fit model had negative coefficients for the wind speed and tow length terms, indicating a lower observed plastic concentration associated with higher wind speed and longer tow length. Comparing the product of the coefficient and the covariate at its median for these two terms, we found that they had similar magnitude effects on plastic concentration. The base model explained 43.7% of the variation in the data based on a deviance comparison. A Tweedie distribution with a scale of 1.6 was the best fitting model based on an examination of the mean−variance relationship. We rejected Poisson, quasi-Poisson, and negative binomial distributions as providing

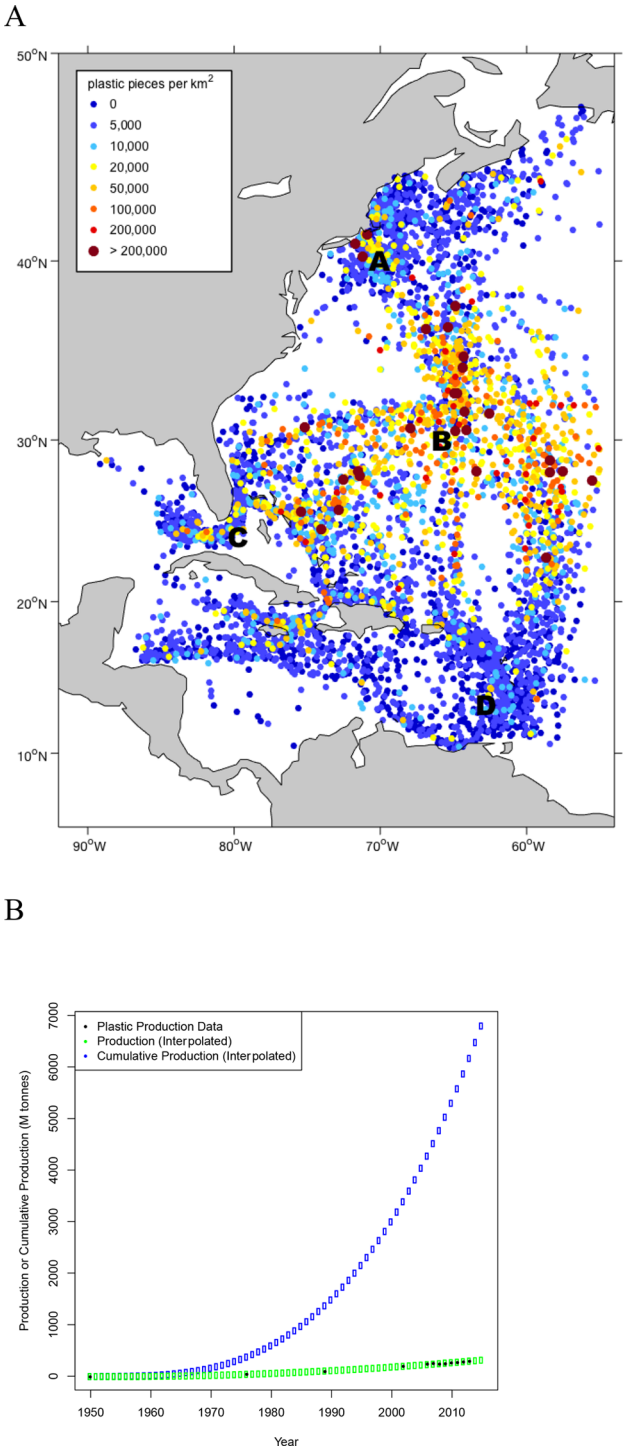

Figure 1. Ocean plastic concentration and global plastic production data included in the analysis. (A) Measured surface plastic concentrations from plankton net tows in the western North Atlantic (number of plastic pieces per km^2). Letters indicate the location of time trends shown in Figure 4. (B) Global plastics production data,[6] interpolated production data, and cumulative production data calculated using interpolated values.

inadequate flexibility to accommodate the large probability mass at zero and the rare very high concentrations.

Incorporating a smooth term for year into the base model indicated a clear pattern of an increase in floating plastics from 1992 to 2015 (Figure 2). Before 1992, the mean plastic

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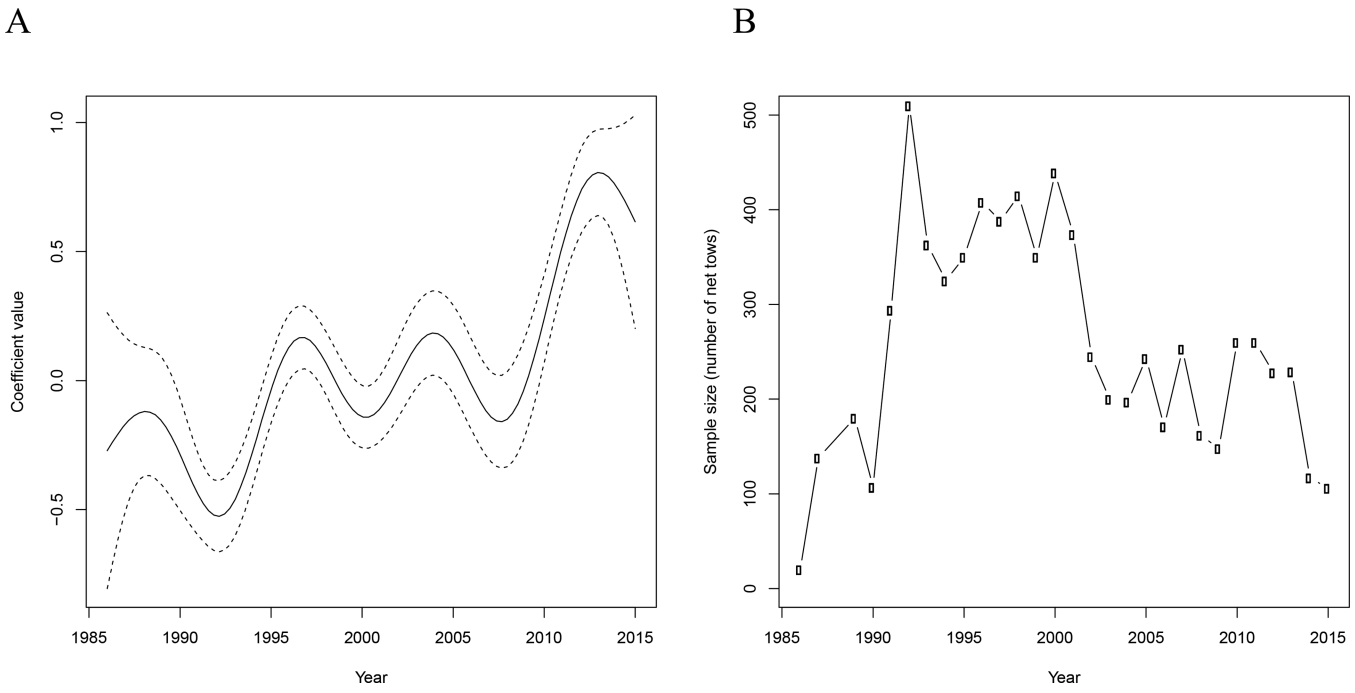

Figure 2. Estimated change in surface plastic concentration since 1950 and the corresponding sample size by year. (A) Value of the time coefficient for surface plastic concentration with time since 1950 using the best fit base model with a static spatial surface. The 95% confidence intervals are shown as dotted lines. Note that smooth terms, such as this one, are forced to have a mean value of 0 for identifiability during estimation. (B) Number of surface plastic concentration measurements from plankton net tows in the data set for each year included in the analysis.

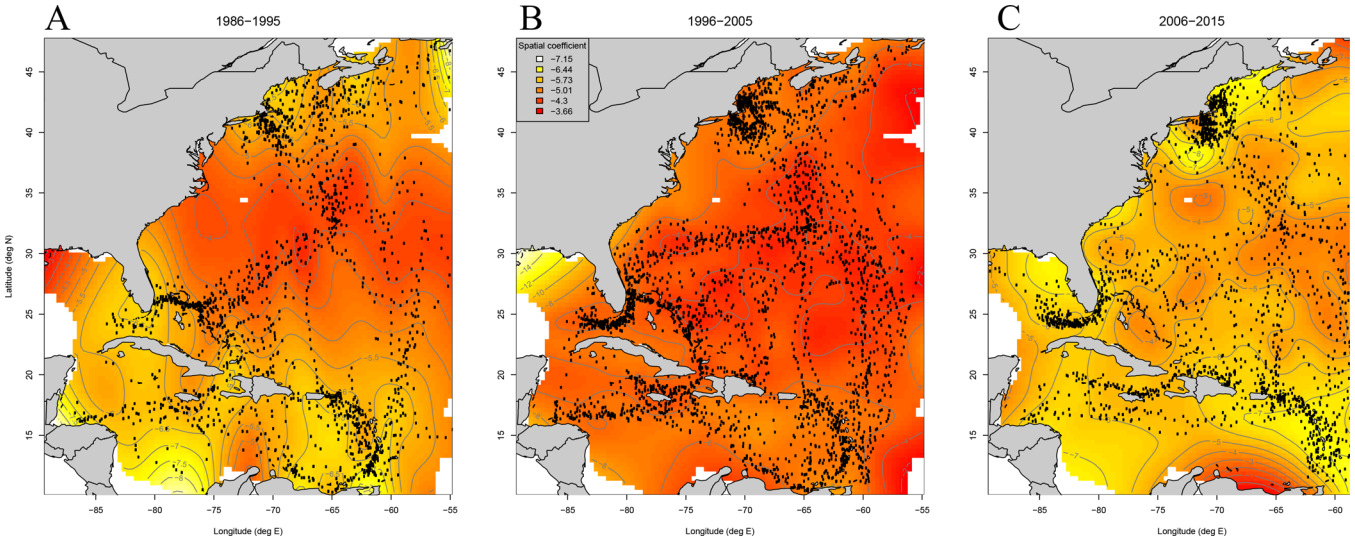

Figure 3. Estimated spatial surface for plastic concentration. The plots are based on the best fit model with a two-dimensional spatial smooth for location, allowing the spatial surface to vary by decade. (A) 1986−1995; (B) 1996−2005; (C) 2006−2015. The spatial coefficient, as shown in the legend, gives the value of the contribution of position in the modeled region to the estimated concentration of plastic fragments. The spatial surfaces are constrained to have a mean value of 0 over all time; thus, the coefficients in the spatial surface represent deviations in the plastic concentration in space from the temporal mean and are therefore unitless. Values on the contour lines give the contribution to the overall model coefficient from the spatial surface. Black dots show the locations of samples in each of the decades.

concentration apparently decreased with time; however, sample sizes were small, yielding very wide confidence intervals (Figure 2). After 1992, the mean concentration increased, and larger sample sizes allowed tighter confidence intervals. Incorporating any of the three temporal variables (year, annual plastic production, and cumulative plastic production) improved the model significantly based on AIC values (Table S2). The best overall model incorporated a second-order relationship with cumulative plastic production as a covariate; no other models were included in the 95% confidence set.

To explore temporal changes in the spatial pattern of plastic particle distribution, we allowed the spatial pattern in the base model to vary across 5 year or 10 year blocks. In both cases, the model fit improved, with only minor differences in the parametric terms between them; thus, we proceeded with the 10 year interval model for simplicity and computational speed. As with the base model with a constant spatial surface, a model

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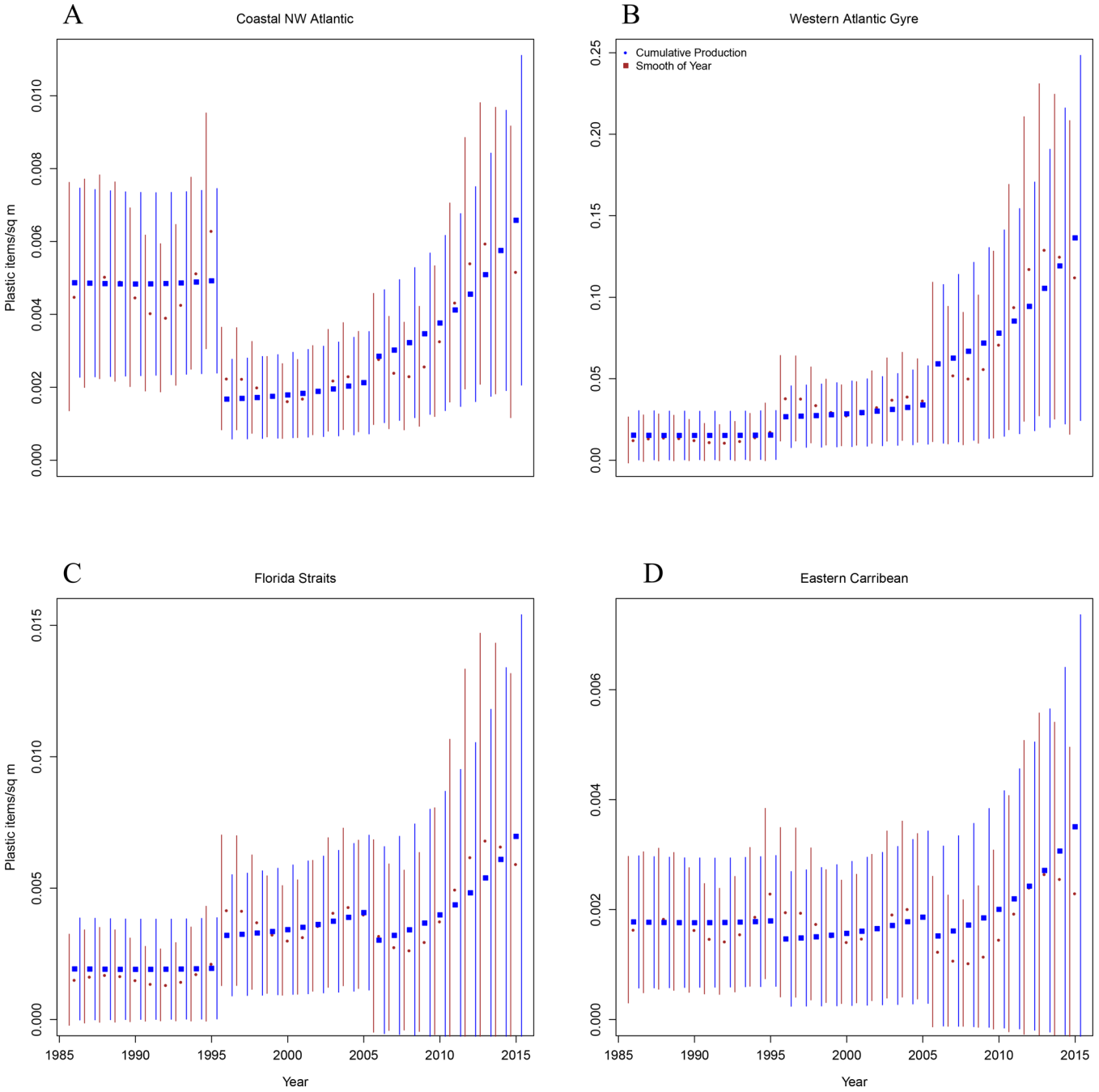

Figure 4. Estimated time trends in surface plastic concentration at four locations under standardized conditions. The plots show the trend based on a parametric model for cumulative plastic production (blue) and a smooth model for year (brown). Locations are (A) coastal northwestern North Atlantic, (B) western North Atlantic subtropical gyre, (C) Florida Straits, and (D) eastern Caribbean Sea. The standardized conditions are a wind speed of 0, tow length at its median value (1852 m), and time of day at noon (12:00). Note the differences in scale on the abscissa of panels (A) through (D). Discontinuities reflect the transitions between spatial surfaces between 10 year intervals. The bars through each point provide the standard error for each estimated mean concentration. Typical for models of counting processes (Poisson, Tweedie, etc.), the standard errors of the estimates scale with the estimated mean. The distribution of samples in our data set and the locations of the four predictions are shown in Figure 1 (black letters).

including a smooth term for year was the best model overall, and the best model for the temporal trend in concentration included a second-order relationship with cumulative production, with no other models included in the 95% confidence set (Table S2). In this model, the squared term for cumulative production was positive, while the first-order term was negative but nonsignificant, although AIC indicated that it should still be included in the model as it provided a significant improvement over a model with only a square term for cumulative production (Table S3). This model, which indicates an accelerating relationship with cumulative production, explained 49% of the variation in the data based on a deviance comparison. Comparing effect sizes at the median covariate value, wind speed and tow length are approximately twice as strong as the temporal variables, suggesting that variation due to sampling error is large

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compared to the underlying temporal trend. However, because cumulative production increases with time, but the other two effects do not, by 2015, the median temporal effect (1.09) exceeded the median effects of wind (−0.92) and tow length (−0.83).

Considering the best fit parametric model with a temporally varying spatial pattern, there is a clear pattern in the spatial distribution of plastic debris in the western North Atlantic, where high concentrations reflect the influence of the subtropical gyre (Figure 3). The strength of spatial gradients in plastic concentration varied over the survey period, with weaker gradients delineating the gyre boundaries in the latter two periods. However, the spatial surfaces should be interpreted with caution since the spatial coverage of sampling varies over time; regions of sparse sampling during any period have wide confidence intervals.

Using the best fit model and focusing on consistently well-sampled areas, we found an overall pattern of increasing plastic concentration across the study region over time, albeit with site-specific time trends (Figure 4 and Table S2). Rare high values in some sites generated temporal discontinuities in our model due to their effect on the decadal approximation of the spatial pattern (Figures 2 and 4A). Overall, sites close to land (offshore of New England, Florida Straits, and the eastern Caribbean Sea) had generally lower concentrations and smaller increases over time compared to the central subtropical gyre (~30°N). The influence of shifts in the spatial distribution of debris together with shifts in sampling distribution over time resulted in sharp temporal discontinuities between study periods near the boundary of the subtropical gyre (~20°N, not shown).

DISCUSSION

Using more than 8000 samples from plankton net data, we found clear support for the hypothesis that the abundance of plastics at the sea surface of the western North Atlantic Ocean has increased with time (Figures 2a and 4). The time trend is most strongly related to cumulative global plastics production. The better fit to cumulative rather than to annual production suggests that the particle loss rate from the sea surface is smaller than the input rate.

Furthermore, the relationship observed suggests that plastic concentration is accelerating compared to cumulative production. We hypothesize that this acceleration may result from particle fragmentation. Global plastics production is reported as mass (tons), whereas plastic particles are reported as a numerical concentration (number of particles per unit area). Most particles collected in plankton nets are ~0.35−10 mm in size and, based upon their size and shape, likely originated from fragmentation of larger objects,[19] which is known to occur when plastics undergo photodegradation and weaken upon exposure to sunlight and other physical processes.

To test the plausibility of this hypothesis, we built a hypothetical fragmentation model[18] (see detail provided in Figure S2), which indicates that, if the time to fragment from a large item (100 g) to smaller particles (0.00001 g) is sufficiently long, and particle removal is minimal, then the total number of particles will accelerate with respect to cumulative production. Furthermore, the model suggests that, if particles are lost from the system at any appreciable rate relative to inputs, either through flux away from the sea surface or by fragmentation to smaller sizes that can be captured by the plankton net, then the relationship between particle count and cumulative production will decelerate, rather than accelerate as observed.

We detected substantial variability associated with all sampling conditions tested: wind speed measured during the tow, tow length, and time of day. The inverse relationship between wind speed and measured surface concentration of microplastics is consistent with studies modeling the turbulent wind-driven mixing that submerges even buoyant materials below the sea surface where the measurements are made.[14,16] The mechanism driving the inverse relationship between tow length and measured surface concentration is unknown. We do, however, posit three hypotheses to explain the pattern. First, the efficiency of water passage through the net might be reduced on longer tows due to larger amounts of biological material accumulating in the net, which could cause a pressure wave at the mouth of the net that diverts seawater and suspended material around the net. A second related possibility is that larger volumes of material resulting from longer tows make visual sorting of the material for microplastics more difficult. Finally, surface concentrations of plankton and other floating materials typically exhibit patchiness or regions of high concentration separated by larger regions of very low concentration. A longer tow would be more likely to sample the larger areas of plastic-free water in between these patches, a hypothesis supported by the fact that the modal value in the data set is zero (35% of values). Finally, there are two potential explanations for the daytime bias in plastic particle concentration. Plankton net samples are typically collected twice per day, at noon and midnight local time, and samples are analyzed onboard the ship within 1−2 h of collection. It is possible that visual selection accuracy is reduced in midnight tows because of analyst fatigue and/or insufficient lighting conditions in the ship's laboratory. An alternative explanation is physical in nature. There is evidence of a diurnal cycle in vertical mixing at the sea surface due to the diurnal daytime heating (nighttime cooling) cycle, which causes reduced (enhanced) turbulent mixing that submerges surface microplastics.[14] Thus, reduced vertical mixing could result in higher microplastics concentration during midday plankton net tows. Further field experiments are required to assess the causes of the statistical variability detected by the GAM and described above, and additional data and associated analyses would undoubtedly help clarify patterns.

Two previous analyses of subsets of this data set[4,5] found evidence of a strong decrease in time in the concentration of industrial resin pellets. The observed decrease presumably reflects a sharp decline in input after the voluntary Operation Clean Sweep program was instituted by the industry in the 1990s to prevent or recapture spilled pellets[20] and suggests that the residence time of pellets at the sea surface is quite short, an apparently contradictory result to the strong increase reported here. However, pellets represent a small fraction of the data set (6% of total particles), whose decreasing trend is overwhelmed by that of rapidly increasing total plastic particles. Also, while pellets are easily identifiable by their characteristic shape and size, only very rarely are ocean plastic particles identifiable as "partial pellets", suggesting that fragmentation typically results in multiple unidentifiable particles that might still be captured and counted (if larger than 0.335 mm) but which would no longer be recorded as "pellets". Thus, the observed reduction in pellet concentration in time is not contradictory; in fact, their fragmentation likely

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contributes to the measured increase in total particles identified here.

Our analysis suggests that the lack of a trend in the previous analysis of this data set (years 1986−2008)[4] was due to three factors: sample timing relative to plastics production, variable sample location, and sampling error. First, intensive sampling of surface microplastics began only in the late 1980s, but plastics production on an industrial scale began in approximately 1950. By the time the first sampling in the data set occurred (1986), more than one-fourth of the total production in the last year of the data set (2015) had already occurred. Thus, any attempt to distinguish a temporal trend is complicated by the accumulation of plastics before the sampling program began. Second, the strength of spatial gradients in plastic concentration varies over time; hence, small variations in the sampling location can result in substantial shifts in the measured surface plastic concentration. Not accounting for this shift also confounds variability in space and time, making it more difficult to identify a temporal trend. Finally, sampling error due to wind mixing, variable tow length, and time of day also obscures a temporal trend, if uncorrected.

IMPLICATIONS

Our results have two important implications. First, the accumulation over time suggests that floating plastics may have a residence time in the ocean equivalent to or greater than the sampling period of our data. This relatively long residence time implies that fluxes away from the sea surface, to the coasts, the seafloor, and the biota, are negligible with respect to the input rate of plastics to the surface ocean. Second, the significant relationship between cumulative plastic production (in tons) and measured ocean plastic concentration (in number per unit area) suggests that the input of plastics into the ocean has not slowed over time. Assuming that plastic waste input from land[2,21] is a major source of ocean plastics (either input in this size range or as larger items that generate smaller plastic fragments), our results imply that waste control efforts have not improved rapidly enough to compensate for increases in global production, a result consistent with recent findings that global plastic waste generation has outpaced plastics recycling and incineration rates.[22] Furthermore, fragmentation also contributes to an increase in ocean plastic counts (as detailed in the Supporting Information).

Based on our model, we estimate that, in 2010, the surface plastic concentration in the western North Atlantic increased by 0.1 particle/m^2 for every ton of plastic produced globally. Using an average particle weight of 0.014 g[4] and a global ocean area of 361.9 million km^2, this yields an increase of 506,000 tons of plastic in the ocean in 2010 or 0.2% of global production.[6] This is an order of magnitude lower than Jambeck et al.'s estimate that between 2% and 5% of global plastic production, by weight, entered the ocean in 2010.[2] The two estimates are not directly comparable since only buoyant plastics in a narrow size range are accounted for in the ocean data presented here. Furthermore, trends in other ocean basins may differ from our North Atlantic estimate because of differences in input rate (i.e., the largest sources of land-based waste are predicted to be Asian countries into the Indian and Pacific Oceans[2]) and transit times. However, this is a substantially better match than previous comparisons between estimated input and observed surface plastic concentrations in the open ocean.[1,17]

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.est.9b04812.

Additional materials and methods,[23−25] measured surface plastic concentration, plastic load in the ocean due to inputs and fragmentation predicted by the hypothetical fragmentation models, sampling intensity at each of the locations where predictions are made for time trends, evaluation of the base model of plastic concentration in the western North Atlantic, AIC values for models incorporating either year or plastic production into the base model, and coefficient estimates for the best fit model, including a time or plastic production (PDF)

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Notes

The authors declare no competing financial interest.

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