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Microplastic pollution in the Greenland Sea: Background levels and selective contamination of planktivorous diving seabirds☆

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ABSTRACT

Microplastics have been reported everywhere around the globe. With very limited human activities, the Arctic is distant from major sources of microplastics. However, microplastic ingestions have been found in several Arctic marine predators, confirming their presence in this region. Nonetheless, existing information for this area remains scarce, thus there is an urgent need to quantify the contamination of Arctic marine waters. In this context, we studied microplastic abundance and composition within the zooplankton community off East Greenland. For the same area, we concurrently evaluated microplastic contamination of little auks (*Alle alle*), an Arctic seabird feeding on zooplankton while diving between 0 and 50 m. The study took place off East Greenland in July 2005 and 2014, under strongly contrasted sea-ice conditions. Among all samples, 97.2% of the debris found were filaments. Despite the remoteness of our study area, microplastic abundances were comparable to those of other oceans, with 0.99 ± 0.62 m^{-3} in the presence of sea-ice (2005), and 2.38 ± 1.11 m^{-3} in the nearby absence of sea-ice (2014). Microplastic rise between 2005 and 2014 might be linked to an increase in plastic production worldwide or to lower sea-ice extents in 2014, as sea-ice can represent a sink for microplastic particles, which are subsequently released to the water column upon melting. Crucially, all birds had eaten plastic filaments, and they collected high levels of microplastics compared to background levels with 9.99 and 8.99 pieces per chick meal in 2005 and 2014, respectively. Importantly, we also demonstrated that little auks took more often light colored microplastics, rather than darker ones, strongly suggesting an active contamination with birds mistaking microplastics for their natural prey. Overall, our study stresses the great vulnerability of Arctic marine species to microplastic pollution in a warming Arctic, where sea-ice melting is expected to release vast volumes of trapped debris.

1. Introduction

Global plastic production is increasing exponentially with a current doubling time of 11 years (PlasticsEurope, 2013; Wilcox et al., 2015). In 2013, 299 million tons of plastic were manufactured in the world, with 57 million tons in Europe alone (PlasticsEurope, 2015). Thompson (2006) estimated that up to 10% of plastics produced end up in the oceans where they may persist and accumulate. In the environment, microplastics (i.e. plastic fragments <5 mm) are either a direct release of primary microplastics such as industrial pellets and plastic beads from cosmetics, or can originate from larger plastic debris that gradually fragment. Marine microplastic pollution is a worldwide phenomenon and

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contamination has been reported on a global scale, from poles to the equator (Browne et al., 2008, 2011).

Little is known about microplastic pollution in the Arctic in comparison with other basins (Bergmann et al., 2016). To our knowledge, there is only one study on microplastic abundance in the water column of the Greenland Sea (Lusher et al., 2015), and one recent study reporting considerable microplastic concentrations in Arctic Sea ice (Obbard et al., 2014). However, several biological monitoring studies have reported ingestion of microplastics by marine animals in this part of the world, mostly by seabirds (4 species, Trevail et al., 2015). Seabirds are indeed particularly exposed because of the frequency with which some species ingest plastics, and because of the emerging evidence of impacts on both bird body condition and transmission of toxic chemicals, which could result in changes in mortality or reproduction (Lavers et al., 2014; Spear et al., 1995; Tanaka et al., 2013). Notably, the northern fulmar (*Fulmarus glacialis*) which regularly ingests plastic (i.e. Van Franeker, 1985; Van Franeker et al., 2011; Moser and Lee, 1992; Robards et al., 1995), is used for monitoring plastic pollution by OSPAR (Oslo/Paris Convention for the Protection of the Marine Environment of the North-East Atlantic) and the European MSFD (Marine Strategy Framework Directive), and supports international legislation aiming at reducing marine litter (OSPAR, 2008; E.C, 2008, 2010).

Recent studies (Schuyler et al., 2015; Wilcox et al., 2015) have shown that seabird and turtle plastic ingestion rates scale with plastic exposure, i.e. if more plastics are introduced into the ocean, ingestion rates can be expected to increase proportionally. For example, more plastic debris were observed in fulmars from the North Sea or from California than in fulmars from presumably cleaner Arctic breeding locations (Van Franeker, 1985). Besides, seabirds and turtles have been found to ingest more items which contrast with the ocean background: darker plastics for turtles which detect prey from below, and lighter plastics for seabirds detecting prey from above (Santos et al., 2016). In addition, seabird contamination is expected to vary according to feeding techniques, with filter-feeders being more contaminated than single-prey catchers, as the former do not target specific items, and surface-feeders being more contaminated than divers because plastics are mainly at the surface (Reisser et al., 2015).

While plastic ingestion is widespread in seabirds, to our knowledge, only a few studies have investigated the interaction between microplastics and little auks (*Alle alle*) (Pedersen and Falk, 2001; Falk and Durinck, unpublished data in Provencher et al., 2014; Fife et al., 2015), the most abundant seabird in the North Atlantic Arctic, with an estimated 40–80 million individuals (Egevang et al., 2003). Little auks are zooplanktivorous birds. They dive within the first 50 m of the water column, and feed mainly on *Calanus* spp. (see Fig. 1 in Frandsen et al., 2014). Prey items, brought back to their single chick, are carried by adults in a gular pouch (Fig. 1). Among studies which recorded microplastic occurrence in chick diet or gizzard content of adult little auks, none have established correlations with environmental parameters such as zooplankton or microplastics abundance in the water column. Furthermore, those studies indicated contrasting results, with 0%, 9%–14% of birds containing plastic debris (with a number of birds dissected of n = 19, 104 and 65, respectively).

In this context, our objectives were (1) to determine and quantify the occurrence of microplastic pollution in coastal waters of the Greenland Sea (East Greenland), (2) to assess if those debris are encountered in little auk chick diet and if their colour or size influence the frequency of little auk microplastic intake and, finally, (3) to compare microplastic occurrence in the water column and little auk diet nine years apart, in the presence of sea-ice within little auk foraging areas (2005), and in its nearby absence (2014).

2. Material and methods

All field work in East Greenland was conducted with the permission of the Greenland Home Rule Government, Ministry of Environment and Nature (Danish Polar Center Scientific Expedition Permit 512-240 and 2014-098814), and under permits granted by the Ethics Committee of the French Polar Institute (MP/12/24/05/05).

2.1. Field survey

We performed at-sea surveys within the foraging areas of little auks from the Ukaleqarteq breeding colony (East Greenland) in 2005 and 2014 (Fig. 2). This area is under the influence of the East-Greenland Current (EGC, Fig. 2a) that carries multi-year sea-ice from the Arctic southwards. Sea-ice conditions are highly variable between years in this area and the front of ice carried by the EGC can be located more or less South (Fig. 2b). We sampled 18 and 20 stations in 2005 and 2014, respectively. Detailed accounts of the at-sea procedures are provided in Karnovsky et al. (2010). In both years, we collected zooplankton with a WP-2 net with a 0.25 m^2 opening area. We performed vertical tows from 50 m to the surface. To assess the filtered water volume, we used a flowmeter in 2005. In 2014, we used a data logger recording depth (G5, CEFAS

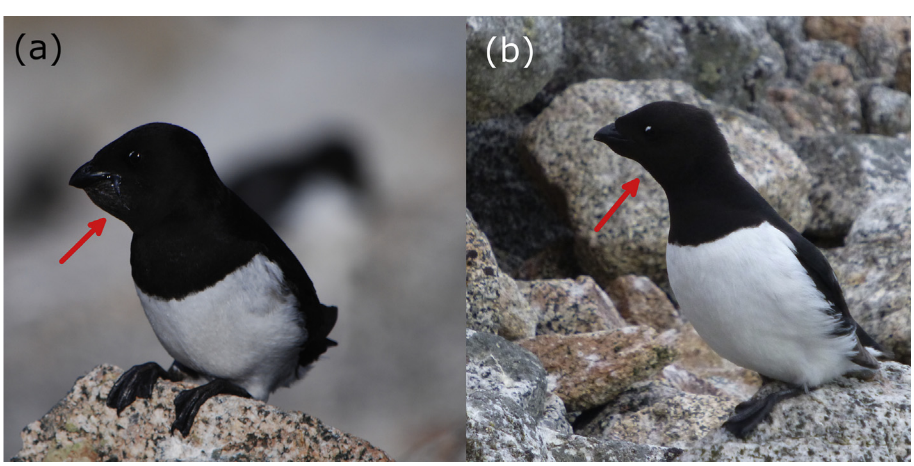

Fig. 1. Little auks bring back food to their chicks in a gular pouch. Breeding little auks with (a) a full gular pouch and (b) an empty one.

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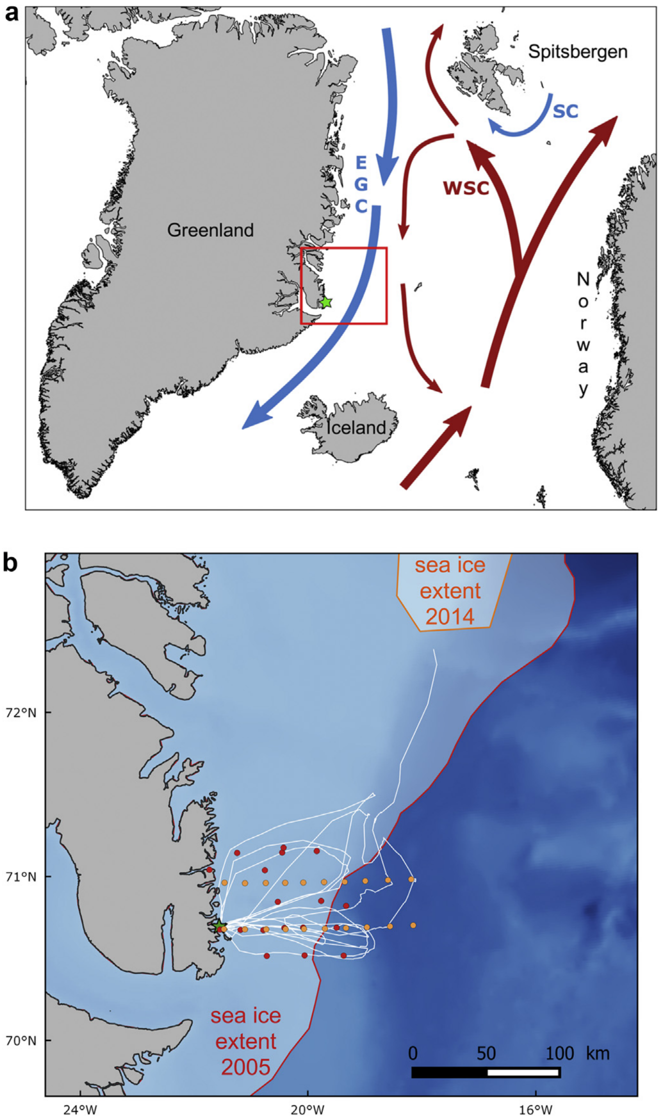

Fig. 2. (a) General study area and (b) location of zooplankton sampling stations and sea ice extent in 2005 (red) and 2014 (yellow). EGC: East Greenland Current. SC: Sørkapp Current, WSC: West Spitsbergen Current. The green star represents the study colony. White lines represent GPS tracks from 2014 (results from Amélineau et al., 2016). Sea ice extents correspond to the daily sea ice extent of the median day of each cruise and were downloaded from the U.S. National Ice Center (http://www.natice.noaa.gov/products/daily_products.html). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Technology Ltd.) and the filtered water volume was calculated from the span of the tow and the opening of the net. In 2005, sampling was performed onboard RV Vagabond from 1 to 11 August within pack-ice and the net mesh size was 500 μm. Samples were stored in sterile plastic containers with 5% formaldehyde solution in sea water, buffered with borax. In 2014, sampling was performed onboard RV Argelvor from 16 to 19 August and no sea ice was observed. The mesh size of the net was 100 μm. Samples were stored in sterile plastic containers with 70% ethanol. Back in the lab, we sieved samples on a 500 μm mesh, and only fraction >500 μm was analyzed for microplastics and zooplankton abundance to allow comparison with 2005 samples. We counted zooplankton and identified it to the lowest taxonomic level. Zooplankton identification results are available in Karnovsky et al. (2010) and Amélineau et al. (2016). In this study, we used *Calanus* counts, which include *C. finmarchicus*, *C. glacialis* and *C. hyperboreus* at stages CIV, CV and CVI, which are the main prey of little auks during summer (Karnovsky et al., 2010).

2.2. Chick diet sampling at the little auk colony

Fieldwork occurred at the little auk colony of Ukaleqarteq (Kap Höegh, East Greenland, 70°44′ N, 21°35′ W; Fig. 2) in 2005 and 2014. Breeding little auks bring back food for their chick in a gular pouch (Fig. 1). We caught birds coming back with a full pouch upon arrival with nooses placed on the rocks surrounding their nests. The pouch content was collected by opening their beak and gently removing the content with a soft rubber paint brush, and stored in a sterile plastic container with 5% formalin in 2005, and with 70% ethanol in 2014. Birds were then weighed, ringed and released. All handling lasted less than 2 min and birds were sampled only once. 26 and 18 birds were sampled in 2005 and 2014, respectively. Captures occurred between 23 July and 7 August in both years (i.e. during the chick-rearing period).

2.3. Microplastic fragments

As a first step, in each sample (either plankton collected at sea or little auk gular pouch content), we identified visually all non-biological particles based on surface characteristics, morphology and physical response (see Zhao et al., 2016 for detailed criteria). Particles were then counted, sorted and classified by colour and by shape (fiber or fragment, Hidalgo-Ruz et al., 2012) under a binocular microscope. Each debris was sized with an increment of 0.1 mm. The sizes were defined by the longest length of each piece and were measured with ImageJ software (Schneider et al., 2012). We classified debris as either light, or dark in colour (Santos et al., 2016).

As a second step, in order to identify microplastics among debris and the nature of polymers, we analyzed a subsample of particles (randomly chosen) using a Fourier transform infrared spectrophotometer (Spectrum Two- ATR Sample base plate Diamond). The spectrum for each particle was compared with several polymer spectra banks (HR Sprouse Polymers by ATR, Aldrich FT-IR Collection Edition II, Hummel Polymer, Hummel Polymer and Additives, Industrial Coatings, Sprouse Polymers by Transmission) and the detection threshold for a correct identification of polymers was set to a match of at least 75%. We then calculated a proportion of microplastics among debris for water column and gular pouch samples, and for all the samples, the number of microplastics per sample was recalculated. For water column samples, the quantities of microplastics were divided by the volume of water filtered to convert them to quantities per unit seawater volume (hereinafter "concentration", as items per m^{-3}). For gular pouches, microplastic counts were adjusted as number of items per complete pouch.

2.4. Microplastic sample contamination

In order to minimize contamination, lab coats, cotton clothing and gloves were worn when sorting the samples. In addition, to estimate contamination when processing the samples (zooplankton identification, counts and sorting), negative controls were performed in sterile glass petri dishes of the same diameter than the ones used for counts. Those Petri dishes were filled up with 70% ethanol and placed under the hood close to the experimenter during the time needed to count and isolate the debris from one sample. This control was made 10 times. We corrected debris counts in samples by the mean control count (7.33 ± 2.8 debris) multiplied by the number of times the sample was opened, from two to four times depending on sample manipulations (once for sampling, once for debris counts, once for sieving, and once for

Table 1
Summary of Fourier Transform Infrared (FT-IR) spectroscopy analyses and microplastic contribution to debris.

Type of sample	Number of samples analyzed	Total number of debris	Number of debris analyzed via FT-IR spectroscopy	Microplastic contribution to debris (%)
Water column	6	1058	168	16.7
Gular pouch	21	1311	166	24.1

zooplankton identification if the subsample analyzed was replaced within the main sample).

3. Results

3.1. Identification of real microplastics among debris

A subsample of 334 debris was analyzed under Fourier Transform Infrared Spectroscopy (FT-IR) in order to separate real plastics from organic debris (Table 1). In total, 16.7% and 24.1% of debris isolated visually from plankton samples and from little auk gular pouches, respectively, were identified as real plastics by spectrometry. Other debris were either unidentified or organic (83.3% for plankton samples and 75.9% for gular pouches). Unless otherwise specified, the following results consider the fraction of identified microplastics among debris only and thus probably underestimate actual plastic concentrations.

3.2. Microplastics and zooplankton counts at sea and in gular pouches

In the water column, mean microplastic concentration was 0.99 pieces.m^{-3} in 2005 (range: 0.15 to 2.64 pieces.m^{-3}) and 2.38 pieces.m^{-3} in 2014 (range: 0.81 to 4.52 pieces.m^{-3}). Microplastic distribution is shown in Fig. 3a. No spatial pattern was observed within the study area. Overall zooplankton and specific *Calanus* spp. (preferred little auk prey in summer) densities are presented in Fig. 3b and c. Total zooplankton abundances were higher in 2014 than in 2005.

The number of microplastics in gular pouches did not differ between 2005 and 2014 (Fig. 4). We found an average of 9.99 and 8.99 microplastics per gular pouch in 2005 and 2014, respectively ($W = 279$, $p = 0.288$). The ratio microplastics/number of prey or microplastics/*Calanus* did not differ between years.

3.3. Nature, size and colour of microplastics

The types of plastics found in zooplankton samples and little auk gular pouches are detailed in Table 2. The main plastic type found in the water column is Polyester (PES, 53%), followed by high and low density polyethylene (23%). In gular pouches, the main plastic type found was Polyvinyl chloride (PVC, 60%) followed by high and low density polyethylene (30%).

The distribution of debris size was similar for the water column and gular pouches, with higher frequencies when the size decreases, except for the smallest sizes (Fig. 5). Median debris length was 0.82 mm in zooplankton samples and 0.77 mm in gular pouches. Debris were classified by shape (fragment/filament) and by colour. Among all samples, 97.2% of the debris found were filaments.

Water column samples contained more dark than light debris (83.4 and 52.9% of dark debris in 2005 and 2014, respectively, Fig. 6a and b). On the contrary, gular pouch samples contained more light than dark debris (25.0 and 18.7% of dark debris, respectively, Fig. 6c and d). The proportion of dark debris was higher in 2005 than in 2014 both in the water column and in the pouches.

4. Discussion

4.1. Microplastics in the Arctic

Little is known about the state of microplastics in the Arctic in comparison with other ocean basins (Trevail et al., 2015). The recent review of Gall and Thompson (2015) on encounters between marine debris and organisms worldwide reported only 5 papers from the Arctic, and to our knowledge there is only one record for surface and water column concentrations of microplastics in the Southwestern Svalbard (Lusher et al., 2015).

Our study revealed high abundances of filaments (97.2%) as similarly described by Lusher et al. (2015) from Svalbard. We observed average abundances of 0.99 ± 0.62 microplastics per m^{-3} and 2.38 ± 1.11 microplastics per m^{-3} in 2005 and 2014, respectively. These values are slightly lower than those found off South-West Svalbard and in the Barents Sea (2.68 ± 2.95 particles per m^{-3}, Lusher et al., 2015), but the mesh size used in this study was also smaller (250 μm). In comparison, Thompson et al. (2004) reported 0.34 debris m^{-3} in Atlantic waters North of Scotland (mesh size used: 270 μm) and Lusher et al. (2014) recorded microplastics density in sub-surface water of the North East Atlantic of 2.46 ± 2.43 per m^{-3} (mesh size used: 250 μm). Our results, therefore, show relatively high concentrations of microplastic litter off East Greenland, considering the remoteness of the Greenland Sea in terms of human activities and the Arctic provenance of the East Greenland Current waters (Fig. 2, Trevail et al., 2015). However, although the Arctic can be considered as almost exempt of plastic emissions, oceanographic processes and bio-transport most likely advect microplastics from other oceanic areas (Mallory, 2008; Provencher et al., 2014). In this context, Enders et al. (2015) suggested a strong dispersal throughout the surface mixed layers for small particles, indicating that plastics can travel extensively along with currents. Therefore, particles encountered in our study area could come either from Southern latitudes with the North Atlantic current, from the eastern Arctic, or even from the Northern Pacific *via* the transpolar drift which ultimately flows along the East Greenland coast. For example, higher microplastic concentrations were observed off Svalbard where water masses are mainly of Atlantic origin compared to off East Greenland (Lusher et al., 2015, Fig. 2). Consequently, when assessing potential levels of plastic pollution in the Arctic, the North Atlantic and Bering Sea have to be considered as potential source areas.

4.2. Decadal change of microplastic concentration

Since mass production of plastic began in the early 1940s, plastic entering in the marine environment has increased in parallel with rates of production, and a decrease in the average size of plastic litter has been observed over time (Barnes et al., 2009), as larger plastic debris reduced continuously into fragments. Consequently, in several places microplastic concentrations have been shown to increase with time over decadal periods (e.g. Thompson et al., 2004). This could explain why microplastic concentration in 2014 was found to be more than twice higher than in 2005 in our study. However, results are not homogeneous worldwide and anytime (Claessens et al., 2011; Law et al., 2010; Thompson et al., 2004). For example Law et al. (2010) did not found any significant increase of microplastic concentration in the Northwest Atlantic Ocean over a 22 years period when processing more than 6000 surface trawls.

Another explanation for microplastic increase in the study area nine years later is the role of the Arctic sea ice extent. Obbard et al.

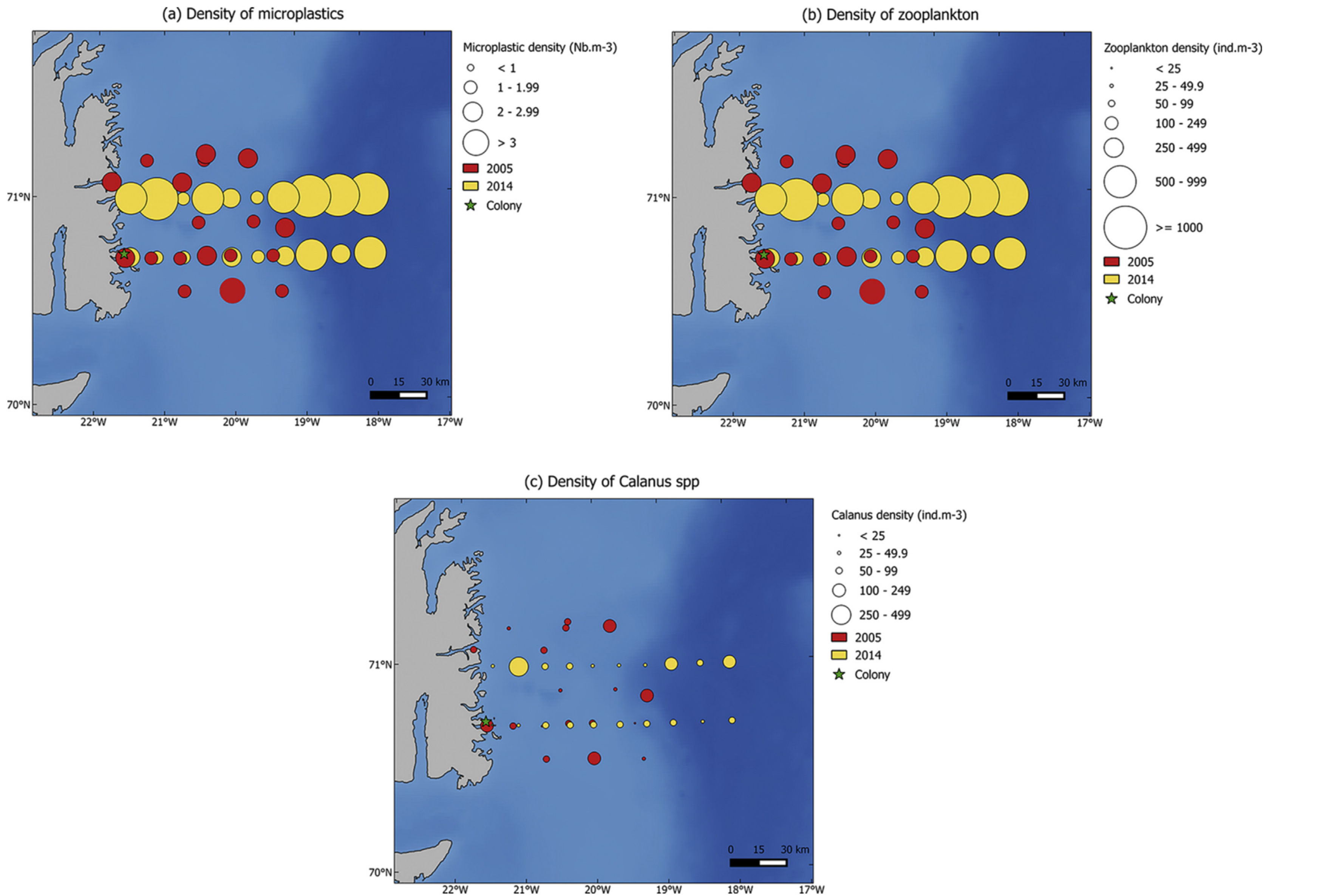

Fig. 3. Density of (a) microplastics, (b) zooplankton and (c) *Calanus* spp. copepods per station in number of items per cubic meter in 2005 (red) and 2014 (yellow). The green star represents the little auk colony. Details on zooplankton data are in Karnovsky et al. (2010) and Amélineau et al. (2016). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

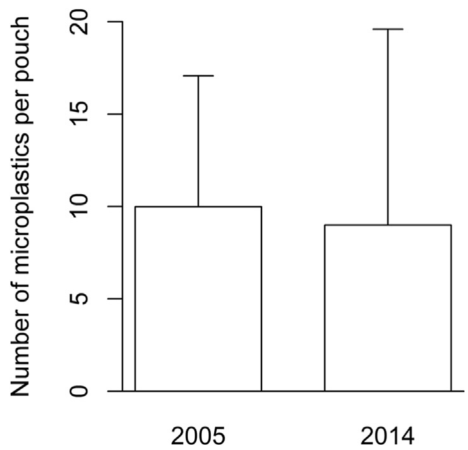

Fig. 4. Number of microplastics per gular pouch samples Values are mean ± SD.

(2014) presented the only study which quantifies plastic concentration in the Arctic Sea ice. They showed high variation in microplastic concentration in sea ice cores, ranging from 38 to 234 debris m^{-3}. Those values are much higher than in highly polluted oceanic gyres and might be due to the concentrating effect of the scavenging phenomenon that accompanies sea ice growth (Obbard et al., 2014). In that regards, the sea ice acts as the sink (freeze up) and source (break up) for plastics. This would imply that when melting, sea ice would release plastic debris into the underlying water column. One should bear in mind, however, that the Arctic sea ice is in constant motion, thus the transport of sea ice trapped particles would play a role in plastic dispersion. Our study took place during two contrasted sea ice extents, and plastic concentrations recorded in 2005 were much lower than those observed in 2014. It is therefore difficult to make a temporal comparison of both datasets as the effect of ice extent is probably superimposed on temporal variability. Anyhow, as suggested by Obbard et al. (2014), microplastic concentrations were much higher when the sea ice extent was reduced.

4.3. *Microplastics characterisation*

In our study, 16.7% and 24.1% of debris isolated visually from plankton samples and little auk gular pouches, respectively, were identified as plastics by spectrometry. This indicates that many of the sorted debris were not microplastics, and our results are much lower than for terrestrial bird gut content analyses (54.9%, Zhao et al., 2016) or for particles from the sea surface (68% Lenz et al., 2015). Enders et al. (2015) also indicated that in their study 25% of the spectra observed presented a pigment signal that totally overlaid the plastic type signal and that therefore a precise identification was not possible. In our study, we might have visually over-sampled microplastic-like particles because, as little auks are feeding on zooplankton, appendages of damaged organisms as well as other plankton organisms might mimic fiber-like pieces. Those organic debris, however, could also be of anthropogenic origin such as natural fibers used for clothing or cordage.

Obbard et al. (2014) and Lusher et al. (2015) have shown that, on average, polyester and nylon were the most abundant microplastics found in the Arctic, with acrylic, polypropylene, polystyrene, and polyethylene showing much lower contributions. Our study also reports a high occurrence of polyester. Nevertheless, the results of Obbard et al. (2014) indicated high variability in microplastic debris composition among their 4 study sites. In consequence, we could suggest that the discrepancy we observed between microplastics composition in the water column and in little auk gular pouches could be explained by either spatial or temporal variability.

4.4. *Little auk contamination*

Plastic ingestion by seabirds is well documented, with the first records dating back to the 60s', and little auks are affected (Table 3, Day et al., 1984; Fife et al., 2015; Provencher et al., 2014; Ryan, 1987). Wilcox et al. (2015) predicted to find plastic in digestive tracks of 99% of all seabird species by 2050 and that 95% of the individuals within these species will have ingested plastic by the same year. To assess current levels of plastic ingestion and to allow for comparison through time and among oceanic regions, Provencher et al. (2014) underlined the importance of standardized baselines and protocols. Little auk gular pouches do not report ingestion rates *sensu stricto* but their collection is not very invasive for the birds compared to removing stomach contents. Therefore, they could be a good indicator within the Arctic especially as they are already commonly collected in different monitored colonies (Harding et al., 2009; Karnovsky et al., 2010; Pedersen and Falk, 2001).

The first observations of plastic ingestion by little auks were made in 1978. While four studies recorded plastics in 0%, 9%, 12% and 14% of adult birds (Fife et al., 2015; Pedersen and Falk, 2001; Provencher et al., 2014; Trevail et al., 2015), our observations revealed that all individuals contained plastic debris in their gular pouches. However, contrary to most studies on plastic contamination in seabirds, we searched for microplastics under a binocular microscope. Consequently, we detected smaller items and this likely explains why we detected a large amount of small filaments that were hardly detectable to the naked eyes, compared to other studies on little auks and seabirds. We therefore separated fragments and filaments in Table 3, in order to make our results more comparable with previous publications on little auk contamination. Despite that, discrepancies between studies may result from these differences in methodology. For the same reason, it is difficult to

Table 2
Proportion of polymer classes found in the water column (n = 30) and in gular pouches (n = 40) and their origin.

Plastic class		Contribution to MP in water column samples (%)	Contribution to MP in gular pouches (%)	Products and typical origin
Low-density polyethylene	LDPE LLDPE	23.3	30	Plastic bags, six-packs rings, bottles, netting, drinking straws
High-density polyethylene	HDPE			Milk and juice containers
Polypropylene	PP	10.0	0	Rope, bottle caps, netting
Polystyrene	PS	0	0	Plastic utensils, food containers
Nylon	PA	3.3	0	Netting and traps
Polyesters	PES	53.3	7.5	Plastic beverage bottles
Polyvinyl chloride	PVC	3.3	60.0	Plastic films, bottles, cups
Cellulose Acetate	CA	6.7	2.5	Cigarette filters
Polytetrafluoroethylene	PTFE	0	0	Cables, printed circuit boards

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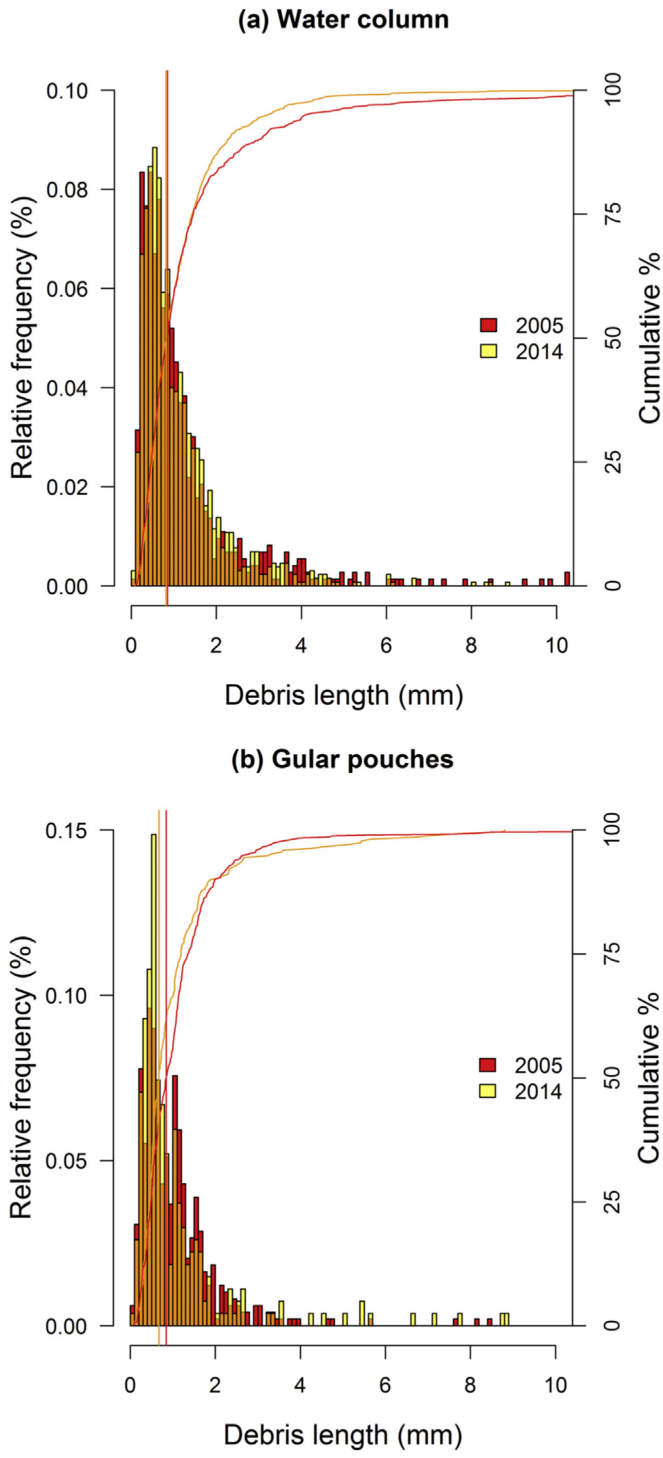

Fig. 5. Debris length histogram in (a) the water column and (b) gular pouches. Vertical lines represent the median value for each sample type and the curves represent cumulative percentage. Red: 2005. Yellow: 2014. Median debris length in the water column: 0.85 mm in 2005 and 0.82 mm in 2014; in gular pouches: 0.84 mm in 2005 and 0.67 mm in 2014. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

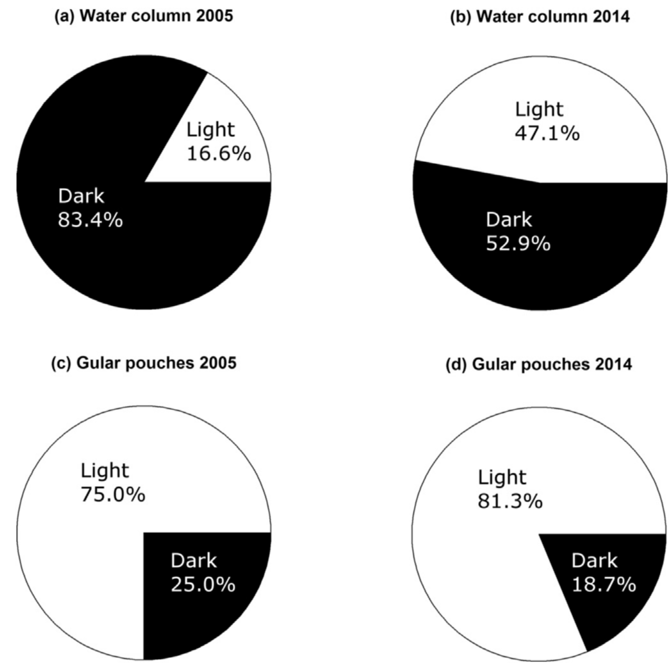

Fig. 6. Proportion of dark and light debris in the water column (a) in 2005 and (b) in 2014, and in gular pouch samples (c) in 2005 and (d) in 2014.

compare our results with other seabird studies for which only debris visible to the naked eye were reported. We found an average of 9.5 microplastic items per gular pouch which is in the same order of magnitude than two other studies reporting on animal microscopic contamination: Zhao et al. (2016) found 10.6 ± 6.4 items per birds on terrestrial species, and Rochman et al. (2015) observed 0 to 21 anthropogenic particles per individuals in seafood from the USA and Indonesia.

Birds can either ingest plastic items directly, or indirectly *via* prey items. We found that little auks ate preferentially lighter debris, rather than darker ones (Fig. 6). This may be the result of an easier target detection by birds, or of a resemblance with prey, as suggested by Zhao et al. (2014, 2016). In nature, little auk prey are light-colored and contrast with the dark ocean background at little auk feeding depths, and microfilaments may mimic contour lines or appendices of crustaceans. Little auks also showed a polymer preference. They caught preferentially polyvinyl chloride (PVC) among all polymer types found in the environment. While we did not find any correlation between polymer type and colour, this preference could suggest that some physical features of PVCs, such as their aspect, light diffusion or the way they move in the water, could make them attractive to little auks. All these observations suggest an active uptake and therefore contamination of little auks by microplastics through confusion with their natural prey.

Regarding prey contamination, several laboratory studies (Cole et al., 2013, 2015; Wilson, 1973) have shown that copepods are able to ingest polystyrene beads, and that the more beads are present in the environment, the more copepods prey on them, to the detriment of their natural phytoplankton prey, thereby impacting zooplankton function and health. As little auks are zooplankton feeders, both primary and secondary consumption of microplastics may be occurring. However, we probably did not detect the latter, as particles taken by zooplankton are one order of magnitude smaller than those taken directly from the ocean by little auks (Cole et al., 2013).

Ingestion of plastics by seabirds is often related to seabirds directly ingesting plastic floating at the surface. However, surface feeders are not the only seabirds capable of ingesting marine debris (Provencher et al., 2014). Indeed, pursuit divers such as Brünnichs guillemots (*Uria lomvia*) and little auks also ingest plastic debris. In their study, Provencher et al. (2014) recorded that 11% of guillemots had at least one piece of plastic debris in their gastrointestinal tracts. In our work, frequencies were much higher, with 100% of

Table 3
Review of plastic ingestion prevalence found in little auks (*Alle alle*).

	Location	Year(s)	Sample size	Fragments prevalence (%)	Filaments prevalence (%)	Sample type	Authors
Literature review	Canadian Arctic	1978–1979	303	presence		Necropsy	Bradstreet (in Day et al., 1984)
	Spitsbergen	1982 & 1984 (summer)	43	12	na	Necropsy	Mehlum and Gjertz (1984) Gjertz et al. (1985) Lydersen et al. (1985)
	Nuuk, SW Greenland	1988–1989 (winter)	19	0	na	Necropsy	Falk and Durinck (in Provencher et al., 2014)
	NW Greenland, Thule area	1997 (summer)	104	9	na	Necropsy	Pedersen and Falk (2001)
	Newfoundland	2013 (winter)	65	14	na	Necropsy	Fife et al. (2015)
This study	East Greenland	2005 (summer)	26	50	100	Gular pouches	This study
	East Greenland	2014 (summer)	18	33	100	Gular pouches	This study

gular pouch samples containing plastic filaments, whereas fragments were found in 33% and 50% of the gular pouches in 2014 and 2005, respectively. Comparison between guillemots and northern fulmars at similar times and locations (Provencher et al., 2009) indicated that guillemots had a significantly lower mass of plastics per unit body mass than fulmars, and that the plastic pieces ingested by guillemots were significantly smaller than the ones ingested by fulmars. As for guillemots, it is likely that little auks exposure to microplastics is occurring during dives, but probably induces less contamination than for surface feeders (Moser and Lee, 1992; Provencher et al., 2014).

5. Conclusion

Our study provides, to the best of our knowledge, the first assessment of microplastic contamination in the water column of the Greenland Sea. Despite being far from anthropogenic activities, the waters off East Greenland appeared to be contaminated by microplastics, at concentrations which are comparable with those of other oceanic basins. These microplastics probably transited *via* the Arctic, according to the provenance of the East Greenland current, and could have been retained in sea ice (Obbard et al., 2014). Further, we demonstrate that microplastics were caught by pursuit-diving seabirds with colour selectivity, strongly suggesting that they are mistaken for prey items and therefore that little auks are actively contaminated. Our results highlight the importance of considering Arctic species as vulnerable to microplastic pollution as the area reflects global microplastic production increase, and they are especially exposed to an enhanced release of microplastics by the vanishing sea ice under climate change combined with an increase of human activities in the Arctic.

Author contribution

DB, AF, DG, JF, NK and AMAH designed the study. NK, AMAH, DG, JF and FA collected the samples. VM, OH, FA, WW and DB performed the analyses. DB and AF wrote the manuscript.

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