



Plastics in stomachs of northern fulmars (*Fulmarus glacialis*) collected at Flemish Cap, Grand Banks of Newfoundland

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ABSTRACT

Incidental studies of plastic ingestion by the northern fulmar (*Fulmarus glacialis*) over a wide geographical range can improve our understanding of the distribution of marine litter in the global oceans and of the processes involved. A sample of 37 stomachs from northern fulmars (*Fulmarus glacialis*) collected in June 2021 near Flemish Cap at the eastern end of the Grand Banks of Newfoundland was analysed for the presence of plastic litter. Overall, 89 % of the birds contained plastic, with on average 6.6 particles, and a mass of 0.093 g per bird. No statistical differences were found in the quantity of plastic between males and females. A proportion of 27 % of all birds contained >0.1 g plastic, exceeding the Fulmar Threshold Value (FTV%) and international target of <10 %. Within an existing model that linked plastic abundance to latitude, the Newfoundland sample represented a clear outlier with a considerably lower FTV% compared to what would be expected. Flemish Cap is situated at the border between the southern tip of the cold and relatively clean Labrador Current coming from the north, and the warm and more polluted waters of the Gulf Stream further south. A logistic model using average annual sea surface temperatures representing North Atlantic current systems was applied and demonstrated a highly significant correlation, with the Newfoundland FTV% fitting much closer to the modelled prediction. This new model improves the understanding of geographical patterns in plastic uptake by fulmars.

1. Introduction

Plastic pollution poses a serious threat to marine ecosystems worldwide. Wildlife can suffer major consequences via entanglement and ingestion (Kühn and Van Franeker, 2020). Despite growing awareness of such problems, plastic production continues to increase and was estimated to exceed over 1 billion tonnes of plastic annually by 2060 (OECD, 2022). In perspective, this is compared to an annual production of 400 million tonnes (Mt) in 2022 and a mere 1.5 Mt. in 1950 (PlasticsEurope, 2023). Annually, a substantial 4.8 to 12 Mt. of plastics may be lost to the oceans from landbased sources (Jambeck et al., 2015). OECD (2022) reports a similar 6.1 Mt. annually leaking into aquatic environments plus 1.7 Mt. directly lost to the oceans. Over the years, OECD (2022) estimates that 139 Mt. of plastic litter has accumulated in rivers and oceans. This emphasizes the urgency to establish effective

solutions to reduce plastic production and plastic waste, unintended loss and direct discards.

Several policy measures have been developed to reduce the amount of plastic waste that ends up in the ocean. In 2002, OSPAR introduced a system of Ecological Quality Objectives (EcoQO's) to monitor the health of the marine system (North Sea Ministerial Conference, 2002). In relation to the issue of marine litter, OSPAR developed an EcoQO for the North Sea that used plastics in stomachs of northern fulmars (*Fulmarus glacialis*, from here on 'fulmar') as a monitoring tool for marine plastic debris (OSPAR, 2008, 2015). The fulmar is an abundant seabird found throughout the North Atlantic and North Pacific oceans (Mallory et al., 2012). Because this species regularly ingests plastic, feeds exclusively at sea, and usually does not regurgitate indigestible prey remains, it has been selected as a suitable candidate to provide information about litter pollution in a certain area and timeframe (Van Franeker and Meijboom,

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2002). The monitoring methodology has been firmly established in international guidelines (OSPAR, 2015). Gradually, OSPAR fulmar studies and their policy target of <10 % of stomachs containing >0.1 g of plastic, have been accepted in the wider EU MSFD (Marine Strategy Framework Directive; EC, 2022). The OSPAR EcoQ Objective is now generally addressed as the Fulmar Threshold Value (acronym 'FTV'; Van Franeker et al., 2021).

Plastic ingestion patterns of the fulmar along the Dutch coast have been documented as far back as the early 1980's (Van Franeker, 1985). Since 2002, all countries around the North Sea have participated in the monitoring (Van Franeker et al., 2011, 2021) and more and more studies in the North Atlantic and North Pacific Oceans apply the Fulmar Threshold Value approach (e.g., Provencher et al., 2017, Avery-Gomm et al., 2012, see Supplement Table 3 for a full list of studies). Together, these studies are crucial for understanding regional pollution levels and the processes that drive litter distribution across vast oceanic areas. Kühn and Van Franeker (2012) first tested the hypothesis that the amount of marine litter decreases with higher latitudes in the Atlantic. They found that the examined sample of Icelandic northern fulmars fitted in a pattern whereby North Sea fulmars had the highest plastic content, followed by those from the Faroe islands, then Iceland, and finally, the least plastic was found in birds from Arctic Canada. The pattern of pollution appeared to correlate with latitude and related human coastal and marine activities that result in considerable input of plastic waste (Kühn and Van Franeker, 2012). Local deviations have been observed, for example Trevail et al. (2015) found that fulmars from Svalbard contained more plastics than would be expected by the

latitudinal model. This illustrates that the geographical pattern of marine plastic pollution is not yet fully understood. In order to improve such understanding OSPAR's Intersessional Correspondence Group of Marine Litter (ICG-ML) is currently considering an extension of its monitoring programme for marine litter in stomachs of fulmars to the Arctic region with programs from Norway, Iceland and Denmark.

This paper adds a new datapoint in the geographical pattern of plastic ingestion for fulmars, derived from fulmars collected in the offshore waters of Flemish Cap at the eastern end of the Grand Banks of Newfoundland (from here on 'Newfoundland Banks', acronym NFB). Newfoundland and Labrador have small fulmar breeding colonies (Nettleship and Montgomerie, 1974) and plastic ingestion by fulmars near these colonies was studied by Avery-Gomm et al. (2018). The international waters far off the Newfoundland coast are known to be an important feeding ground for many fulmars from the large North Atlantic fulmar populations (Brown, 1970; Amélineau et al., 2021; Dehnhard, 2022). By analysing fulmar stomachs from these offshore waters, we aim to further improve knowledge of the geographical pattern of plastic ingestion by fulmars and thereby on the processes involved in pollution levels across the North Atlantic Ocean.

2. Materials and methods

On the 11th of June 2021, a sample of 37 northern fulmars was collected from the Faroese fishing vessel Arctic Viking, targeting shrimps near Flemish Cap at the eastern end of the NFB, at position 48.33°N – 45.25°W (Fig. 1). This location is situated in international

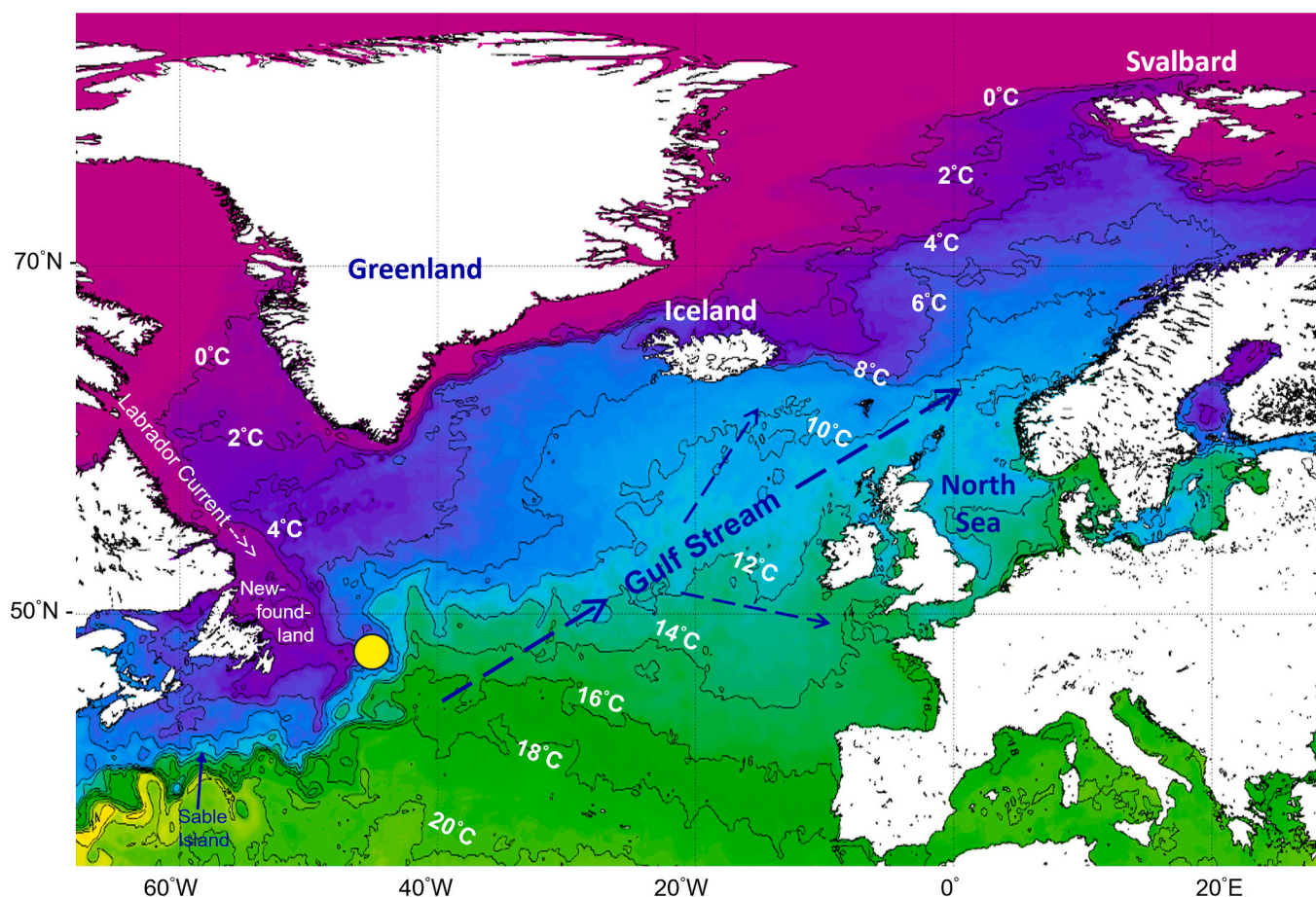


Fig. 1. Position of the NFB sampling location in the North Atlantic Ocean in the context of geographical latitude, major ocean currents and Sea Surface Temperature (SST) gradients in early June 2024 (adapted from <https://www.ospo.noaa.gov/data/sst/contour/global.c.gif>; version June 7, 2024). The yellow circle shows the sampling location at Flemish Cap. The NFB have an average annual SST of around 2 °C to 4 °C, but are close to a sharp border with much warmer water in the Gulf Stream. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

waters, 560 km (302 nm) off the Canadian coast. Arctic Viking was fishing by bottom trawling at about 400 m depth. Fulmars concentrated around the ship because net losses and discards of shrimps and small fishes provided attractive prey. The birds were caught for human consumption with a long-handled net (fleyg; Jensen, 2012). Corpses were skinned and cleaned on board, but the heads, along with the attached oesophagus, stomachs, and in many cases the intestines were preserved for research and kept frozen until they could be examined.

Biometric head measurements were taken in order to assign probable sex by calculating a discriminant score (Van Franeker and Ter Braak, 1993). The three available head measurements for the NFB fulmars are head length (HB), culmen length (CL), and bill depth at gonys (BD2). An update of the original discriminant program provided by Van Franeker and Ter Braak (1993) was given in Van Franeker et al., (2022). Instead of the small source file for different species of fulmarine petrels used in Van Franeker and Ter Braak (1993) and Van Franeker et al., (2022), we now based the discriminant formula on the very large set of data for all northern fulmars from the North Atlantic measured and sexed by Van Franeker and Kühn ($n = 3451$). The generalized discriminant formula using the three available head-measurements was: $WG3Atl = HB + (0.8056 * BD2) + (-0.4497 * CL)$. Cutpoints were separately specified for double light fulmars (colourphase LL) as cutpoint = 91.49211; and for coloured fulmars (colourphases L, D, and DD) as cutpoint = 89.15922. Colouration of the current sample was derived from yes or no grey feathering on top of head and upper part of the neck. High Arctic coloured breeding populations (*Fulmarus glacialis glacialis*) are smaller sized than the double light fulmar populations (*F. g. auduboni*) breeding mostly in lower Arctic and temperate zones (Van Franeker and Wattel, 1982; Van Franeker, 1995). A mix of these subspecies may occur in any offshore oceanic area of the North Atlantic, including the seas off Newfoundland and Labrador (Brown, 1970; Amélineau et al., 2021; Dehnhard, 2022). Using the colour-specific cutpoints, the discriminant score assigned 93.7 % of 3451 North Atlantic fulmars to the correct sex. Similar reliability of assigned sex in the sample of birds from the NFB may be expected.

The proventriculus, gizzard, and when available the intestines were separately examined by standard methods of the fulmar monitoring program (e.g. OSPAR, 2015; Van Franeker et al., 2021). The stomachs were cut open and contents were rinsed in cold tap water using a sieve with a 1 mm mesh size. Contents were examined using a binocular microscope and sorted into marine litter, natural food, and natural non-food items. Plastics were split into different subcategories (industrial plastics, and user plastics comprising of sheets, threads, foams, fragments and other plastics), after which they were counted and weighed using an electronic Sartorius weighing scale with an accuracy of 0.0001 g. When subcategories weighed as 0.0000 g, they were considered to weigh 0.0001 g. The polymer composition of all plastic items was identified by Fourier Transform Infrared Spectroscopy (FTIR) analysis, using the Shimadzu IRSpirit and the integrated software program. Polymer compositions were accepted when reliability was over the 80 % threshold (Kühn et al., 2021). Some items were cut in half, or sliced or scraped along the surface in order to provide a clear surface for the FTIR measurement. Pressure on particles caused fragmentation of some of them. For these reasons there may seem occasional discrepancies between numerical details in Supplement Table S1 and the photos of samples in the Supplement.

The intestines that could be preserved were cut in fragments and treated with 1 M potassium hydroxide (KOH) in glass jars. The KOH solution efficiently digests most of the organic material, while preserving the mass, morphology, and chemical integrity of most plastic polymers (Kühn et al., 2017; Karami et al., 2017; Dehaut et al., 2016). The samples were then placed in a shaking bath set to 120 rpm at a temperature of 35 °C for seven days. The remaining contents were sieved over a 1 mm mesh and analysed in the same way as stomach contents.

The data for both mass and number of plastics were not normally distributed. Therefore differences between quantities of plastics

ingested related to sex and stomach compartments were tested using the non-parametric Mann-Whitney U test (Genstat 22nd edition; VSN International, 2017). To compare proportions between samples with respect to the frequency of occurrence (FO%) and the FTV% for birds exceeding the Fulmar Threshold Value of 0.1 g of plastic in the stomach, the Epitools Z-test was used (<https://epitools.ausvet.com.au/ztesttwo>). Lastly, a logistic General Linear Model (GLM) approach (Genstat 22nd edition) based on binomial proportions was used to determine the presence of potential trends for FTV% in relation to latitude and sea surface temperatures. A General Linear Mixed Model (GLMM; Genstat 22nd edition) was used to evaluate the combined effect of both variables. Annual averages for sea surface temperatures were derived from <https://atlas.climate.copernicus.eu/atlas/lmoCdxCm>. A map of early June sea surface temperatures (the period of our sampling) was derived from <https://www.ospo.noaa.gov/data/sst/contour/global.c.gif>. The logistic regression analysis uses a logit transformation based on the number of fulmars in the sample and the number of fulmars exceeding the FTV, in relation to an environmental variable such as latitudinal position or average sea surface temperature. For all tests, the statistical significance level was set at $p < 0.05$.

3. Results

Based on the entire sample of 37 fulmars, the average number of plastics with standard error was $6.6 \pm se 1.2$ particles, with an average total mass of 0.093 ± 0.024 g (Table 1). Plastic items were found in 33 of 37 birds (%FO: 89 %). Ten of the 37 stomachs (27 %) exceeded the FTV criterion of containing >0.1 g of plastic.

The discriminant score from head measurements led to the assignment of 14 females and 23 males in our NFB sample. Due to the type of sample (head + digestive system only), age could not be assessed. Most fulmars were of the LL colourphase, there were only two coloured birds, one female and one male. Individual details on measurements, discriminant scores and assigned sex are provided in Supplement Table S1. None of the differences between the sexes in plastics ingested were statistically different in Mann-Whitney U tests and Epitools Z tests. Significantly more plastic was found in the gizzard compared to the proventriculus, for both mass and number (Mann-Whitney U test $p < 0.001$), whereas in the 22 available samples of intestines zero plastic particles were detected (Table 1B).

Fulmars contained significantly more user plastics than industrial plastics by number and mass (Mann-Whitney U test $p < 0.001$). This was evident for separate sexes and different parts of the digestive system (Table 2). User plastics represented about 94 % of the total plastic mass, largely made up by fragments (Supplement Table S2). For individual birds, detailed information on the presence of different categories and subcategories of plastics in the stomachs is provided in Supplement Table S2 and photos. The FTIR analyses revealed that more than half (52 %) of all 245 plastic items found were classified as polyethylene (PE), followed by a substantial proportion (19 %) polypropylene (PP).

Within the NFB sample, 27 % of the birds exceeded the Fulmar Threshold Value of 0.1 g of plastic in the stomach. The FTV% datapoint for the NFB sample and for other recent sources listed in Table S3 were added in a new run of the logistic model created by Van Franeker et al. (2022) which illustrated a latitudinal decline in ingested plastics (Supplement Table S3; Fig. 3). The Generalized Linear Model (GLM) logistic regression of the binomial proportions of fulmars in the studies exceeding 0.1 g of plastic demonstrates a significant negative correlation with the latitude at which they were collected ($p < 0.001$, Supplement Table S4). Although this correlation was found to be significant, Fig. 3 demonstrates that our current study (datapoint in yellow) is a clear outlier with a considerably lower FTV% compared to what would be expected at this latitude according to the logistic model.

The latitudinal model had its origin in the situation in the eastern North Atlantic, with densely populated and industrialized areas in the south and gradually lower levels of human influences when moving to

Table 1

Presence of plastic in the stomachs of 37 NFB fulmars, subdivided by A. sex and B. different parts of the digestive system. Shown are the proportion of birds with plastic in the stomach (%FO, frequency of occurrence), average number and mass with standard error, median mass, geometric mean mass and proportion of birds containing >0.1 g of plastic (FTV%).

A.	Sample		Average number		Average mass		Median	GEOMETRIC	
	n	%FO	n ± se	g ± se	Mass (g)	Mean (g)	FTV%		
All	37	89 %	6.6 ± 1.2	0.093 ± 0.025	0.042	0.0266	27 %		
Female	14	100 %	5.9 ± 1.8	0.079 ± 0.022	0.059	0.0414	36 %		
Male	23	83 %	7.0 ± 1.7	0.101 ± 0.038	0.042	0.0202	22 %		

B.	Sample		Average number		Average mass		Median	GEOMETRIC	
	n	%FO	n ± se	g ± se	Mass (g)	Mean (g)	FTV%		
Proventriculus	37	11 %	0.2 ± 0.1	0.002 ± 0.002	0.000	0.0002	0 %		
Gizzard	37	89 %	6.4 ± 1.1	0.091 ± 0.024	0.040	0.0264	27 %		
Intestines	22	0 %	0.0 ± 0.0	0.000 ± 0.000	0.000	0.0000	0 %		

Table 2

Types of plastic items, subdivided into industrial granules and user plastics (sheets, threads, foams, fragments and other plastics), found in the stomachs of 37 NFB fulmars, subcategorized by A. sex and B. different parts of the digestive system.

A.	Sample	%FO	Industrial plastics		%FO	User Plastics	
			avg number			avg mass	
			n ± se	g ± se		n ± se	g ± se
All	37	27 %	0.4 ± 0.1	0.009 ± 0.003	89 %	6.2 ± 1.1	0.083 ± 0.022
Female	14	21 %	0.4 ± 0.3	0.009 ± 0.005	100 %	5.5 ± 1.6	0.070 ± 0.018
Male	23	30 %	0.4 ± 0.2	0.009 ± 0.004	83 %	6.6 ± 1.6	0.091 ± 0.034

B.	Sample	%FO	Industrial plastics		%FO	User plastics	
			avg number			avg mass	
			n ± se	g ± se		n ± se	g ± se
Proventriculus	37	3 %	0.0 ± 0.0	0.001 ± 0.001	11 %	0.2 ± 0.1	0.001 ± 0.001
Gizzard	37	27 %	0.4 ± 0.1	0.009 ± 0.003	89 %	6.0 ± 1.1	0.082 ± 0.022
Intestines	22	0 %	0.0 ± 0.0	0.000 ± 0.000	0 %	0.0 ± 0.0	0.000 ± 0.000

the north. In detail, the observed trend was somewhat contradicted by results of [Trevail et al. \(2015\)](#) who found that birds from Svalbard contained more plastic than would be expected in comparison to the low levels observed in the Canadian Arctic at similar latitudes ([Fig. 1](#), Supplement Table S3). The explanation for this difference between the eastern and western side of the Atlantic may be found in ocean currents that may play an important role in transporting plastic waste over vast distances. The warm Gulf Stream carries water from the Gulf of Mexico, along the United Kingdom and Norwegian coast all the way to the Arctic Ocean ([Van Sebille et al., 2012](#); [Cózar et al., 2017](#); [Halsband and Herzke, 2019](#)). In contrast, in the western North Atlantic, the Labrador Current carries cold polar waters southwards to the Newfoundland area. It originates in sparsely populated and non-industrialized Arctic areas further north, and may be expected to be relatively clean. The opposite currents are clearly reflected in [Fig. 1](#) showing sea surface isotherms in early June, around the date when the fulmars from the NFB were collected.

In order to create a logistic model similar to that in relation to latitude but which reflects these ocean current patterns, we assessed the average annual sea surface temperatures in the vicinity of all available datasets on plastic ingestion by fulmars (Supplement Table S3). We used average annual temperatures because the fulmar data sets are highly variable, some covering fulmar collections throughout the year, some only for specific seasons, and some even on a single date. [Fig. 4](#) shows the highly significant correlation ($p < 0.001$) of the logistic regression for FTV% in relation to the annual SST (Table S5). In this analysis, the NFB sample is much closer to the modelled gradient in SST than when related to latitude. There are still other samples that deviate from the

model, most strongly so for the data for Ireland ([Acampora et al., 2016](#)), but this was a relatively small sample of only 14 fulmars, which may not be representative.

Both the latitudinal ([Fig. 3](#)) and SST ([Fig. 4](#)) logistic GLM model reveal highly significant ($p < 0.001$) correlations to the quantities of plastic (FTV%) found in fulmar stomachs. Latitude and SST covary in a complicated manner, but when evaluating both factors in a GLM-Mixed model, it becomes clear that SST represents the dominant element ($p < 0.001$) with an insignificant additional contribution of latitude ($p = 0.367$) to the mixed model.

4. Discussion

In the NFB fulmars, the average mass of ingested plastic, and the proportion of birds exceeding the 0.1 g level (FTV%) were considerably lower than predicted by the model for correlation between latitude and the FTV% in [Van Franeker et al., \(2022\)](#). This was the case for both males and females, with no significant difference in the quantity of plastics in the stomach between the sexes. Whether the NFB samples were influenced by age of the birds involved remains unclear, but likely the sampled fulmars consisted of a mix of different ages and different areas from all over the North Atlantic area. Nearly all the NFB birds were of the double light colourphase (LL). Only two birds were of the coloured morphs which occur in the Canadian Arctic and the high Arctic populations in the far north and east of the north Atlantic Ocean ([Van Franeker and Wattel, 1982](#); [Van Franeker, 1995](#)). The majority of the NFB birds likely originate from the large LL populations in the temperate to low Arctic regions of the Atlantic such as Iceland, Jan Mayen, the



Fig. 2. Example of one of the heavier plastic loads found in stomachs from the NFB (sample NFB-2021-016, with 0.6534 g of plastic). See Supplement for photos of all NFB stomach samples.

Faroe Islands and the UK and from west Greenland (Brown, 1970; Amélineau et al., 2021; Dehnhard, 2022).

Along the eastern side of the North Atlantic, the pattern of decreasing plastics from the French English Channel up to the Arctic indicates that part of the plastics entering the water in the southern areas, is not detected further north (Isobe and Iwasaki, 2022; Kaandorp et al., 2023). Such decrease may be caused by many factors (Andrady, 2015) like sinking to deeper water, deposition in the ocean bottom or coastal sediments, being blown onshore, fragmentation and degradation by animal ingestion, mechanical- and light degradation, or even degradation by micro-organisms. Along the western side of the North Atlantic, the clean Arctic Labrador Current bounces against the warm and polluted waters of the Gulf Stream (Ma et al., 2022). Fulmars in the NFB area may easily travel the relatively short distance from the polluted Gulf Stream water to the cold and clean water of the Labrador Current, which could explain rather outlying high values seen in two samples NFB-2021-016 (Fig. 2) and NFB-2021-029. Fulmars collected on beaches of Sable Island differ hugely from the NFB fulmars having much higher loads of plastics ingested, on average 26 items weighing 1.09 g (Bond et al., 2014), while being only a few hundred kilometres further south. Such rapid changes in the Sea Surface Temperature (SST) or ingested plastics in fulmars are not found along the eastern side of the North Atlantic.

5. Conclusion

By adding a new datapoint of plastic ingestion by fulmars this paper provides valuable information regarding geographical patterns in marine litter pollution levels. Because of the poor fit of the NFB datapoint in the existing latitudinal model, we looked into the effects of ocean currents and created a similar model using sea surface temperatures. This

model shows a gradient with fewer fulmars with >0.1 g of plastic at lower sea-surface temperatures. Like the earlier latitude model we believe this to be a consequence of distance to densely populated and industrialized source areas and transport of litter by oceanic currents. The eastern Atlantic currents flow northwards, while in the western sector they run in the opposite direction.

The models presented in this paper are possible because a diverse community of scientists from widely separated regions use standardized methods for assessing plastics in fulmars (OSPAR, 2015). Standardization in this type of research allows large-scale analyses across both time and space (Provencher et al., 2019). When looking into further detail than just the FTV%, many variables other than just sample size may affect results, such as substantial sex and age differences between samples, seasonality, type of collection, and spatial limits of collection (Van Franeker et al., 2022). Current knowledge is insufficient to include such details as covariates in the models, but continued research may prove very useful.

CRedit authorship contribution statement

Sterre de Bruin: Writing – review & editing, Writing – original draft, Investigation, Data curation. **Jan A. van Franeker:** Writing – review & editing, Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **André Meijboom:** Writing – review & editing, Supervision, Investigation, Formal analysis. **Jens-Kjeld Jensen:** Writing – review & editing, Resources, Conceptualization. **Bjarni Jacobsen:** Writing – review & editing, Resources. **Susanne Kühn:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation.

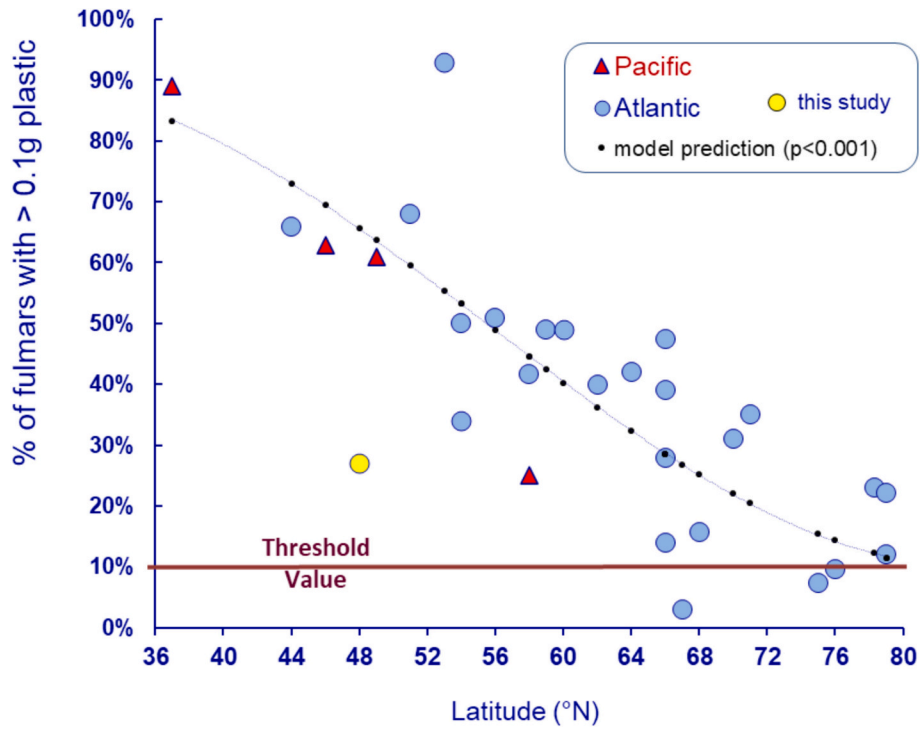


Fig. 3. Logistic model of the percentage of fulmars containing >0.1 g plastic (FTV%), plotted against the latitudes of sampling locations from various studies. Pacific studies are represented as red triangles and Atlantic studies as blue circles. The result from the current study at the NFB is depicted as the yellow circle. The dotted line demonstrates the modelled prediction for expected percentages along different latitudes (see Supplement Table S3 for details and References). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

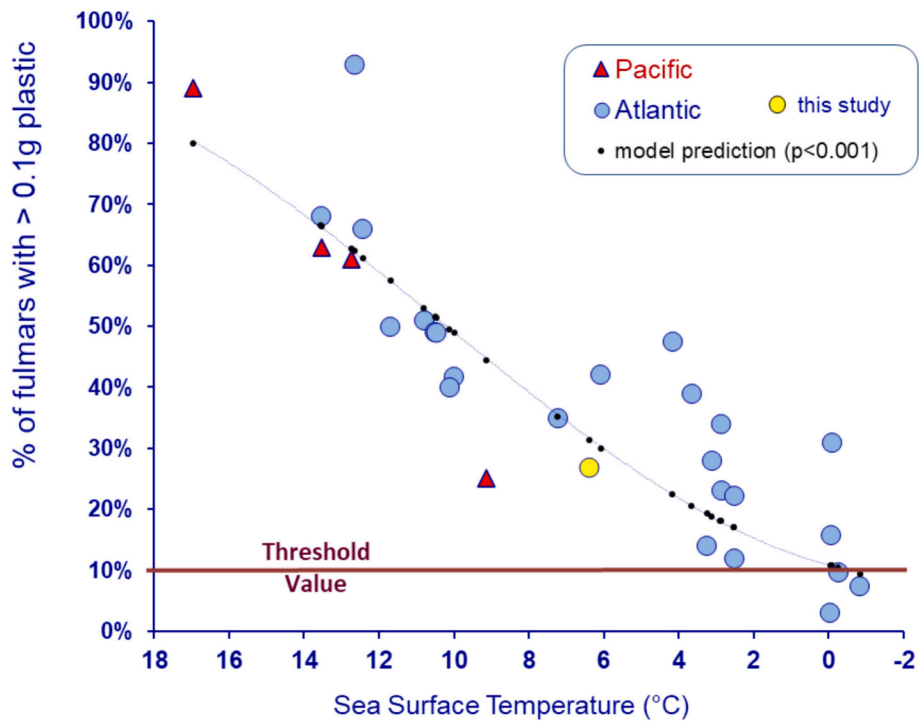


Fig. 4. Logistic model of the percentage of fulmars containing >0.1 g plastic plotted against the annual average Sea Surface Temperature (SST) of sampling locations from various studies. Pacific studies are represented as red triangles and Atlantic studies as blue circles. The result from the current study is depicted as the yellow circle. The dotted line demonstrates the modelled prediction for expected percentages along different water temperatures. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.marpolbul.2025.117894>.

Data availability

The data underlying this article are available in the article and in its online supplementary material.

References

- Acampora, H., Lyashevskaya, O., Van Franeker, J.A., O'Connor, I., 2016. The use of beached bird surveys for marine plastic litter monitoring in Ireland. *Mar. Environ. Res.* 120, 122–129. <https://doi.org/10.1016/j.marenvres.2016.08.002>.
- Amélineau, F., Merkel, B., Tarroux, A., Descamps, S., Anker-Nilsson, T., Bjørnstad, O., Bråthen, V.S., Chastel, O., Christensen-Dalsgaard, S., Danielsen, J., Daunt, F., Dehnard, N., Ekker, M., Erikstad, K.E., Ezhov, A., Fauchald, P., Gavrilo, M., Hallgrímsson, G.T., Hansen, E.S., Harris, M.P., Helberg, M., Helgason, H.H., Johansen, M.K., Jónsson, J.E., Kolbeinsson, Y., Krasnov, Y., Langset, M., Lorentsen, S.H., Lorentzen, E., Melnikov, M.V., Moe, B., Newell, M.A., Olsen, B., Reiertsen, T., Systad, G.H., Thompson, P., Þórarinsson, T.L., Tolmacheva, E., Wanless, S., Wojczulanis-Jakubas, K., Áström, J., Strøm, H., 2021. Six pelagic seabird species of the North Atlantic engage in a fly-and-forage strategy during their migratory movements. *Mar. Ecol. Prog. Ser.* 676, 127–144. <https://doi.org/10.3354/meps13872>.
- Andrady, A.L., 2015. Persistence of plastic litter in the oceans. In: Bergmann, M., Gutow, L., Klages, M. (Eds.), *Marine Anthropogenic Litter*. Springer, Cham, pp. 57–72. https://doi.org/10.1007/978-3-319-16510-3_3.
- Avery-Gomm, S., O'Hara, P.D., Kleine, L., Bowes, V., Wilson, L.K., Barry, K.L., 2012. Northern fulmars as biological monitors of trends of plastic pollution in the eastern North Pacific. *Mar. Pollut. Bull.* 64, 1776–1781. <https://doi.org/10.1016/j.marpolbul.2012.04.017>.
- Avery-Gomm, S., Provencher, J.F., Liboiron, M., Poon, F.E., Smith, P.A., 2018. Plastic pollution in the Labrador Sea: an assessment using the seabird northern fulmar *Fulmarus glacialis* as a biological monitoring species. *Mar. Pollut. Bull.* 127, 817–822. <https://doi.org/10.1016/j.marpolbul.2017.10.001>.
- Bond, A.L., Provencher, J.F., Daoust, P.Y., Lucas, Z.N., 2014. Plastic ingestion by fulmars and shearwaters at Sable Island, Nova Scotia. *Canada. Mar. Poll. Bull.* 87, 68–75. <https://doi.org/10.1016/j.marpolbul.2014.08.010>.
- Brown, R.G.B., 1970. Fulmar distribution: a Canadian perspective. *Ibis* 112, 44–51. <https://doi.org/10.1111/j.1474-919X.1970.tb00074.x>.
- Cózar, A., Martí, E., Duarte, C.M., García-de-Lomas, J., van Sebille, E., Ballatore, T.J., Eguíluz, V.M., González-Gordillo, J.I., Pedrotti, M.L., Echevarría, F., Troublé, R., Irigoien, X., 2017. The Arctic Ocean as a dead end for floating plastics in the North Atlantic branch of the thermohaline circulation. *Sci. Adv.* 3, e1600582. <https://doi.org/10.1126/sciadv.1600582>.
- Dehaut, A., Cassone, A.-L., Frère, L., Hermabessiere, L., Himber, C., Rinnert, E., Rivière, G., Lambert, C., Soudant, P., Huvet, A., 2016. Microplastics in seafood: benchmark protocol for their extraction and characterization. *Environ. Pollut.* 215, 223–233. <https://doi.org/10.1016/j.envpol.2016.05.018>.
- Dehnard, N., 2022. Eissturmvogel - Verbreitung im Sommer und Winter, basiert auf Trackingdaten, 43. Seevögel (Sonderheft, Dez. 2022; in German with English summary), pp. 58–64. <https://www.jordsand.de/2023/01/25/sonderheft-%C3%BCber-eissturmvogel-ver%C3%B6ffentlicht/>.
- EC 2022. MSFD CIS Guidance Document No. 19, Article 8 MSFD, May 2022. European Commission, Brussels. 193pp. <https://www.researchgate.net/publication/361461227>.
- Halsband, C., Herzke, D., 2019. Plastic litter in the European Arctic: what do we know? *Emerg. Cont.* 5, 308–318. <https://doi.org/10.1016/j.emcon.2019.11.001>.
- Isobe, A., Iwasaki, S., 2022. The fate of missing ocean plastics: are they just a marine environmental problem? *Sci. Total Environ.* 825, 153935. <https://doi.org/10.1016/j.scitotenv.2022.153935>.
- Jambeck, J.R., Geyer, R., Wilcox, C., Siegler, T.R., Perryman, M., Andrady, A., Narayan, R., Law, K.L., 2015. Plastic waste inputs from land into the ocean. *Science* 347, 768–771. <https://doi.org/10.1126/science.1260352>.
- Jensen, J.-K., 2012. Mallemukken på Færøerne / The fulmar on the Faroe Islands. Nolsoy, Torshavn.
- Kaandorp, M.L.A., Lobelle, D., Kehl, C., Dijkstra, H.A., van Sebille, E., 2023. Global mass of buoyant marine plastics dominated by large long-lived debris. *Nat. Geosci.* 16, 689–694. <https://doi.org/10.1038/s41561-023-01216-0>.
- Karami, A., Golieskardi, A., Choo, C.K., Romano, N., Ho, Y.B., Salamatinia, B., 2017. A high-performance protocol for extraction of microplastics in fish. *Sci. Total Environ.* 578, 485–494. <https://doi.org/10.1016/j.scitotenv.2016.10.213>.
- Kühn, S., Van Franeker, J.A., 2012. Plastic ingestion by the northern fulmar (*Fulmarus glacialis*) in Iceland. *Mar. Pollut. Bull.* 64, 1252–1254. <https://doi.org/10.1016/j.marpolbul.2012.02.027>.
- Kühn, S., Van Franeker, J.A., 2020. Quantitative overview of marine debris ingested by marine megafauna. *Mar. Pollut. Bull.* 151, 110858. <https://doi.org/10.1016/j.marpolbul.2019.110858>.
- Kühn, S., van Werven, B., van Oyen, A., Meijboom, A., Bravo Rebolledo, E.L., van Franeker, J.A., 2017. The use of potassium hydroxide (KOH) solution as a suitable approach to isolate plastics ingested by marine organisms. *Mar. Pollut. Bull.* 115, 86–90. <https://doi.org/10.1016/j.marpolbul.2016.11.034>.
- Kühn, S., van Oyen, A., Bravo Rebolledo, E.L., Ask, A.V., van Franeker, J.A., 2021. Polymer types ingested by northern fulmars (*Fulmarus glacialis*) and southern hemisphere relatives. *Environ. Sci. Pollut. Res.* 28, 1643–1655. <https://doi.org/10.1007/s11356-020-10540-6>.
- Ma, Y., Lu, Y., Hu, X., Gilbert, D., Socolofsky, S.A., Boufadel, M., 2022. Model simulated freshwater transport along the Labrador current east of the grand banks of Newfoundland. *Front. Mar. Sci.* 9, 908306. <https://doi.org/10.3389/fmars.2022.908306>.
- Mallory, M.L., Hatch, S.A., Nettleship, D.N., 2012. Northern fulmar (*Fulmarus glacialis*), version 2.0. In: Poole, A.F. (Ed.), *The Birds of North America* Cornell Lab of Ornithology. <https://doi.org/10.2173/bna.361>. Ithaca, NY, USA.
- Nettleship, D.N., Montgomerie, R.D., 1974. The northern fulmar, *Fulmarus glacialis*, breeding in Newfoundland. *American Birds* 28, 16. <http://sora.unm.edu/sites/default/files/journals/nab/v028n01/p00016-p00016.pdf>.
- North Sea Ministerial Conference, 2002. Ministerial Declaration of the Fifth International Conference on the Protection of the North Sea. Bergen declaration. Bergen, Norway, pp. 50. <http://www.regjeringen.no/upload/kilde/md/rap/2002/0002/ddd/pdfv/156076-engelsk.pdf>.
- OECD, 2022. Global Plastics Outlook Policy Scenarios to 2060. Policy highlights. Organization for Economic Cooperation and Development, OECD Report, pp. 28. <https://read.oecd-ilibrary.org/view/?ref=11431143481-88j1bxuktr&title>.
- OSPAR, 2008. Background document for the EcoQO on plastic particles in stomachs of seabirds. OSPAR commission, biodiversity series publication number: 355/2008 London, pp. 13. <https://www.ospar.org/documents?v=7109>.
- OSPAR, 2015. Guidelines for Monitoring of Plastic Particles in Stomachs of Fulmars in the North Sea Area. OSPAR Commission Agreement 2015–03 (Source: EIHA 15/5/12 add.1). London, p. 26. <https://www.ospar.org/convention/agreements?q=fulmar&t=32281&a=&s>.
- PlasticsEurope, 2023. Plastics Europe - Fast Fact Report with Data up to 2022. PlasticsEurope Association of Plastics Manufacturers, Brussels, p. 1. <https://plasticseurope.org/knowledge-hub/plastics-the-fast-facts-2023/>.
- Provencher, J.F., Bond, A.L., Avery-Gomm, S., Borrelle, S.B., Bravo Rebolledo, E.L., Hammer, S., Kühn, S., Lavers, J.L., Mallory, M.L., Trevail, A., van Franeker, J.A., 2017. Quantifying ingested debris in marine megafauna: a review and recommendations for standardization. *Anal. Methods* 9, 1454–1469. <https://doi.org/10.1039/c6ay02419j>.
- Provencher, J.F., Borrelle, S., Bond, A.L., Lavers, J.L., Van Franeker, J.A., Kühn, S., Hammer, S., Avery-Gomm, S., Mallory, M.L., 2019. Recommended best practices for plastic and litter ingestion studies in marine birds: collection, processing, and reporting. *Facets* 4, 111–130. <https://doi.org/10.1139/facets-2018-0043>.
- Trevail, A.M., Gabrielsen, G.W., Kühn, S., Van Franeker, J.A., 2015. Elevated levels of ingested plastic in a high Arctic seabird, the northern fulmar (*Fulmarus glacialis*). *Polar Biol.* 38, 975–981. <https://doi.org/10.1007/s00300-015-1657-4>.
- Van Franeker, J., Wattel, J., 1982. Geographical variation of the fulmar *Fulmarus glacialis* in the North Atlantic. *Ardea* 70, 31–44.
- Van Franeker, J.A., 1985. Plastic ingestion in the North Atlantic fulmar. *Mar. Pollut. Bull.* 16, 367–369. [https://doi.org/10.1016/0025-326x\(85\)90090-6](https://doi.org/10.1016/0025-326x(85)90090-6).
- Van Franeker, J.A., 1995. Kleurfasen van de Noordse Stormvogel *Fulmarus glacialis* in de Noordatlantische Oceaan [Colourphases of the fulmar *Fulmarus glacialis* in the North Atlantic]. *Sula* 9, 93–106. <https://natuurtijdschriften.nl/pub/553831>.
- Van Franeker, J.A., Meijboom, A., 2002. Litter NSV - Marine Litter Monitoring by Northern Fulmars. A Pilot Study. Alterra, Wageningen, p. 72. <http://edepot.wur.nl/45695>.
- Van Franeker, J.A., Ter Braak, C.J.F., 1993. A generalized discriminant for sexing Fulmarine petrels from external measurements. *Auk* 110, 492–502. <https://doi.org/10.2307/4088413>.

- Van Franeker, J.A., Blaize, C., Danielsen, J., Fairclough, K., Gollan, J., Guse, N., Hansen, P.L., Heubeck, M., Jensen, J.K., Le Guillou, G., Olsen, B., Olsen, K.O., Pedersen, J., Stienen, E.W., Turner, D.M., 2011. Monitoring plastic ingestion by the northern fulmar *Fulmarus glacialis* in the North Sea. *Environ. Pollut.* 159, 2609–2615. <https://doi.org/10.1016/j.envpol.2011.06.008>.
- Van Franeker, J.A., Kühn, S., Anker-Nilssen, T., Edwards, E.W.J., Gallien, F., Guse, N., Kakkonen, J.E., Mallory, M.L., Miles, W., Olsen, K.O., Pedersen, J., Provencher, J., Roos, M., Stienen, E., Turner, D.M., van Loon, W.M.G.M., 2021. New tools to evaluate plastic ingestion by northern fulmars applied to North Sea monitoring data 2002–2018. *Mar. Pollut. Bull.* 166, 112246. <https://doi.org/10.1016/j.marpolbul.2021.112246>.
- Van Franeker, J.A., Jensen, J.-K., Simonsen, P.J., Bravo Rebolledo, E.L., Kühn, S., 2022. Plastics in stomachs of northern fulmars *Fulmarus glacialis* collected at sea off East Greenland: latitude, age, sex and season. *Mar. Biol.* 169, 45. <https://doi.org/10.1007/s00227-022-04029-8>.
- Van Sebille, E., England, M.H., Froyland, G., 2012. Origin, dynamics and evolution of ocean garbage patches from observed surface drifters. *Environ. Res. Lett.* 7, 044040. <https://doi.org/10.1088/1748-9326/7/4/044040>.
- VSN International, 2017. Genstat Reference Manual (Release 19) Part 1 Summary Part 2 Directives Part 3 Procedures. VSN International, Hemel, Hempstead, UK. <https://genstat.kb.vsnl.co.uk/knowledge-base/online-documentation>.