

Zooplankton, phytoplankton and pervasive anthropogenic particles along a zonal tropical and subtropical North Atlantic transect: a multi-vessel citizen-science image survey

Howard Dryden¹ and Diane Duncan¹

¹GOES Foundation / Seahorse Point Nature Laboratory, Bastimentos, Bocas del Toro, Panama

Correspondence to Howard Dryden (howard@goesfoundation.com; ORCID 0000-0002-5068-2113)

Abstract

Few surveys have measured plankton and pollution particles in the top metre of the open ocean, and to our knowledge none has counted both together along an east-to-west crossing of the tropical and subtropical North Atlantic. In this preliminary citizen-science survey, thirteen sailing yachts crossing from the Canary Islands and Cape Verde to the Caribbean in January and February 2022 filtered half-litre samples of surface seawater. The filters were photographed under a microscope, and automated image analysis sorted 18,142 particles larger than 20 micrometres in 1,466 photographs, which together represent 146.6 litres of seawater. The sorting was checked by eye on 600 particles and repeated by a second scorer. Dark, combustion-like particles appeared in 70% of the photographs, plastic fibres in 27% and plastic fragments in 3%, alongside Saharan dust and plant debris, and almost all particles were smaller than 250 micrometres. Five animals, two copepods and three shrimps, were found in the samples, while separate plankton net tows over the same crossing, with a 120-micrometre mesh and 22 to 44 cubic metres of water filtered per tow, caught 0.2 to 0.5 animals per cubic metre. The amount of Saharan dust in the samples was 13 to 36 per cent below the amount predicted from satellite observations of dust deposition, which is consistent with the method. All particle types were identified by their appearance alone and still need chemical confirmation. The survey provides a first baseline for this ocean region and shows how yacht crews could help to monitor pollution at the ocean surface.

26 1. Introduction

27 Three depth terms recur through this paper and are defined here at first use: the microlayer (<1
28 mm), the near-surface layer (0 to 1 m, the layer this survey sampled), and the epipelagic (0–200 m);
29 we use them consistently throughout, including in figure captions and table headings.

30 This is a citizen science project built around what an ocean-going sailing vessel can achieve safely
31 with a small crew underway without winches, wire, laboratory space or power. The technique does
32 not replicate oceanographic sampling at depth and relies on a large number of samples to accurately
33 measure zooplankton in oligotrophic water, due to the small sample volume; this characteristic
34 makes the equipment particularly well-suited for citizen science projects. The technique offers
35 coverage because cruising vessels cross oceans that research vessels typically avoid, on tracks and at
36 times without funding. The GOES filter is designed to be as simple as possible in order to minimise
37 operator error and contamination and to deliver, as accurately as possible, an analysis of all particles
38 in surface seawater down to a nominal 20 μm .

39

40 The trade-wind tropical and subtropical North Atlantic sampled here is an oligotrophic, subtropical-
41 gyre-influenced region crossed by the North Equatorial and Canary currents, where surface
42 productivity is expected to be low. Saharan dust supplies iron (Jickells et al., 2005), while nitrogen
43 and phosphorus limit growth, and iron and phosphorus together limit nitrogen fixation in the
44 eastern part of the region (Mills et al., 2004; Moore et al., 2013). Our expectation on sailing was
45 accordingly modest but not zero for microzooplankton. Mesozooplankton are scarce in such water,
46 but sampling down to a nominal 20 μm should reveal the smaller fraction, copepod nauplii, early
47 copepodites and other 20–200 μm metazoan stages.

48 The surface itself was chosen deliberately, because the two largest-volume polymers ever produced
49 are polyethylene and polypropylene (Geyer et al., 2017), both of which are less dense than seawater
50 and therefore float (Kooi et al., 2017), and together they dominate the polymers recovered at the sea
51 surface (Erni-Cassola et al., 2019). The buoyant plastic fraction concentrates in the top few
52 centimetres, falling away with depth as biofilm increases density and wind-induced mixing carries it
53 below the surface (Kukulka et al., 2012; Reisser et al., 2015). A conventional research survey that
54 samples below the surface, or through a coarse tow mesh, cannot see most of what is presented in
55 this report.

56 What is also poorly known is the standing stock of the smallest surface plankton and the burden of
57 anthropogenic particles in the 20–250 μm range because conventional oceanography samples are
58 mainly from 5–200 m depths and rarely resolve this size fraction at the ocean surface. That gap is
59 not only one of depth but also of biology: some surface-dwelling zooplankton carry a distinct blue
60 carotenoid pigmentation, evidently serving as UV protection and camouflage at the air–sea
61 boundary (Rahlff et al., 2018). The fauna and habitat of the sea-surface microlayer and the top few
62 centimetres remain far less studied than the deeper water column. Because so few surveys sample
63 this specific layer, its standing zooplankton stock is not well understood; this survey is offered as a
64 step toward filling that gap.

65

66 Every ocean has a surface microlayer (SML): a distinct skin covering about 71% of the Earth's
67 surface, somewhere between 1 and 1,000 μm thick (Engel et al., 2017; Wurl et al., 2017), with the
68 sharpest physical and chemical gradients confined to the uppermost 50 μm (Zhang et al., 2003). The
69 film is made of proteins, carbohydrates and lipids from marine plankton, and it is laced with
70 particulate matter, sub-micron and microplastic, black carbon soot and chelated metals (Garrett,

1967; Williams et al., 1986; Cunliffe et al., 2013). The SML is not an inert layer but a living biofilm of bacteria and nanoplankton suspended in a mucopolysaccharide gel with lipids and surfactants. The SML damps turbulence, throttles gas exchange and seeds aerosols and clouds (O'Dowd et al., 1997; Cunliffe and Murrell, 2009; Cunliffe et al., 2013). Natural surfactants reduce the air–sea transfer velocity of CO₂ by 23% at concentrations common in the microlayer and by a further 62% inside slicks (Mustaffa et al., 2020), and a reduction of up to 32% has been measured in the Atlantic (Pereira et al., 2018). Cyanobacterial surface blooms have been observed to inhibit evaporation from the skin layer (Wurl et al., 2018).

The oceans supply 86% of global evaporation (Trenberth et al., 2007), and the resulting atmospheric water vapour is the largest single contributor to greenhouse warming. Water vapour represents about 50% of the present-day greenhouse effect (Schmidt et al., 2010) and the strongest feedback on CO₂-driven warming. Its abundance climbs with temperature, through the Clausius–Clapeyron relation, so what happens at the air–sea boundary matters (Held and Soden, 2000). Our proposition is simple: the SML is a biologically influenced boundary that phytoplankton maintain and that pollution could be degrading.

86

The question this survey sets out to answer is what the surface layer holds: how many plankton and how many anthropogenic particles are present in the top metre, and at what sizes. Behind that measurement sits a larger question, whether the biological regulation of what we consider the most climatically significant surface on Earth, an interface covering about 71% of the planet and central to a range of global biogeochemical and climate-related processes (Wurl et al., 2017), is being disrupted by anthropogenic particle pollution in ways that current models do not represent. In our

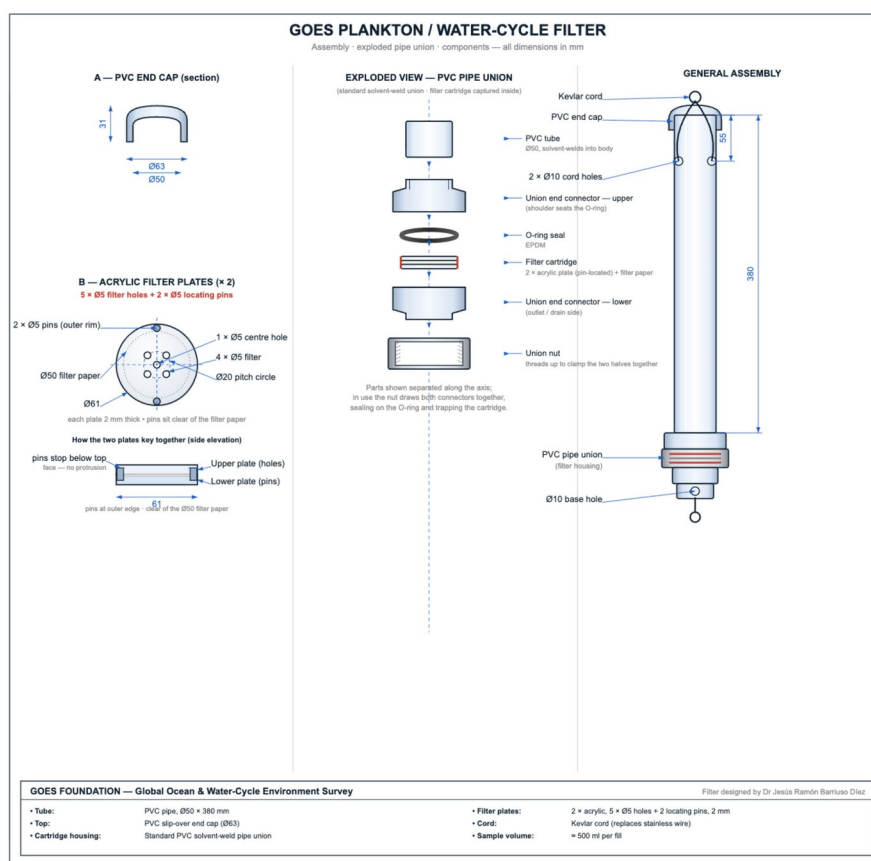
93 view, this is one of the more important unasked questions for Earth system modelling. The answer
94 depends on data from the ocean surface, which is currently not being collected.

95

96 **2. Methods**

97 **2.1 Sampling filter**

98 The sampling filter, shown in Fig. 1, is a self-contained cartridge, a Ø50 mm × 380 mm PVC tube with
99 a slip-over end cap. It houses two acrylic filter plates (each with one central and four Ø5 mm holes
100 on a Ø20 mm pitch circle) within a standard PVC solvent-weld pipe union, suspended on a stainless
101 steel wire during this survey, and a Kevlar cord is specified for future campaigns for durability. The
102 GOES filter was designed by Howard Dryden and manufactured by Calplas (Sect. 10). The GOES field
103 guide for volunteers, available at [https://goesfoundation.com/water-sampling-field-guide-for-](https://goesfoundation.com/water-sampling-field-guide-for-volunteers/)
104 volunteers/, provides complete build details. The design draws a fixed 0.5-litre sample of seawater
105 on each fill, independent of the vessel's speed through the water, and because it hangs from its cord,
106 it filters vertically. It therefore provides a reproducible, semi-quantitative measure of the particle
107 content of a known 0.5-litre volume of water, nominally retaining particles of 20 µm and larger. The
108 filter paper is a Camlab product, 1173270, Grade 4, equivalent to Whatman Grade 4 filter paper. Grade
109 4 has a nominal particle retention of 20 to 25 µm, and as the cake builds during gravity filtration,
110 smaller particles are also retained. Even so, most cells smaller than 20 µm pass the filter, and these
111 pico- and nanophytoplankton supply about 82 per cent of primary production in the North Atlantic
112 gyre (Tilstone et al., 2017), so the phytoplankton class of this survey describes only
113 microphytoplankton and larger colonies.



114

115 **Figure 1.** The GOES plankton/water-cycle filter: general assembly, exploded view of the standard PVC pipe-union
 116 housing, and the two acrylic filter plates (one central + four Ø5 mm filter holes on a Ø20 mm pitch circle, keyed by
 117 two Ø5 mm locating pins on the outer rim, clear of the Ø50 mm filter paper). Note the distinction between the Ø50
 118 mm tube mouth, through which the 0.5-litre sample enters, and the Ø5 mm filtration apertures downstream of
 119 collection, which size-select nothing. The cartridge draws a fixed 0.5-litre sample independent of the vessel's speed
 120 through the water and, suspended on its line (stainless steel wire in this survey), filters vertically allowing for boat
 121 motion and capturing most particles above a nominal 20 µm.

122 Surface samples were collected by participating crews at ~12-hour intervals (12:00 and 24:00 hrs,
 123 local time) from the stern or leeward side of the vessel; the tube is flushed three times with ambient
 124 water, dropped to fill by immersion, and capped as soon as it leaves the water, remaining capped
 125 until the moment of examination. Sampling at local noon and midnight on each vessel keeps the
 126 solar time of collection consistent across the transect, independent of longitude. Once capped, the
 127 cartridge is left to drain for four hours before the plates are opened for imaging. Each plate is then
 128 exposed to the air for five minutes or less, the time it takes to open the cartridge, photograph the five
 129 apertures and close it again. Volunteers were instructed to avoid fleece and other fibre-shedding

130 synthetic clothing while sampling as a control on airborne fibre contamination. Samples were
131 filtered to $\sim 20\ \mu\text{m}$ and photographed on digital microscopes at a 5 mm field of view, with position,
132 date and time logged. The microscopes carry a sensor of at least 5 megapixels and a polarising filter.
133 In the accepted photographs, the fitted 5 mm disc spans a median of 1,456 pixels (range 842 to 1,792),
134 giving a median pixel pitch of $3.4\ \mu\text{m}$ (range 2.8 to $5.9\ \mu\text{m}$), so a $20\ \mu\text{m}$ object spans about six pixels.
135 A small copepod of $300\ \mu\text{m}$ spans about 90 pixels at the same pitch, which is enough to show its
136 outline, but transparent animals flattened on the wet filter paper are harder to see, and some may
137 have been missed. The colour and shape rules are least reliable at that limit, and the lower bound of
138 the power-law fits in Sect. 3.9 sits at the detection limit. Positions were taken from the image GPS,
139 where the file carries one, or otherwise from the field spreadsheet. Per-image timestamps are
140 available only for the Copepod crossing; the sampling dates of all vessels fall between 8 January and
141 6 February 2022 (Fig. 2). The Emma summer folders carry camera date stamps from 19 May to 31
142 July 2022.

143 Images were analysed with the deposited pipeline described in Sect. 3.2: Frame curation with a per-
144 file exclusion log, local background subtraction, connected-component detection and sizing of every
145 object $\geq 20\ \mu\text{m}$ (scaled against the 5 mm filter disc fitted in each photograph), classification by stated
146 elongation, saturation, hue and darkness rules with unresolved objects left unidentified, and
147 individual visual inspection of every object $\geq 250\ \mu\text{m}$. The scripts and their complete per-image
148 output are archived with the data. Two field habits explain most of the rejected images across the
149 whole survey. Many volunteers left the polarising filter off the microscope during the photo shoot.
150 Without that filter, the paper reflects the light and washes out the objects on the disc. Reflection
151 alone set aside 471 photographs, the largest single block in the exclusion log. Other volunteers did
152 not bring the microscope into sharp focus before the photograph. A blurred frame smears each grain
153 into the paper, so the objects cannot be measured. Better training on these two habits would raise

154 the yield of usable photographs in the next campaign. Net-tow validation: a 120 μm plankton net
155 (0.30 m mouth) was towed at the surface at 1 to 2 knots for 10 min per haul: ten daytime and four
156 night hauls, mid-Atlantic; filtered volume was computed as net mouth area $\times$ tow distance. Per-
157 station counts, all particle sizes and the crew logs are deposited in the Zenodo record listed in Sect. 7,
158 in the workbook GOES_ALL_DATA.xlsx.

159 **2.2 Quality control**

160 A procedural blank was run on the yacht Copepod during the crossing and showed no obvious
161 contamination; the other volunteer crews did not run blanks, and a blank-sample step has since
162 been added to the field guide for future campaigns. A volunteer with access to particle-free reverse
163 osmosis water, ultrafiltered water, or water passed through a 0.6 μm ceramic filter can run that
164 water through the same steps as a real sample to serve as a procedural blank. The recommended
165 rate is one blank for every 20 working samples. A blind classification check was also run on the
166 trade-wind crossing archive using four marking sheets. These were a pilot sheet of 180 objects, 30
167 from each of six machine classes, and two clean rounds of 300 objects each, with 50 objects from
168 each of the five major machine classes and 25 each from plastic particles and unidentified in each
169 round, which together reached 100 objects for each of the five major machine classes and 50 each for
170 plastic particles and unidentified. The objects were drawn at random and shown to the lead author
171 with the machine class hidden and the order shuffled. A marker arrow pointed to each object; faint
172 rings and halos were ignored as reflection and residual water artefacts, and the eye verdicts were
173 scored against the machine to give the per-class accuracies and the corrected concentrations
174 reported in the Results. All 780 marked objects from the four sheets were afterwards rescored blind
175 by a second scorer; twelve objects lacking a verdict from one scorer were excluded, and the
176 agreement statistics for the remaining 768 pairs are reported in Sect. 3.7 and Table 3.

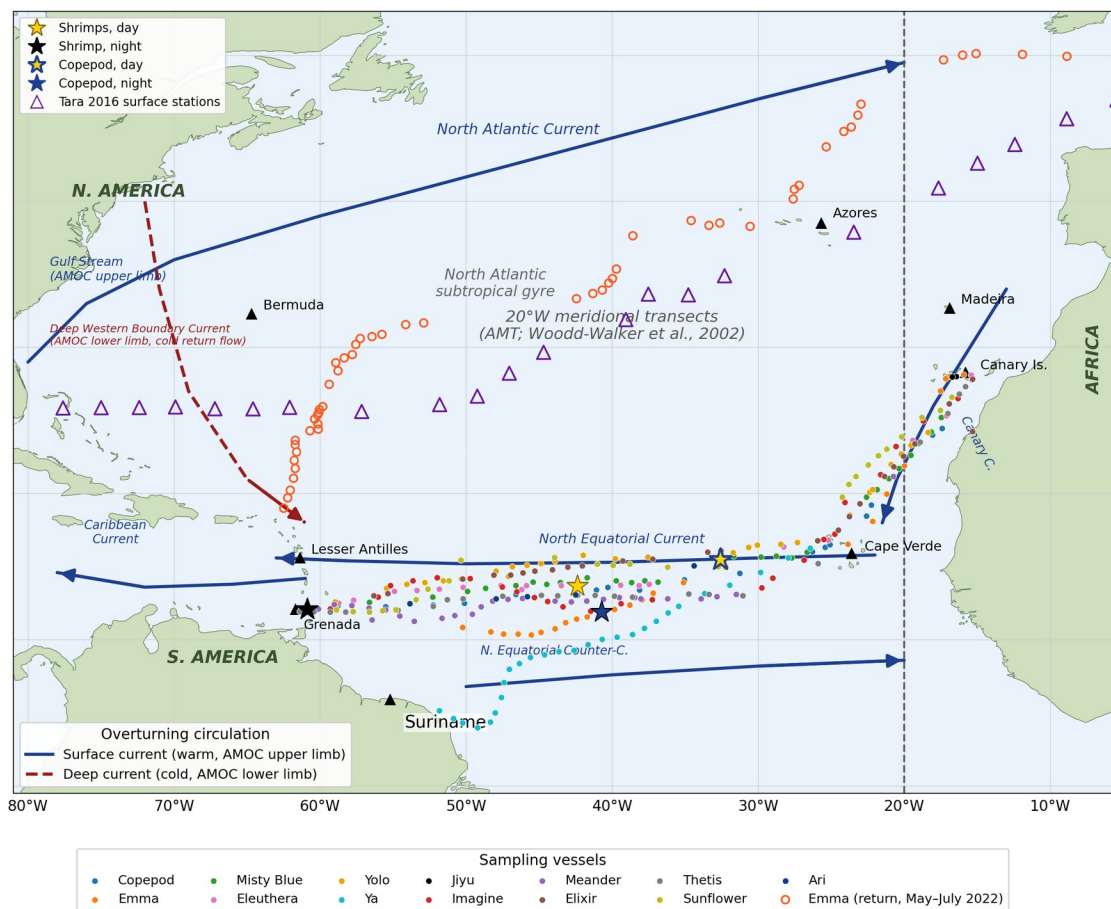
177 **2.3 Statistical analysis**

178 Sect. 3.2 describes the two statistical treatments used throughout this paper, the Wilson score
179 intervals and the Poisson model for the zooplankton count, and their results are summarised in Sect.
180 3.9.

181 **3. Results**

182 **3.1 Study region, vessels and timing**

183 The survey covers the zonal trade-wind corridor from the Canary Islands and Cape Verde to the
184 Caribbean and Suriname, framed to the east by the West African coast and to the west by the Lesser
185 Antilles and the South American shelf, and shaped by the North Atlantic subtropical gyre, the
186 Canary Current, and the North Equatorial Current (Fig. 2). Thirteen sailing vessels contributed
187 counted photographs; each vessel's photograph count, span and dates are listed in the deposited
188 data (Sect. 7). The sailing vessel Copepod was skippered by the authors, to which the sampling dates
189 of the other vessels are referenced (Fig. 2). One vessel (Emma) additionally carried out a higher-
190 latitude North Atlantic return leg from May to July 2022 (Fig. 2); that leg is the only part of the
191 archive outside the trade-wind belt and outside the January–February crossing season, returning via
192 the Azores back to the United Kingdom.



193

194 **Figure 2.** Study region, vessels and circulation. The vessels, along with their recorded stations, are marked for
 195 reference as they crossed the zonal trade winds from the Canary Islands and Cape Verde to Grenada and Suriname,
 196 with Madeira, Bermuda and the Lesser Antilles shown for reference. The trade-wind crossing was sampled between
 197 8 January and 6 February 2022 on all vessels; the vessel Emma additionally sampled a higher-latitude North Atlantic
 198 return leg (to ~50° N) between 19 May and 31 July 2022. Open purple triangles mark the twenty-two surface stations
 199 of the Tara Pacific expedition's 2016 North Atlantic crossing that fall within the map area, plotted from the
 200 published station positions of the high-speed-net data set (Mériguet et al., 2024, 2025), whose 25–35° N band
 201 overlaps the Emma return leg compared in Sect. 3.3. The dashed line at 20° W marks the meridional corridor
 202 sampled by the Atlantic Meridional Transect programme (Aiken et al., 2000) and by Woodd-Walker et al. (2002).
 203 Stars mark the stations where animals were found, drawn in two colours for the blue copepods and one colour for
 204 the shrimps, with yellow for a daytime sample, and black (shrimp) or blue (copepod) for a night one. Blue arrows
 205 mark the surface currents and the dashed red line the deep western boundary current of the overturning
 206 circulation, drawn schematically for orientation. The two counted copepods are Misty Blue on 22 January 2022 at
 207 15.48° N, 32.60° W by day, and Emma on 6 February 2022 at 11.91° N, 40.73° W at night. The three large shrimps are
 208 Eleuthera on 26 January 2022 at 13.68° N, 42.38° W by day, with two shrimps under one star, and Misty Blue on 5
 209 February 2022 at 12.08° N, 60.88° W after dark, and all five are reported in Sect. 3.3. Each star marks one station, so
 210 the five animals appear as four stars. Coastlines © Natural Earth.

211

212 3.2 Image-analysis pipeline

213 The GOES sampler is a self-contained 0.5-litre cartridge: a Ø50 mm × 380 mm tube whose 50 mm
214 mouth admits the sample, and two acrylic plates at its base are drilled with five aligned 5 mm holes,
215 sandwiching a 20 µm nominal filter paper. The 500 mL of sample water collected in the tube gravity-
216 filters through these five holes, concentrating the solids onto five 5 mm diameter sections on the
217 filter paper. The microscope's field of view is 5 mm, so five photographs cover the whole water
218 sample, and few particles or organisms escape detection.

219

220 Collection and handling follow the protocol given in full in Sect. 2 (Fig. 1): the tube is flushed three
221 times with ambient water, filled by immersion, capped immediately on recovery and drained for
222 four hours, with samples taken on a fixed schedule at local noon and midnight, filtered to ~20 µm
223 and photographed under a microscope. The complete image archive, including the photographs
224 recovered from the vessels' spreadsheet files, comprises 2,290 image files, of which 2,046 are usable
225 sample photographs of the trade-wind crossing after removal of duplicates, thumbnails, screen
226 captures and photographs of equipment. A documented curation stage then judges every photograph
227 individually, and the full list, one row per photograph with its decision and reason, is deposited
228 together with the underlying data. That list accepts 1,466 of the 2,046 and sets aside 580. The
229 exclusions are 471 for reflection, where the polarising filter was not used; 68 where the counted area
230 runs off the frame; 30 in a folder set aside on instruction; 6 in a hand-picked folder that is not a
231 station sample; 4 duplicate views of the same filter; and one photograph excluded by name. The 271
232 photographs of the summer return leg are curated separately and are not drawn from that pool.
233 Seven hundred and eighty objects were inspected blind by the lead author across the four marking
234 sheets, 600 of them in the two clean rounds that supply the confusion matrix, and all 780 were
235 rescored by a second scorer.

Each accepted photograph shows one 5 mm filter aperture and represents 0.1 litre of filtered seawater ($0.5 \text{ litre} \div 5 \text{ holes}$), counted as 0.081 litre after masking to the inner 90 per cent of the disc's diameter, which removes edge artefacts and leaves $0.9^2 = 81\%$ of the disc's area ($0.1 \times 0.81 = 0.081 \text{ litre}$). The 1,466 curated photographs together filter 146.6 litres, of which 118.7 litres fall inside the counted area. The photographs were then analysed by a deterministic pipeline that is deposited in full. Each image is background-subtracted, and every object larger than $20 \mu\text{m}$ is detected and sized against the 5 mm filter disc, which is found separately in each individual photograph. Each object is then classified by a stated colour, brightness and elongation rule as phytoplankton, microzooplankton, plastic particle, plastic fibre, dark opaque particle, mineral grain, plant debris or unidentified. Size is recorded as the diameter of a circle of the same area as the object, and every size distribution and percentile in this paper uses that measure for every class, fibres included. The fibre lengths given in Table 1 are long-axis measurements, the minor-axis width multiplied by the elongation, whereas Fig. 4 plots fibres by equivalent diameter like every other class, so the two should not be read against each other. In total the pipeline sized and classified 18,142 objects across the 1,466 curated photographs. Every number in this paper is traceable to a named image file, and the scripts, per-image output, and curation list are archived alongside the data (Sect. 7) so that anyone can rerun the analysis end to end.

Two separate statistical treatments are applied to these particle counts throughout the analysis. Station-level percentages in Table 1 are reported with 95% confidence intervals, calculated by the Wilson score method, which stays reliable when many stations show a zero count for a class. For the zooplankton result, the expected number of animals in a filtered volume is modelled as a Poisson process, and the probability of observing any given count is calculated at different true densities (Sect. 3.3).

3.3 Zooplankton numbers in the filter samples

Every object of 250 μm and above in the whole archive was checked by eye, which confirmed two copepods, both blue surface-living animals of the kind adapted to life at the air–sea boundary, and three larger decapods.

Three larger decapods, recovered from standard 0.5-litre samples, are allocated to the samples of their stations and marked with stars in Fig. 2. A planktonic shrimp of about 7 mm was photographed after dark on 5 February 2022 at a Misty Blue station. Two shrimps, one about 14 mm and the other above 20 mm, were photographed against a ruler by the Eleuthera crew at their daytime station on 26 January 2022 (13.68° N, 42.38° W). The Misty Blue shrimp sits in frames excluded as duplicate views, and the Eleuthera shrimp lies outside the 5 mm circle, as animals of this size can jump or wash off the filter during handling. Displacement of this kind moves an animal off the 5 mm counted disc but not out of the filter, so all three decapods were still drawn from the 0.5-litre sample. These records indicate that the 0.5-litre GOES sampler with a 50 mm opening admits and holds large zooplankton, although an animal of that size does not always stay on the counted disc.

A surface net-tow survey, by day and by night, measured a stock of 0.2 to 0.5 individuals m^{-3} (Sect. 3.8). At that density, the expected count in the 118.7 litres of GOES filter should be well under one, with a 94% to 98% chance of counting zero by chance alone. The five animals recovered sit well above that expectation, and on the 146.6 litres filtered they give a density of 34 individuals m^{-3} , with an exact 95% Poisson interval of 11 to 80, which excludes the net-tow value. The filtered volume is the denominator throughout this paper, because the two copepods lie on the filter discs of counted photographs, one of them (Fig. 5a) at the rim outside the 90 per cent counting mask, and the three decapods were displaced from the 5 mm counted disc during handling but remained on the filter; all five therefore belong to the whole 0.5-litre samples rather than to the counted apertures. The roughly hundredfold gap between the two methods cannot be resolved with the present data, because both estimates carry wide uncertainty, and no tow and grab sample were taken at the same

284 time and place. Everything that enters the tube is retained on the filter and photographed, whereas a
285 towed net loses animals due to escape, extrusion through the mesh, and washing.

286 On paper, the 0.5-litre grab sample would appear less suitable than a net tow for a census of sparse
287 mesozooplankton in oligotrophic water because of the small volume of water captured. The results
288 suggest a different position, since the GOES sampler yielded five zooplankton. Given that the tube is
289 thrown into the water, there is probably less chance for large zooplankton to avoid collection; direct
290 comparison of a net tow sample and GOES plankton sampler at the same time and location would
291 help to answer this question. The GOES sampler is also ideally suited to capture the 20 to 250 μm
292 fraction that nets cannot retain (Sect. 3.8, Table 2).

293

294 No surface (0–1 m) zooplankton data at 20 μm resolution exist for the tropical and subtropical
295 North Atlantic, and the earlier surface work in the basin at coarser mesh sizes is reviewed in Sect.
296 4.1. The closest depth-resolved precedent, despite its different setting, is a 0–15 m sampling layer in
297 the eastern Gulf of Mexico, which showed marked daytime depletion of many mesozooplankton
298 species near the surface (Hopkins, 1982); its shallowest layer still integrates the top 15 m rather than
299 the top metre, so only the qualitative pattern is carried across to this survey. The nearest published
300 work is a set of depth-integrated biomass size spectra for the tropical and subtropical Atlantic,
301 whose zooplankton come from net tows and optical profiles reaching hundreds of metres rather
302 than the top metre (Fock et al., 2026).

303 Because no prior baseline exists for surface zooplankton density in the tropical and subtropical
304 North Atlantic, we cannot tie the abundance of mesozooplankton or scarcity of microzooplankton in
305 this survey to a specific cause. The counts of larger zooplankton exceed the net-tow values, so the
306 word scarcity applies here only to the microzooplankton of 20 to 200 μm (Sect. 4.5). Plausible

307 mechanisms for a genuine near-surface scarcity of that fraction include visual predation and
308 damagingly high ultraviolet exposure in this high-clarity water (Johnsen and Widder, 2001; Tedetti
309 and Sempéré, 2006; Al-Aidaros et al., 2015), the same pressures to which the blue pigmentation of
310 neustonic pontellid copepods is a recognised adaptation (Rahlff et al., 2018). Few surveys have
311 sampled the top metre anywhere in the ocean, and we are aware of none at this resolution dedicated
312 to the tropical and subtropical North Atlantic. The only quantitative surface (0–1 m) comparison
313 found is the Tara Pacific mesozooplankton data (Mériguet et al., 2024, 2025), from thirteen high-
314 speed-net stations between 25° N and 35° N and between 70° W and 32° W, overlapping the May to
315 July 2022 return leg of Emma, shown in Fig. 2; the comparison, therefore, concerns that subtropical
316 gyre water.

317 Emma's zero-animal count in 22 litres is statistically indistinguishable from the median of 1.1
318 copepods m^{-3} that Tara recorded across those thirteen stations. Emma's 18 radiolarians in 22 litres,
319 roughly 800 m^{-3} (within the global range for radiolarians; Boltovskoy et al., 2010; Tréguer and De La
320 Rocha, 2013; Sect. 4.5), occupy the sub-330 μm fraction that Tara's 330 μm mesh cannot retain, with
321 Tara recording a median of only 0.02 Rhizaria m^{-3} . The two results describe different fractions of
322 the same community rather than disagreeing.

323 Depth-integrated values are larger still: across the tropical and subtropical stations of the Malaspina
324 circumnavigation, daytime abundance in the 0–200 m epipelagic layer was usually above 200
325 individuals m^{-3} on a 300 μm mesh (Fernández de Puelles et al., 2019). That survey found no
326 significant difference among ocean basins, with depth the dominant factor and the highest values
327 near upwelling areas (Fernández de Puelles et al., 2019).

328 We therefore treat the surface count of this survey as broadly consistent with the oligotrophic, non-
329 upwelling water (Fig. 6). The reading fits the wider regional picture: a six-decade assessment of the

330 Northeast Atlantic, overlapping the higher-latitude return leg, reported parallel declines in
331 phytoplankton biomass and zooplankton abundance, with none of the assessed pelagic habitats
332 achieving “Good Environmental Status,” a category that their integration method cannot at present
333 assign to any habitat (McQuatters-Gollop et al., 2026).

334

335 **3.4 Dark opaque particles and microplastic**

336 Anthropogenic particles were distributed across almost the whole length of the transects. Dark
337 opaque particles, hereafter the dark-particle class, were present in 70.2% of the photographs (6,671
338 objects), microplastic particles in 3.1% and microfibrils in 26.7%. That class is an optical category
339 whose chemical identity is not confirmed, although black carbon is the most likely composition, and
340 the class is defined in Sect. 3.7.

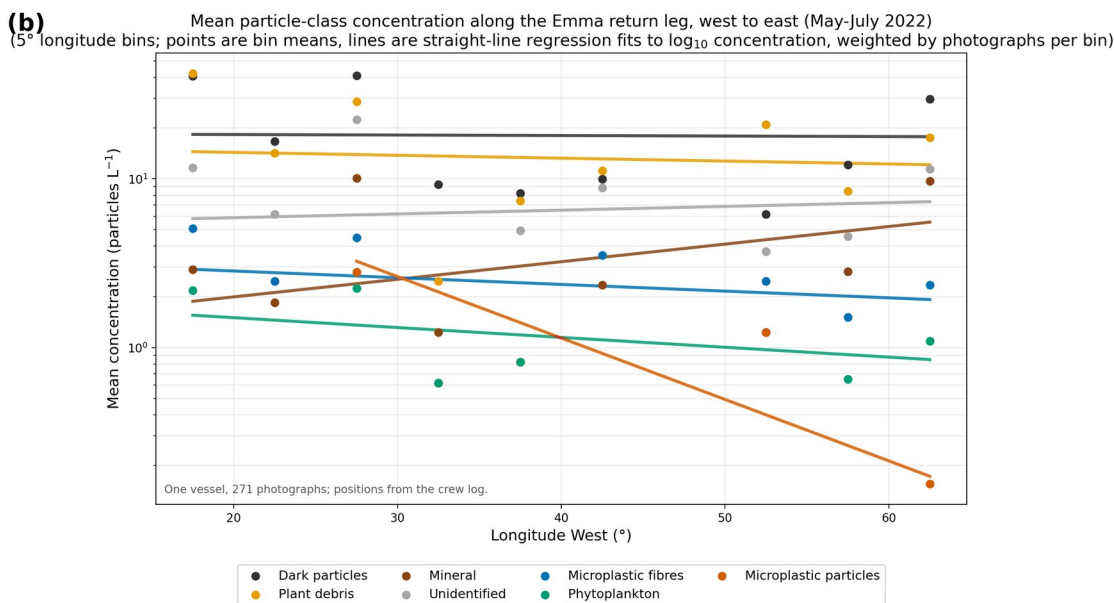
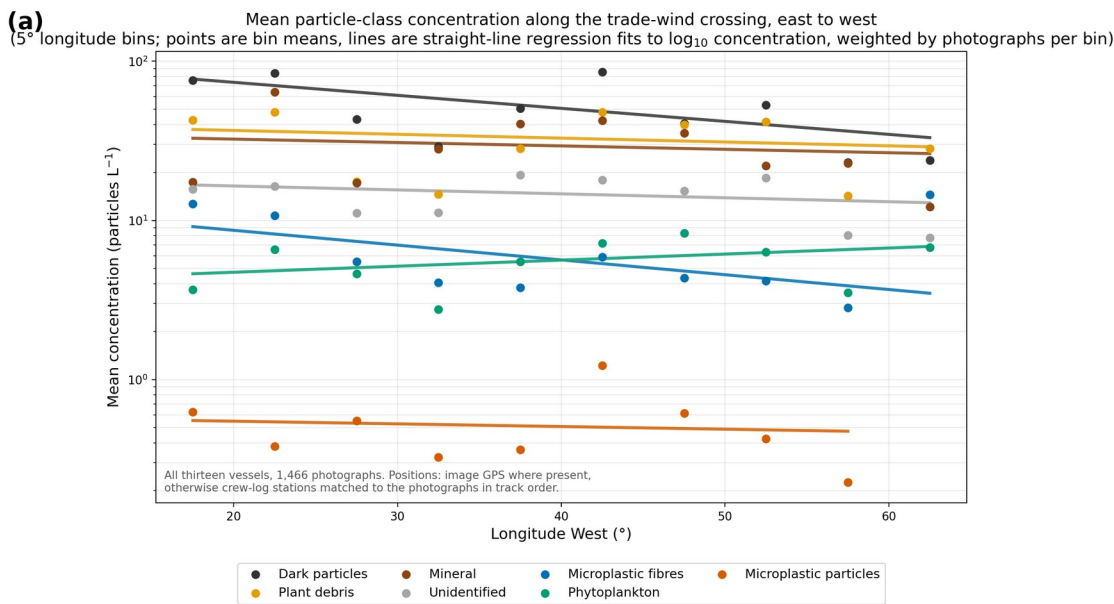
341 Plastic and black carbon are now documented throughout the open ocean, including the Atlantic
342 water column, the remote marine atmosphere and polar snow. These materials even reach the fauna
343 of deep-sea hydrothermal vents located more than 2,000 m below the surface (Bond et al., 2013;
344 Cózar et al., 2014; Allen et al., 2019; Bergmann et al., 2019; Pabortsava and Lampitt, 2020; Trainic et
345 al., 2020; Aves et al., 2022; Lee et al., 2026), indicating that the pervasiveness observed is expected.

346 Expressed as concentrations (Table 1; each photographed Ø5 mm aperture represents 0.1 litre of the
347 0.5-litre draw), the class loads are strongly right-skewed, and most photographs hold zero or one
348 object of a given class, so a per-photograph median would be zero for most classes; mean values
349 across the whole archive are therefore reported. A blind eye check of 600 of these objects across two
350 rounds (Sect. 3.7; Methods) measured the error of each machine class and fed that error back
351 through the whole count. After that correction, the trade-wind crossing means become 64.2 L⁻¹ for
352 dark opaque particles, 28.0 L⁻¹ for plant debris, 24.1 L⁻¹ for mineral grains, 9.0 L⁻¹ for

353 phytoplankton, 5.0 L^{-1} for microplastic fibres and 1.4 L^{-1} for microplastic particles, while 21.1 L^{-1}
354 proved to be stains, unknown or rejects. Because photographs along one track sample similar water,
355 the vessel is the independent sampling unit, and thirteen vessels give only a rough estimate of the
356 between-vessel scatter (per-vessel means are listed in Table S1 of the Supplement), so no population-
357 level confidence interval is attached to these means, and the decimal place is carried for traceability
358 rather than as a claim of that precision.

359 An east-to-west gradient was tested for all thirteen vessels, which together contribute the 1,466
360 counted photographs; the class means show no strong longitudinal gradient (Fig. 3). The otherwise
361 even dispersion of plastic across the open ocean, far from any land source, is consistent with
362 atmospheric deposition in rainfall as the most likely pathway (Allen et al., 2019; Brahney et al.,
363 2021). The dark-particle-class result is a provisional finding in its own right: optically classified dark
364 combustion-like particles dominated the anthropogenic particle load, yet few marine plastics
365 surveys report it, and many sampling designs discard this material. Black carbon is among the
366 strongest environmental sorbents of hydrophobic organic contaminants, binding them one to two
367 orders of magnitude more strongly than amorphous organic matter (Cornelissen et al., 2005). If the
368 plastic vector for such compounds is modest relative to other pathways (Koelmans et al., 2016), black
369 carbon is by far the stronger sorbent in the same water, yet it is going almost entirely unmeasured. A
370 monitoring gap of that size in the surface ocean is a result.

371 Physical setting shapes this pattern: most of the transect crosses the oligotrophic interior of the
372 subtropical gyre, but wind-driven coastal upwelling along the Northwest African margin near the
373 Canary Current and wake-driven mixing downstream of the Canary and Cape Verde islands can
374 locally enrich near-surface productivity and redistribute buoyant particles. The trade wind drift and
375 the North Equatorial Current then carry surface material westward toward the Caribbean.



376

377 **Figure 3.** Mean particle-class concentration in 5° longitude bins, from the analysis reported here. (a) The trade-
 378 wind crossing, east to west, with all thirteen vessels contributing; positions are per-image GPS where the file carries
 379 one, and otherwise the crew log stations are matched to the photographs in track order, which is an assumption
 380 that is stated as one. Points are bin means, and lines are straight-line regression fits to the logarithm of
 381 concentration against longitude, weighted by the number of photographs in each bin. No class shows a fitted
 382 longitudinal slope that is statistically significant at the 5 per cent level (the steepest, for microplastic fibres and dark
 383 opaque particles, have $p = 0.08$ and $p = 0.07$ in the weighted logarithmic fits of Sect. 3.9); three weak per-photograph
 384 rank correlations reach nominal significance and are discussed in Sect. 3.9. This supports the statement in the text
 385 that there is no strong east-to-west gradient. Zooplankton, with only five confirmed animals in the whole archive, is
 386 far too scarce to plot on the logarithmic axis, and microplastic fibres exceed microplastic particles in every
 387 longitude bin. All classes are optical and pending spectroscopic confirmation (Sect. 3.7). (b) The Emma return leg
 388 from May to July 2022, west to east (one vessel; positions from crew-log stations matched in track order), with points
 389 and fitted lines constructed as in panel (a); the classes are the machine classes before the eye-check correction.

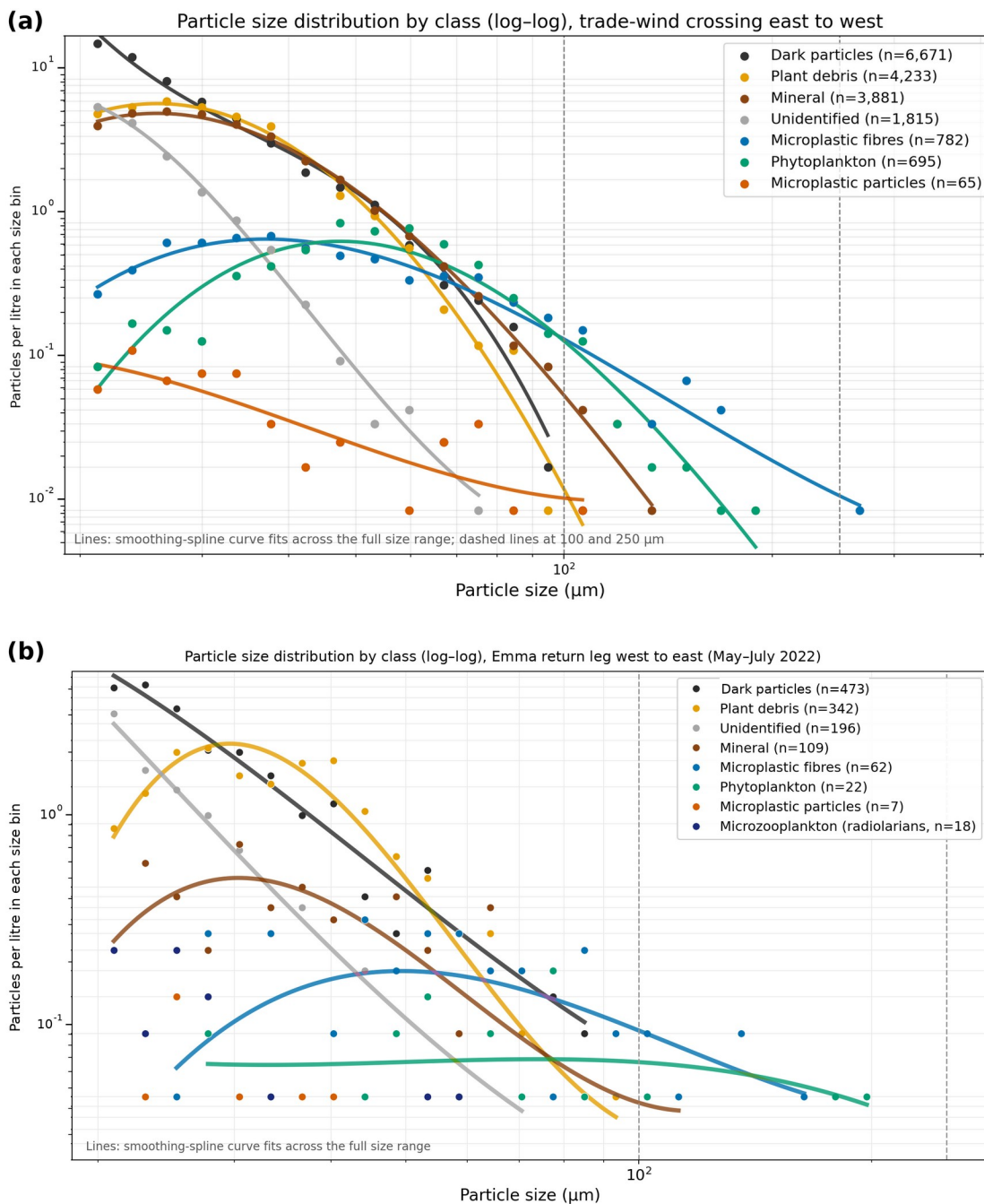
390

391 Dark opaque particles, mineral grains and plant debris are compared against longitude in Fig. 3. No
392 class shows a longitudinal slope that reaches significance at the 5 per cent level, and every
393 confidence interval spans zero ($p = 0.07$ for dark opaque particles, $p = 0.69$ for mineral grains and p
394 $= 0.62$ for plant debris). The fitted slopes all fall towards the west; the dark-particle slope is the
395 steepest of the three, at about 17 per cent for every 10° of westward travel against about 5 per cent
396 for the other two, but a slope that fails the test is not a gradient, so the survey records no east-to-
397 west structure in any class (Sect. 3.9).

398
399

400 **3.5 The surface field is overwhelmingly sub-100 μm**

401 The particle field was very small: 99.99% of all classified objects measured below 250 μm and 99.6%
402 measured below 100 μm , bunched against the nominal 20 μm filtration and imaging limit (Fig. 4).
403 The three decapods of Sect. 3.3, at 7 mm to above 20 mm, were recovered outside the counted
404 apertures, while the two copepods on the counted discs measured about 1,600 μm . Particle
405 abundance is concentrated at the smallest resolvable size; the true particle burden, including the
406 sub-micron fraction that the SML preferentially binds, is certainly higher than these counts, which
407 should be read as a floor.



408

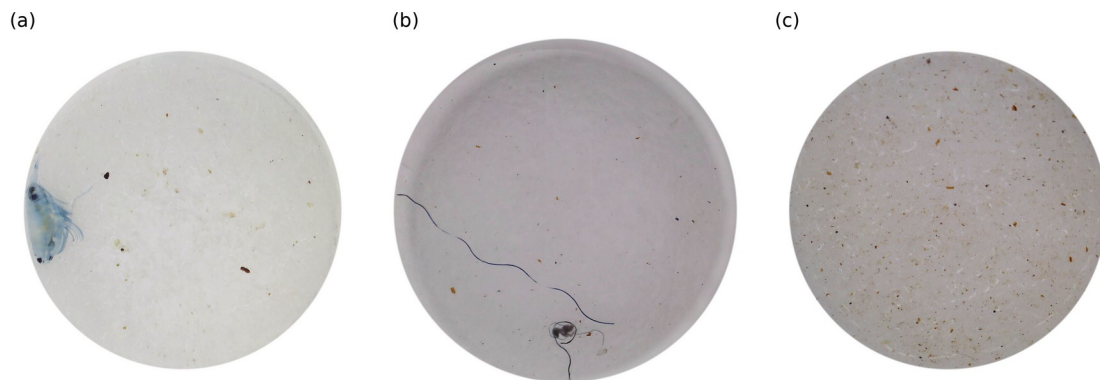
Figure 4. Smoothed particle size distribution by class (log-log), from the analysis reported here. (a) The trade-wind crossing (18,142 objects; class totals given as n in the legend; fibres are plotted by equivalent diameter like every other class, with lengths given in Table 1). Dashed lines mark 100 and 250 μm ; points are the concentration in each size bin, in particles L^{-1} of the 118.7 counted litres, and solid lines are smoothing-spline curve fits across the full size range. The power-law exponents quoted below are fitted over 20–100 μm , where counts are robust. The granular classes fall steeply with size, with fitted exponents of -3.6 (95% CI -4.1 to -3.2) for dark opaque particles, -3.6 (-4.5 to -2.8) for plant debris and -2.8 (-3.3 to -2.3) for mineral grains, all with $p < 0.0001$. Plastic fibres are nearly flat across the fitted range, at -0.5 (-0.9 to 0.0 , $p = 0.048$), and form the distinct larger mode, which reaches an equivalent diameter of 254 μm in the single largest case, a fibre 2.3 mm long; phytoplankton rises with size at $+0.8$ ($+0.1$ to $+1.6$, $p = 0.038$), as expected for cells and colonies rather than fragments. Plastic particles show a pattern closer to fibres than to the other granular classes, at -1.1 (-2.1 to -0.2 , $p = 0.026$), though this estimate rests on only

420 65 objects. The two counted copepods, each about 1,600 μm , are not included in the graph (Sect. 3.3). (b) The Emma
421 return leg from May to July 2022 (1,229 objects; class totals given as n in the legend; fibres are plotted by equivalent
422 diameter), with points giving the concentration in each size bin, in particles L^{-1} of the 22.0 counted litres, and lines
423 giving smoothing-spline curve fits.

424

425 3.6 Example fields and their contents

426 To illustrate the material recorded at individual stations, Figure 4 shows three representative filter
427 fields, each from a different station, that is, from a separate 0.5-litre filter sample, not three of the
428 five holes of one filter. At each station the total sample volume is 500 mL, passed through the five Ø5
429 mm filter holes, so each imaged field represents the particle content of approximately 100 mL of
430 filtered seawater. They span the range encountered: one of the two blue copepods, collected by the
431 vessel Emma, one of only five animals confirmed in the whole survey; a single long blue plastic fibre,
432 blue being the colour identified as plastic with the most confidence; and a field of brown mineral
433 grains together with black combustion carbon. Identifications from the images: “partially
434 combusted carbon” denotes dark, colourless particles, an optical description that may also include
435 dark plastics or minerals. Most of the minerals from the Saharan dust are either invisible or brown
436 to yellow in colour and are unlikely to be confused with the dark class. Microplastic-versus-
437 phytoplankton assignment for some objects is provisional pending FTIR/Raman confirmation.



438

439 **Figure 5.** Representative filter fields (white or pale grey background; faint grey circle marks the 5 mm field
440 boundary). (a) one of the two blue copepods; (b) a single long blue plastic fibre, several millimetres long, and a black
441 fibre coil; (c) brown mineral grains together with black combustion carbon. Each panel is from a different station (a
442 separate 0.5-litre filter sample), not a different hole of the same filter; each field shows the particle content of
443 approximately 100 mL of filtered seawater. Material identifications shown here are optical and provisional, pending
444 spectroscopic confirmation (Sect. 3.7).

445

446 **3.7 Validation and limitations of the classification**

447 The analysis reported here uses a deposited, deterministic pipeline that anyone can run; every
448 number in this paper can be reproduced end to end from the archived scripts, their per-image
449 output and the curation list (Sect. 7). The GOES filter geometry fixes the sampled volume at each
450 station, a single common microscope design was used across all vessels, and every number comes
451 from the imagery rather than from any volunteer judgement. Volunteers without training cannot
452 reliably name small, degraded particles by eye at this image resolution, so the lead author inspected
453 every object of 250 μm and above one by one; an independent, if exploratory, measurement of the
454 surface zooplankton stock comes from the surface net tow (Sect. 3.8, Table 2), in which the animals
455 are photographed and individually identifiable.

456 The particle classification is an optical heuristic that is classifier-sensitive: an independent detection
457 pass reproduces the total particle load to within about 10%, but the split between plastic, dark
458 particles and unidentified material shifts with the classification rules. Particle identities could be
459 determined by spectroscopic confirmation (FTIR or Raman); however, for a citizen science project
460 with hundreds and possibly thousands of volunteers, this is not possible for every particle. Visual
461 sorting without spectroscopy is known to misidentify a large share of suspected microplastic
462 particles (Löder and Gerdt, 2015), which is why the plastic classes are treated as optical classes
463 throughout this paper. Identification accuracy and representativeness are different qualities, and a
464 few highly accurate identifications can describe the ocean surface less well than many

465 identifications of known and moderate accuracy. A single Raman-confirmed identification is highly
466 accurate for that particle, but that result says nothing about particles at other locations or times.
467 Optically classified particles with known misclassification rates, replicated across thousands of
468 locations and times, describe the distribution, abundance and trend of particle classes across the
469 ocean surface in a way that individual spectroscopic analyses cannot provide. However, it may be a
470 useful exercise and a way to train the image analysis system if the precautions and frequent testing
471 are implemented. A subset of particles will be submitted for FTIR or Raman confirmation in the next
472 campaign to anchor the optical classes against measured identities.

473

474 The dark-particle class is an optical description of dark, colourless particles and could include
475 sediment, shadow or dark plastic. Among these possibilities, black carbon is considered the most
476 likely composition, followed by black plastic and tyre particles as the next most likely, while mineral
477 grains are deemed the least likely due to the dominance of iron oxide coatings, such as haematite
478 and goethite, in Saharan dust reaching the survey area, which appear brown to yellow rather than
479 black (Sect. 3.6). *Sargassum* fragments, abundant across much of the transect (Sect. 4.6), are a
480 plausible contributor to the plant debris, phytoplankton and unidentified organic classes; a hand
481 check of the largest round green objects found most to be plant material rather than single living
482 cells.

483

484 Saharan dust was directly observed, the sails of SV Copepod darkening with brown dust off North
485 Africa. Under the microscope the grains are nearly clear, made visible by ferric oxide, haematite or
486 goethite coatings, and were often difficult to separate from plant debris, unlike the dark opaque
487 particles and blue plastic fibres. Their 30 μm median sits within the 4 to 32 μm modal range of

488 Saharan dust reaching this ocean (van der Does et al., 2016). The grains are tabular rather than
489 equant, with a median long-to-short axis ratio of 1.8 measured here against published medians of
490 1.70 for length-to-width and 0.40 for height-to-width (Huang et al., 2023; Kandler et al., 2011). A
491 grain of those proportions holds 0.31 of the volume of a sphere of the same projected area, which is
492 the three tenths used for the mass conversion in Sect. 4.2.1, taken at a mineral density of 2,650 kg
493 m⁻³, which is the density of quartz.

494 The plastic classes carry a colour bias, because blue is the only colour identified as plastic with
495 confidence. A blue pigment is usually synthetic and resists ultraviolet light, while a faded brown or
496 colourless fibre may be a plastic that has lost its dye in sunlit surface water or a natural cotton or
497 plant fibre. The plastic count is therefore most secure for blue items and should be read as a lower
498 bound.

499 The classification was tested against the eye of the lead author on four blind marking sheets, with
500 the machine class hidden and the order shuffled. The sheets were a pilot of 180 objects, 30 from each
501 of six classes, followed by two clean rounds of 300 objects each, which together supplied 100 objects
502 from each of the five major classes and 50 each from the plastic particle and unidentified classes.
503 The pilot sheet used a ring marker that could hide the edge of an object and was not pooled, so the
504 confusion matrix rests on the 600 objects from the two clean rounds. Feeding the resulting error
505 rates back through the counts gives the corrected concentrations reported in Sect. 3.4. Each of the
506 five major classes rests on 100 checked objects, while the plastic particle and unidentified classes
507 rest on 50, so class accuracy carries an uncertainty of roughly 10 percentage points for the major
508 classes and roughly 14 for the other two.

509

510 A second scorer (D. Duncan, co-author) then separately and blindly reclassified all 780 objects on
511 the four sheets; twelve objects that lacked a verdict from one scorer were excluded, leaving 768
512 pairs. The agreement between the scorers was 65.4% (Cohen's kappa = 0.577, n = 768), stable across
513 all four object sets (kappa 0.545 to 0.599). Agreement rose to 78.5% (kappa = 0.648) when the seven
514 classes were collapsed into anthropogenic, natural and other groups. The second scorer assigned
515 35.9% of objects to the anthropogenic group against the first scorer's 40.8%. According to the scale
516 of Landis and Koch (1977), a seven-class kappa of 0.577 indicates moderate agreement, while a
517 three-group kappa of 0.648 indicates substantial agreement; therefore, the graded confidence below
518 places class-level results in the provisional tier. The thresholds of that scale are conventional rather
519 than derived, and they have been criticised as arbitrary (Feinstein and Cicchetti, 1990), so they are
520 used here only as a label. The full cross-tabulation of the two scorers is given in Table 3.

521 Disagreements were concentrated among the visually similar pale particles, and the second scorer
522 assigned fewer objects to the phytoplankton class (18 compared to 53), indicating that the scarcity of
523 living cells is not an artefact of a single scorer's judgement. However, the same disagreement applies
524 to the reported concentration, as the more conservative scorer would have assigned about one third
525 as many objects to that class, indicating that the phytoplankton figure should be interpreted as an
526 upper bound.

527 **Table 3.** Cross-tabulation of the eye classifications of the two scorers for the 768 marked objects with a verdict from
528 both (rows, scorer 1, H. Dryden; columns, scorer 2, D. Duncan). The column headed Other collects stains, rejects and
529 objects that fit no class. Agreement on the diagonal is 502 of 768 (65.4%, Cohen's kappa 0.577); collapsed to
530 anthropogenic (dark particles, plastic fibre, plastic particles), natural (mineral, plant debris, phytoplankton) and
531 other, agreement is 603 of 768 (78.5%, kappa 0.648). The pilot sheet of 180 objects is included here but not in the
532 confusion matrix of the blind trial.

Scorer 1 \ Scorer 2	Dark particles	Mineral	Plant debris	Plastic fibre	Plastic particle	Phytoplankton	Other	Row total
Dark particles	135	10	11	1	4	0	34	195
Mineral	7	90	24	0	1	1	12	135

Scorer 1 \ Scorer 2	Dark particles	Mineral	Plant debris	Plastic fibre	Plastic particle	Phytoplankton	Other	Row total
Plant debris	6	28	121	2	4	0	27	188
Plastic fibre	2	0	5	42	5	0	2	56
Plastic particle	12	0	0	1	45	0	4	62
Phytoplankton	3	7	16	1	0	17	9	53
Other	5	2	20	0	0	0	52	79
Column total	170	137	197	47	59	18	140	768

533

534 Airborne contamination is constrained by the cartridge design, which keeps the filter capped from
535 collection until the five minutes or less needed to photograph it (GOES Foundation, 2026), and
536 volunteers avoided fibre-shedding clothing while sampling; a procedural blank run by the lead
537 author on the yacht Copepod showed no obvious contamination (Sect. 2.2). Because that blank
538 showed no obvious contamination, a decision was made not to ask the other volunteer crews to run
539 blanks. Minimising the work and potential sources of errors by the volunteers is important; the
540 same principle applies to waterborne contamination.

541 Near-field sources, none of which was tested directly, are weighed briefly. Recovered fibres, at a
542 median length of 121 μm , with only eight of the 782 fibres above 1 mm, sit far below the millimetre
543 scale of rope shedding, and cordage would not reach water drawn from the stern, regardless. Most
544 cruising antifouling paints today are self-polishing, eroding through molecular-scale hydrolysis
545 rather than shedding particles, and paint particles reported elsewhere as pollutants trace mainly to
546 maintenance rather than routine erosion at sea (Yebra et al., 2004; Turner, 2010). Rain remains a
547 possible pathway, but a submerged rail does not apply, since sampling did not occur in conditions

rough enough for one. A sailing vessel, orders of magnitude smaller than a research ship, and under sail, draws little pollution into the sampled water regardless. Waterborne contamination from the vessel itself was nevertheless not measured and remains a limitation in its own right, so with respect to vessel sources the particle concentrations are an upper bound on the environmental load, while with respect to particle size they remain a floor (Sect. 3.5). Dacron or Kevlar sailcloth sheds poorly under normal loads, and hull or fitting shedding at a detectable level would mean the vessel was already failing structurally. The next campaign will sample from the leeward side only, carry paired upwind and downwind samples as an explicit vessel-source test, fit a flow meter to the tow net, collect sealed and exposure blanks at the point of analysis and increase sampling to four times daily instead of two to strengthen the rarer classes.

Taken together, the validation exercises support a graded confidence in the results. High confidence attaches to particle detection, approximate size, total abundance and the presence of the broad optical categories. Moderate confidence attaches to the blue plastic fibres and to the large objects confirmed by eye. Low and provisional confidence attaches to the phytoplankton, to the chemical identity of the dark-particle class, and to the separation of mineral grains from plant debris and the non-blue microplastics, each of which awaits spectroscopic confirmation. The two-scorer comparison supports this grading, with agreement substantially higher on the broad anthropogenic-against-natural grouping.

566

567 **3.8 Exploratory surface net tow, day and night**

To test whether the zooplankton numbers in the surface grab samples were an artefact of the small sampled volume, the lead author towed a plankton net at the surface in the mid-Atlantic. This was a one-off confirmation of the imaging protocol, not part of the replicable multi-vessel method: a

571 plankton trawl is not equipment other citizen-science crews are expected to carry, and the GOES
572 cartridge is the instrument intended for wider volunteer deployment (Sect. 5). A 120 μm mesh net of
573 0.30 m mouth diameter was towed at 1 to 2 knots for 10 minutes per haul, straining roughly 22,000
574 to 44,000 litres (mouth area $0.071 \text{ m}^2 \times 309$ to 617 m towed). The tabulated densities divide by the 2-
575 knot upper-bound volume, so slower tows would raise the true densities by up to a factor of two. The
576 animals caught in each haul were photographed and counted individually from the photographs,
577 without stain or fixative, and the catches were not preserved. Because many zooplankton migrate
578 downward by day and rise at night, ten hauls were made in daylight (12:00–15:00, local time) and
579 four after dark. Two caveats remain: the 120 μm mesh retains larger taxa while passing the smallest
580 copepods and nauplii, and filtered volume is computed from two geometries rather than a flow
581 meter.

582 The net returned a surface zooplankton stock of $0.2\text{--}0.5 \text{ m}^{-3}$, day and night, with night density
583 about two and a half times the daytime value, consistent with diel vertical migration, although
584 passive nighttime mixing remains a possible alternative explanation. This sits below the Tara Pacific
585 median of 1.1 copepods m^{-3} for comparable gyre water (Sect. 3.3), even though the 120 μm mesh
586 used here is finer than the 330 μm mesh of that survey; incomplete filtration, net avoidance by
587 larger animals or clogging of the fine mesh could each reduce the catch, and none of them was
588 measured. With only fourteen hauls it is an indicative measurement rather than a statistically
589 powered survey; zooplankton distributions are patchy, and a larger, replicated haul programme
590 would be needed before the point estimate is treated as precise.

591 **3.9 Statistical analysis**

592 Every statistical result in this paper comes from the deposited per-photograph counts, and the code
593 that produces them is archived with the data (Sects. 6 and 7). The presence percentages in Table 1

594 carry Wilson score intervals, which stay reliable when many photographs hold a zero count for a
595 class. The zooplankton result is tested with the Poisson model of Sect. 3.2, which shows that even a
596 zero count in 118.7 litres would have agreed with the surface stock that the net tow measured; the
597 five animals recovered exceed that expectation (Sect. 3.3).

598 Longitudinal structure is tested for all thirteen vessels, which together supply the 1,466 counted
599 photographs. For each class, the mean concentration in each five-degree longitude bin is fitted
600 against longitude by weighted least squares on the logarithm of concentration, with a Spearman
601 rank correlation on the individual photographs as a check. No class shows a significant fitted slope,
602 with every confidence interval spanning zero, although dark opaque particles ($p = 0.07$) and
603 microplastic fibres ($p = 0.08$) come closest, both falling towards the west. Three rank correlations
604 reach significance for dark opaque particles ($\rho = -0.22$), microplastic fibres ($\rho = -0.15$) and the
605 unidentified class ($\rho = -0.07$). All three are weak, and because photographs along one track
606 sample similar water, the effective sample size is far below 1,466; so these coefficients may reflect
607 the sampling structure rather than a real gradient. The survey therefore provides no statistical
608 evidence for an east-to-west gradient in any class at the level of the fitted bins and only weak rank
609 correlations at the level of individual photographs (Fig. 3). With the vessel as the principal
610 independent sampling unit, thirteen vessels allow the test to rule out only gradients large enough to
611 emerge above the between-vessel scatter, so the absence of a detected gradient does not exclude
612 weaker spatial structure. No population-level confidence intervals are reported for the
613 concentrations, because thirteen vessels give only a rough estimate of the between-vessel variance
614 (the vessel means of the machine classes, listed in Table S1 of the Supplement, have standard
615 deviations of 63 L^{-1} for dark opaque particles, 31 L^{-1} for plant debris, 30 L^{-1} for mineral grains and
616 4.5 L^{-1} for microplastic fibres, against the archive means of Table 1); the Wilson intervals of Table 1
617 describe counting precision within the archive only.

618 The size distribution of each class is fitted as a power law over the 20 to 100 micrometre range,
619 where the bin counts are reliable. The granular classes fall steeply with size, with fitted exponents
620 near -3.6 for dark opaque particles, -3.6 for plant debris and -2.8 for mineral grains, each
621 significant at $p < 0.0001$ (Fig. 4); plastic fibres are almost flat, and phytoplankton rises gently with
622 size, as whole cells and colonies do rather than fragments. These class shapes were never built into
623 the classifier, so their agreement with the expected physics is independent support for the
624 classification.

625 **3.10 The summer return leg, west to east**

626 One vessel, Emma, returned from west to east at a higher latitude between 19 May and 31 July 2022,
627 and her 271 accepted photographs yielded 27.1 litres of filtered seawater, 22.0 litres of which were
628 counted after masking, sampled on the same protocol (154 photographs in daylight and 117 after
629 dark). The machine classes give 21.5 L^{-1} dark opaque particles, 15.6 L^{-1} plant debris, 8.9 L^{-1}
630 unidentified, 5.0 L^{-1} mineral, 2.8 L^{-1} plastic fibre, 1.0 L^{-1} phytoplankton and 0.3 L^{-1} plastic particle,
631 for a total of 55.2 L^{-1} . That becomes 56.0 L^{-1} once the radiolarian class described next is added,
632 compared to 152.8 L^{-1} on the trade-wind crossing. Eighteen radiolarians, identified individually by
633 eye, form a microzooplankton class of 0.8 L^{-1} , and animal zooplankton stayed at zero in this leg's
634 counted photographs.

635 Applying the trade-wind crossing confusion matrix of Sect. 3.7 to this leg gives indicative corrected
636 values of 24.6 L^{-1} dark opaque particles, 10.7 L^{-1} plant debris, 5.4 L^{-1} mineral, 3.6 L^{-1}
637 phytoplankton, 1.9 L^{-1} plastic fibre and 0.7 L^{-1} plastic particle. Of the remainder, 8.1 L^{-1} proves to
638 be stains or rejects, and the unidentified row resolves mostly to dark opaque particles. The
639 correction is indicative rather than measured, because the blind trial drew trade-wind-crossing
640 objects from many vessels, while this leg comes from one vessel and one camera. The longitudinal

641 structure of the leg is shown in Fig. 3b, beside the trade-wind crossing in Fig. 3a for direct
642 comparison of the two crossings, and the size distribution of every class is shown in Fig. 4b next to
643 the size distribution for the trade-wind crossing in Fig. 4a.

644 3.11 Survey at a glance: both crossings

645 **Table 1.** Survey at a glance: machine classes before the eye-check correction, with the trade-wind crossing (1,466
646 photographs, 146.6 litres filtered, 0.081 litre counted per photograph after masking to the filter disc) beside the
647 summer return leg sailed by Emma west to east (271 photographs, 22.0 litres counted). Because the distributions are
648 strongly right-skewed, each class is given as its overall mean concentration, together with the share of photographs
649 in which it appears; a per-photograph median carries no information at 0.081 litre per photograph. Counts include
650 only particles $\geq 20 \mu\text{m}$ from the complete 18,142-object inventory, in which the two copepods sit in a separate
651 mesozooplankton class outside the seven particle classes; the classification is optical, pending spectroscopic
652 confirmation, with the per-class confidence grades in Sect. 3.7. The microzooplankton row lists the eighteen
653 radiolarians identified individually by eye during the summer leg. The Wilson intervals measure within-archive
654 counting precision, not population uncertainty, because the vessel, not the photograph, is the independent sampling
655 unit (Sect. 3.9). Bracketed values are the blind-check eye-corrected concentrations (Sect. 3.4, 3.10); the unidentified
656 row corrects to zero because it resolves mainly to dark opaque particles, with the remainder (21.1 L^{-1} trade-wind
657 crossing, 8.1 L^{-1} summer return, not shown as a row) proving to be stains or rejects rather than a real particle class.

Class	Trade-wind crossing, east to west		Summer return, Emma, west to east		Notes
	Photos present	Conc. (L^{-1} , mean)	Photos present	Conc. (L^{-1} , mean)	
Zooplankton	0.2% (five confirmed) (0.1–0.6)	0.03	0% (0.0–1.4)	0	Two blue copepods were confirmed on the filter discs of counted photographs, one at the rim outside the counting mask, and three larger decapods from the same samples are allocated to their stations; the concentration is on the 146.6 litres filtered (Sect. 3.3); none on the summer leg.
Microzooplankton (radiolarians)	0% (0.0–0.3)	0	5.5% (3.4–8.9)	0.8	18 radiolarians identified by eye on the summer leg; a targeted eye check of every object between 60 and 250 μm on the crossing found none.
Phytoplankton	24.1% (22.0–26.3)	5.9 (9.0)	7.0% (4.5–10.7)	1.0 (3.6)	pigmented aggregates, diatoms; 695 and 22 objects.
Dark opaque particles	70.2% (67.8–72.5)	56.2 (64.2)	68.3% (62.5–73.5)	21.5 (24.6)	6,671 and 473 objects
Microplastic	3.1%	0.5 (1.4)	2.6%	0.3 (0.7)	coloured fragments, 65 and 7 objects

Class	Trade-wind crossing, east to west		Summer return, Emma, west to east		Notes
	Photos present	Conc. (L^{-1} , mean)	Photos present	Conc. (L^{-1} , mean)	
particles	(2.4–4.2)		(1.3–5.2)		
Microfibres	26.7% (24.5–29.1)	6.6 (5.0)	16.6% (12.6–21.5)	2.8 (1.9)	782 and 62 fibres; trade-wind crossing median length 121 μm (quartiles 86 and 195 μm , longest 2.3 mm), elongation 11:1.
Mineral	57.2% (54.7–59.7)	32.7 (24.1)	28.0% (23.0–33.7)	5.0 (5.4)	3,881 and 109 objects: grains judged by hue against plant debris
Plant debris	54.9% (52.4–57.4)	35.6 (28.0)	54.6% (48.7–60.4)	15.6 (10.7)	4,233 and 342 objects; grains judged by hue against minerals
Unidentified	51.0% (48.4–53.5)	15.3 (0)	42.1% (36.3–48.0)	8.9 (0)	1,815 and 196 objects: neutral grains near the 20 μm floor

658

659 **Table 2.** Surface net-tow observations of zooplankton density, day and night (120 μm mesh, 0.30 m mouth, 1–2
660 knots, 10 min per haul). Filtered volume is computed from tow geometry, assuming complete filtration; any
661 clogging, extrusion through the mesh or net avoidance would make the true densities higher than tabulated, so
662 these values are lower bounds. Night density is $\sim 2.5\times$ daytime, consistent with diel migration, yet remains below 0.5
663 m^{-3} .

Set	Hauls	Zooplankton (m^{-3})
Daytime (12:00–15:00)	10	~ 0.2
Night (after dark)	4	~ 0.5 ($\approx 2.5\times$ daytime)

664

665

666 4. Discussion

667 4.1 Comparison with previous surveys of the region

668 Systematic plankton and particle surveys of the open tropical and subtropical North Atlantic are
669 sparse, and those that exist have run meridionally, north to south along a line of longitude. They
670 include the Atlantic Meridional Transect between the United Kingdom and the South Atlantic
671 (Aiken et al., 2000), the 20° W surface zooplankton transect of Woodd-Walker et al. (2002), and the
672 meridional synthesis of Vereshchaka et al. (2017). For plastics, Pabortsava and Lampitt (2020)
673 sampled beneath the surface along the AMT line, and Cózar et al. (2014) drew on a global
674 circumnavigation. Like the GOES crossing, these lines sampled unproductive open gyre water well
675 off the continental shelf, so the contrast drawn here is between comparable waters. Prior surface
676 work in this basin includes the neuston-net archive of Law et al. (2010) in the western gyre, the
677 neuston survey of Holdway and Maddock (1983) and the 2016 Tara Pacific crossing at 25° to 35° N
678 (Mériguet et al., 2025).

679 To our knowledge, the GOES survey is the first zonal transect of the trade-wind belt to count
680 plankton and particles together at 20 µm resolution.

681

682 **4.2 Comparison with other methods**

683 If the citizen-science imaging method is to stand as a result in its own right, it must be set against
684 conventional tools: plankton nets, pumps, the Continuous Plankton Recorder (CPR) and laboratory
685 microscopy or flow cytometry, which sample with standardised gear and calibrated volumes but at
686 higher cost and usually integrated over depth. A recent multi-gear synthesis of biomass size spectra
687 for the tropical and subtropical Atlantic illustrates that character: its zooplankton records come
688 from net tows and optical profiles reaching hundreds of metres, which need literature-derived
689 conversion factors because no two gears sampled alike. Its authors note that surface sampling

690 captures a markedly smaller share of the migrating zooplankton biomass than night-time depth-
691 integrated tows (Fock et al., 2026).

692 The standard CPR unit samples through a 1.27×1.27 cm aperture on 270 μm silk at roughly 10 m
693 depth and filters 3.2 to 3.8 m^3 , a volume that itself varies with ship speed and clogging (Jonas et al.,
694 2004; Hunt and Hosie, 2006). Against that, our confirmation net's 300 mm mouth on 120 μm mesh at
695 the surface is wider in aperture, finer in mesh and shallower in depth, straining roughly 22 to 44 m^3
696 per haul, some 6 to 14 times more water. The two instruments are complementary rather than one
697 being simply coarser.

698 The GOES method inverts that balance: it resolves the 20–200 μm fraction exactly at the air–sea
699 interface, accurately delivers dense spatial coverage across under-sampled basins, and scales to a
700 distributed volunteer fleet. There are tens of thousands of blue water yachts that traverse all oceans,
701 from the tropics to the high Arctic, from estuaries and coastal waters to the deep ocean. If a small
702 percentage of these vessels deployed a standardised sampler to measure surface particles, which
703 were then analysed by an optimised automated image analysis procedure, our knowledge of the
704 oceans' surface water would be greatly expanded.

705 The key point is a sharp, in-focus image from a microscope of at least 5 megapixels fitted with a
706 polarising filter. The system's accuracy will continue to improve as the database expands and
707 particles are identified. Most pollution starts on land, with land run-off and riverine input, or
708 atmospheric deposition and rainwater dispersal. The GOES filter does not need to be restricted to
709 ocean-going vessels; samples may also be collected from rivers, lakes, piers, by hand from the coast,
710 small coastal vessels and even rainwater, which may be checked. All of the information can be fed
711 into the database to help develop a complete profile of all particles and plankton, from land and sky

712 to ocean, to give a detailed map of particles and plankton on the ocean surface and pollution sources
713 across all vectors.

714 **4.2.1 An independent check on the mineral count**

715 The mineral class permits a sharper check against independent measurement. The survey counted
716 32.7 grains L^{-1} , the machine count before the eye-check correction, at a median diameter of 30 μm ,
717 and while that count is measured, the conversion to mass depends on grain shape, because an
718 optical diameter carries no thickness. Treated as plates at three tenths of the volume of a sphere of
719 the same optical diameter (Sect. 3.7), and summed grain by grain across every measured diameter,
720 the 3,881 grains give 0.73 $\mu\text{g L}^{-1}$; scaling that figure by the eye-corrected count of 24.1 grains L^{-1}
721 (Sect. 3.4) gives about 0.54 $\mu\text{g L}^{-1}$, and the machine count is carried below because the grain-by-
722 grain sizes belong to that set, with the corrected value given as the lower estimate. The mass sits in
723 the coarse tail of the size distribution, because the largest fifth of the grains carry three fifths of the
724 total, so the median describes the distribution rather than serving as the input to the conversion.
725 The dust flux supplies a prediction that is independent of the microscope. About 139 million tonnes
726 settle each year over the 21.2 million square kilometres of the deposition corridor (Yu et al., 2015;
727 Kaufman et al., 2005), and balancing that flux against settling velocity predicts 0.84 $\mu\text{g L}^{-1}$ for the
728 slower-sinking plates. The measured load of 0.73 $\mu\text{g L}^{-1}$ sits thirteen per cent below that prediction,
729 and the corrected load of 0.54 $\mu\text{g L}^{-1}$ sits 36 per cent below. The prediction assumes a steady state
730 between deposition and settling in the absence of turbulent mixing, in which plates settle more
731 slowly than compact grains of the same optical diameter, which would leave the top metre within
732 about an hour in still water. An optical count made on a volunteer yacht landing within 13 to 36 per
733 cent of a satellite dust budget supports the GOES filter in this size class, although grain shape enters
734 both sides of the comparison, so the agreement is a consistency check rather than an independent
735 confirmation of the mass. The measured load ranges from 15,000 to 52,000 tonnes over that area,

736 with the lower figure representing plates and the upper figure representing the same grains treated
737 as compact spheres; this amount corresponds to one to three hours of the annual supply, indicating
738 that the layer turns over quickly. The microlayer nevertheless retains particles at the interface for
739 minutes to hours (Ebling and Landing, 2017; Tovar-Sánchez et al., 2020).

740 **4.3 Sources of marine pollution and their implications**

741 Scale provides a sense of the stakes involved, although the figures below are illustrative scaling
742 exercises rather than actual measurements. Cumulative releases of manufactured persistent organic
743 pollutants into the environment reached about 20 million tonnes by 2020 (Li et al., 2023); how much
744 of that burden has entered the oceans is unknown.

745 **4.3.1 Dark opaque particles and lipophilic chemical pollution**

746 The SML attracts lipophilic “forever” chemicals (per- and polyfluoroalkyl substances, PFAS, and
747 related persistent organic pollutants, POPs), microplastics, and hydrophobic black-carbon soot from
748 the incomplete combustion of fossil fuels and biomass. Toxic chemical concentrations in the SML
749 can be many times higher than in the water below (Wurl and Obbard, 2004). A meta-analysis finds
750 organic matter systematically enriched there, with median enrichment factors of about three for
751 particulate organic carbon and above two for nitrogen-rich compounds (Silva et al., 2026), so the
752 layer accumulates pollution at the precise interface where plankton live.

753 Hydrophobic black carbon and plastic preferentially adsorb these chemicals and can carry them
754 into the base of the food web (Bond et al., 2013; Ziccardi et al., 2016). Plastic resin pellets from coastal
755 waters carry persistent organic pollutants (POPs) such as PCBs and DDE at up to about a million
756 times the concentrations found in the surrounding seawater (Mato et al., 2001); partially combusted
757 carbon sorbs the same compounds even more strongly (Cornelissen et al., 2005), a point that is
758 largely overlooked. Both classes occur across the open Atlantic far from land (Cózar et al., 2014;

759 Pabortsava and Lampitt, 2020). The same burden of combustion and chemical pollution is a leading
 760 environmental cause of human disease and premature death, so cutting it serves planetary and
 761 human health together (Landrigan et al., 2020; Fuller et al., 2022). Macroplastic ingestion is now a
 762 quantified cause of mortality in seabirds, marine mammals and sea turtles at surprisingly small
 763 doses (Murphy et al., 2025).

764 The dark class is an optical description and not a statement of origin. Soot itself cannot account for
 765 it, because an aged soot aggregate measured at a remote North Atlantic site is 0.21 to 0.28 μm across
 766 (China et al., 2015), a hundred times below the 20 μm floor of this method. The angular majority is
 767 consistent with char, the solid residue of burning, reported at 1 to 100 μm with axis ratios of 1.5 to 2.4
 768 (Han et al., 2010; Gilgen et al., 2018). The small round fraction is consistent with the spheroidal
 769 carbonaceous particles that coal and heavy fuel oil produce above 1,000 $^{\circ}\text{C}$ (Swindles et al., 2015).

770 Tyre and road wear, coal dust, bitumen, brake wear and dark volcanic glass all present as black
 771 angular objects of the same size, and transmitted-light microscopy cannot separate them (Gao et al.,
 772 2022; Kovochich et al., 2021).

773 Tyre and road wear is the most cited candidate for several reasons. Global generation is 2.9 to 5.9
 774 million tonnes a year (Evangelidou et al., 2020; Kole et al., 2017), and the number-median diameter of
 775 34 μm (Kovochich et al., 2021) lies inside the 20 to 92 μm range recorded here. The material has also
 776 been measured in northern Atlantic marine air (Goßmann et al., 2023a) and concentrates in the sea-
 777 surface microlayer that this survey samples (Goßmann et al., 2023b). Two objections remain open,
 778 and both concern transport rather than appearance. Modelled long-range transport covers particles
 779 of only 0.5 to 10 μm (Evangelidou et al., 2020), so no published model delivers a 30 μm tyre particle to
 780 this longitude. The particles are also denser than seawater, at 1.4 to 1.9 g cm^{-3} , settling at 0.2 to 0.7
 781 mm s^{-1} (Dittmar et al., 2025), so they would persist in the top metre only where the supply from

782 above is continuous. The class total in Table 1 is therefore unchanged, and spectroscopy is needed
783 before any source is assigned.

784 **4.3.2 Plastic**

785 For plastic fibres, the measured shedding rate is 124 to 308 milligrams of fibre per kilogram of fabric
786 per wash (De Falco et al., 2019); with an assumed 20 to 52 washes in a garment's first year, washing
787 the full annual polyester output (78 million tonnes; Textile Exchange, 2025) would shed between
788 about 195,000 tonnes, at the lowest rate and fewest washes, and 1.2 million tonnes of fibre in one
789 year. This is an illustrative figure rather than a measurement, because part of that output is never
790 laundered, garments are washed beyond their first year, and the number of washes is an
791 assumption. Applying this survey's own concentration to the top 1 metre of the world's oceans gives
792 an extrapolation of about 25,000 tonnes of plastic fibres (about 2 to 13% of that shedding estimate),
793 assuming the sampled corridor is globally representative. There is a high degree of uncertainty with
794 this figure, since buoyant plastic concentrates in the top few centimetres and its concentration falls
795 away with depth (Kukulka et al., 2012; Reisser et al., 2015; Kooi et al., 2017).

796 The equivalent exercise for the dark-particle class gives a range of 374,000 to 748,000 tonnes, about
797 5 to 10% of the roughly 7.5 million tonnes of black carbon estimated to enter the atmosphere
798 worldwide each year from fossil fuel and biomass burning (Bond et al., 2013). That budget includes
799 the sub-micron aerosol, which this method cannot detect, as well as the coarse char that it can
800 detect; therefore, the ratio establishes a scale but does not provide a direct comparison. The
801 extrapolation applies a subtropical gyre concentration to the whole ocean surface and should not be
802 read as an estimate for coastal, polar, equatorial or upwelling waters.

803

804 Three comparisons against independent estimates fall within a factor of about two of each other.
805 The plastic fibre extrapolation is about 2 to 13 per cent of one year of laundry shedding, the dark-
806 particle extrapolation is about 5 to 10 per cent of one year of black carbon emission, and the mineral
807 load sits 13 to 36 per cent below the satellite dust prediction of Sect. 4.2.1. Only the mineral
808 comparison tests the method, because measurement and prediction are both concentrations in the
809 same water over the same corridor, whereas the other two set a standing stock against an annual
810 supply and depend on the unknown fraction of that supply which reaches the surface. Together they
811 place the survey within the broad range that independent global budgets predict, which is the first
812 question any extrapolation from 146.6 litres must answer.

813

814 **4.3.3 Aerosol transportation**

815 The sea surface does not merely store pollution but also returns part of the burden to the
816 atmosphere. Rising bubbles scavenge the microlayer and burst at the surface, ejecting film-bound
817 material as sea-spray aerosol (O'Dowd et al., 1997; O'Dowd et al., 2004), and because the SML
818 concentrates microplastic, nanoplastic, and their adsorbed chemicals at concentrations far above the
819 underlying water, that spray is correspondingly enriched. Microplastic is measured in the remote
820 marine atmosphere (Trainic et al., 2020) and is quantified as an ocean-sourced limb of a global
821 atmospheric plastic cycle (Brahney et al., 2021). It can seed cloud and ice aloft (Aeschlimann et al.,
822 2022), and it returns in rain and snow from remote mountain catchments to polar snow (Allen et al.,
823 2019; Bergmann et al., 2019; Aves et al., 2022). The old adage that the solution to pollution is dilution
824 fails for this film-bound class: the material partitions into the surface skin and is redistributed
825 rather than diluted away, and because many of these chemicals break down only slowly, their
826 environmental burden persists for decades after release. Carbon particles adsorb as well as absorb

827 these chemicals and may stabilise them at high concentrations for aerosol transport, a subject that
828 requires investigation and for which the GOES filter is ideally suited.

829

830 **4.4 The surface microlayer, clouds and evaporation: a hypothesis for further work**

831 The sea-surface microlayer already suppresses air–sea CO₂ exchange by a substantial, measured
832 fraction (Pereira et al., 2018), can inhibit evaporation under surface blooms (Wurl et al., 2018), and
833 supplies the biogenic aerosol that seeds marine cloud condensation nuclei (O’Dowd et al., 2004). We
834 consider it the most climatically significant surface on Earth. Whether its condition also measurably
835 alters the rate of ocean evaporation, and so the water-vapour feedback on climate disruption, is an
836 open, testable question that this survey’s particle and plankton data cannot answer; we state it here
837 as a mechanism for future investigation rather than a finding of this study. A quantitative test would
838 need paired eddy-covariance measurements of latent heat flux inside and outside natural slicks, set
839 against measured surfactant cover, and we intend to pursue that test in a separate paper.

840 **4.5 Missing microzooplankton**

841 Toxic loading is known to affect grazing zooplankton elsewhere (Desforges et al., 2015; Ma et al.,
842 2020); we note this as a candidate mechanism rather than an established explanation, since the
843 survey documents a co-occurrence of absent microzooplankton and abundant anthropogenic
844 particles and cannot by itself establish cause.

845 Five zooplankton were recovered: two copepods of about 1,600 µm on the filter discs of counted
846 photographs, one of them at the rim outside the counting mask, and three decapods of about 7 mm
847 to above 20 mm allocated to the samples of their stations (Sect. 3.3), together scaling to 34
848 individuals m^{−3} on the full filtered volume of 146.6 litres. More striking is the absence of

849 microzooplankton, the 20 to 200 μm class that includes copepod nauplii and small radiolarians. A
850 microzooplankton bin was added to the classification, and every object between 60 and 250 μm in
851 the curated archive, 776 objects in all, was then inspected by eye at full resolution; 585 of these are
852 compact particles, and none of them is an animal, while the remaining 191 are elongated filaments.
853 Below 60 μm an object spans fewer than about eighteen pixels, which is too coarse for the
854 appendages, spines or reticulate wall that identify these animals, so the count of zero applies to the
855 identifiable fraction of the class rather than to the whole class. The eighteen radiolarians of the
856 Emma leg measured about 20 to 60 μm (Fig. 4b), below the 60 μm lower limit of the eye check on the
857 crossing, so the zero count on the crossing applies to objects of 60 μm and above, and an eye check of
858 the crossing archive down to 20 μm remains to be done.

859

860 Emma's higher-latitude run found 18 radiolarians in 22 litres, about 800 m^{-3} , within the 1 to 5,000
861 individuals m^{-3} range reported for radiolarians in the upper 1,000 m of the world's oceans
862 (Boltovskoy et al., 2010; Tréguer and De La Rocha, 2013), which shows that the method detects this
863 size class in principle. That leg's machine-class particle background, at 56.0 L^{-1} (Sect. 3.10), was
864 roughly 2.7 times sparser than the 152.8 L^{-1} of the trade-wind crossing (Sect. 3.4), so detection
865 efficiency for small organisms against the denser trade-wind crossing particle field is likely lower
866 still, and genuine absence and detection failure cannot be fully separated. The filter paper stays wet
867 throughout the four-hour drainage, so soft-bodied ciliates and flagellates may not survive alive, and
868 whether they remain intact for imaging without a fixative was not tested. We expected many more
869 of these small animals along the trade-wind crossing, but none were confirmed.

870 Ferric dust from the Sahara may also act on the surface layer through coagulation and flocculation
871 reactions. Saharan dust deposition has been shown to increase the formation of aggregates from

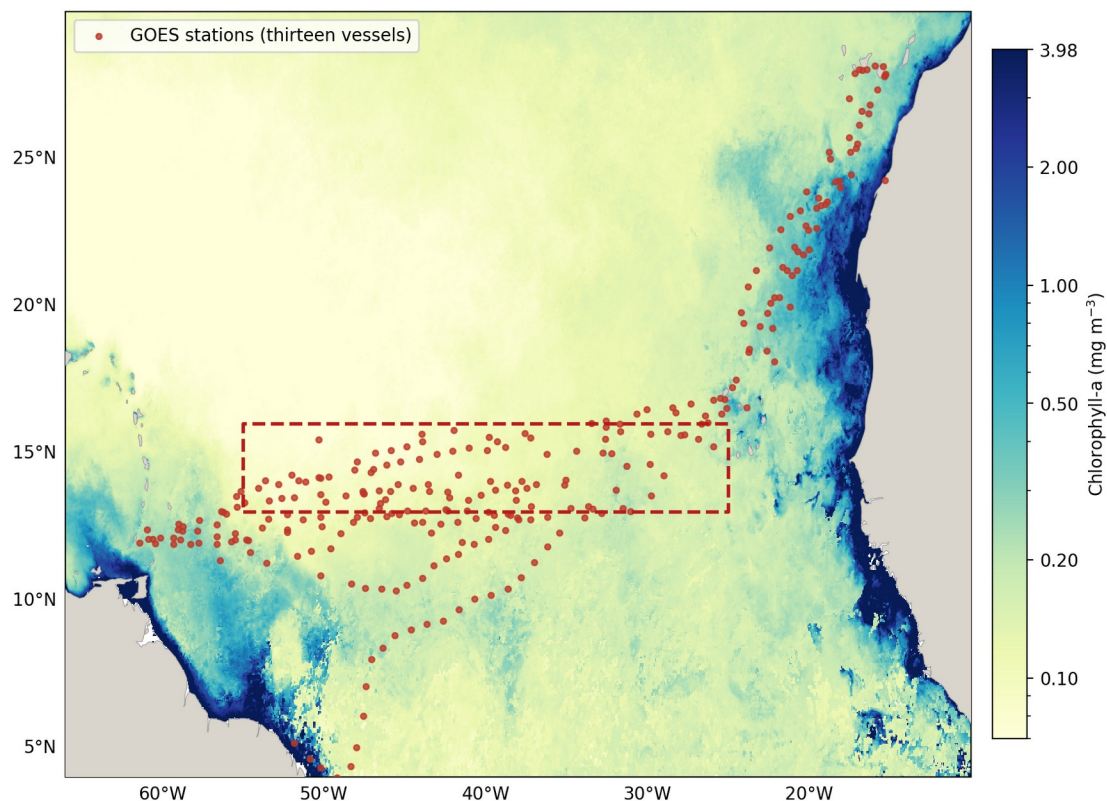
872 particles and organic matter in surface water (van der Jagt et al., 2018). Most of the iron in dust
873 arrives as insoluble oxide, and only about 1 to 2% dissolves (Jickells et al., 2005), so the coagulant
874 analogy below applies to that small dissolved fraction. Dissolved ferric iron is a coagulant in
875 seawater systems (Edzwald and Haarhoff, 2011), so it could lower the zeta potential of suspended
876 particles and raise the micro-viscosity of the surface layer, which would bear more heavily on
877 organisms that swim at low Reynolds number than on larger animals (Purcell, 1977; Larsen and
878 Riisgård, 2009). Neither zeta potential nor viscosity was measured here; no published study
879 demonstrates this mechanism in open oligotrophic water, and the absence of microzooplankton is at
880 least as consistent with detection failure against a dense particle background, so the idea is recorded
881 as untested speculation and not as an explanation.

882

883 Zooplankton also regenerate nutrients in the surface layer through grazing, sloppy feeding and
884 excretion (Barbeau et al., 1996), so their loss removes part of that recycling. In much of the ocean,
885 this process would tip a patch toward the iron-limited high-nutrient, low-chlorophyll (HNLC)
886 condition (Tyrrell et al., 2005), but iron is not scarce under the steady Saharan dust supply here
887 (Jickells et al., 2005), and nitrogen and phosphorus limit growth in this water (Mills et al., 2004;
888 Moore et al., 2013). The locally consistent outcome of grazer loss would therefore be a drawdown of
889 surface nitrate and phosphate as ungrazed production exports organic matter to depth, although the
890 satellite record shows no bloom in this water (Fig. 6).

891 Independent satellite ocean colour confirms the oligotrophic setting of the crossing. The median
892 surface chlorophyll-a over the trade-wind transect box in January and February 2022, the months of
893 the crossing, is 0.11 mg m^{-3} , and 86% of the box lies below a commonly used operational
894 oligotrophic threshold of 0.15 mg m^{-3} . Elevated chlorophyll is confined to the Mauritanian and

895 equatorial upwellings and the continental margins, and the January to February median for 2012 to
 896 2021 gives 0.12 mg m^{-3} , so the pattern is climatologically stable (Fig. 6). An entirely independent
 897 instrument therefore agrees with the microscopy that this is biologically impoverished water.



898

899 **Figure 6.** Satellite chlorophyll-a concentration (MODIS-Aqua monthly product, mean of January and February 2022,
 900 the months of the crossing; logarithmic colour scale; cloud gaps, 5.6% of ocean pixels, filled from the January to
 901 February mean of 2012 to 2021) across the study region, with the GOES sampling stations (red) and the trade-wind
 902 transect box (dashed). The crossing runs through the oligotrophic core of the subtropical gyre (transect-box median
 903 0.11 mg m^{-3} , with 86% of box pixels below a commonly used operational threshold near 0.15 mg m^{-3}), while elevated
 904 chlorophyll is restricted to the Mauritanian and equatorial upwellings and the continental margins. The January to
 905 February climatology for 2012 to 2021 gives a box median of 0.12 mg m^{-3} , so the pattern is climatologically stable.
 906 Chlorophyll-a data © NASA Ocean Biology Processing Group (MODIS-Aqua), served by NOAA CoastWatch ERDDAP.
 907 Coastlines © Natural Earth.

908

909 4.6 Sargassum

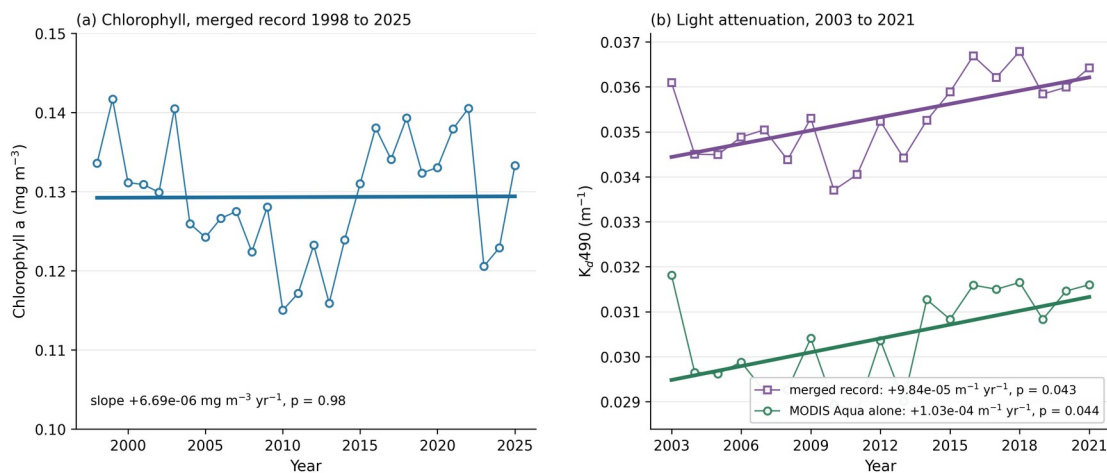
910 Before 2011, satellite estimates put the standing stock of pelagic *Sargassum* at roughly 1 to 2 million
 911 tonnes of wet weight across the Sargasso Sea and the Gulf of Mexico (Gower and King, 2011). With

912 nutrient supply from Amazon River discharge and West African upwelling, the biomass of the Great
913 Atlantic *Sargassum* Belt then peaked above 20 million tonnes in June 2018 (Wang et al., 2019;
914 Lapointe et al., 2021), and the belt surpassed 30 million tonnes in 2025 (Zhou et al., 2026). A recent
915 analysis of the drivers attributes that growth mainly to the deepening of the winter mixed layer and
916 to the recycling of nutrients within the belt itself, with sea surface temperature exerting almost no
917 influence (Zhou et al., 2026). Project yachts were frequently caught in giant mats of this pelagic
918 macrophyte, which competes with phytoplankton for phosphate, nitrate and other nutrients
919 (Lapointe et al., 2021). As phosphate falls, *Sargassum* increasingly takes up arsenate through the
920 same phosphate transporter, so the tissue reaching the Caribbean is heavily loaded with arsenic
921 (Devault et al., 2021; Rodríguez-Martínez et al., 2020; McGillicuddy et al., 2023). Because the switch
922 happens only once phosphate is scarce, that burden is consistent with reported phosphate
923 limitation, although we measured neither dissolved phosphate nor arsenate and draw no direct
924 conclusion from our data.

925 A bloom of this mass, drawing on the same surface nutrient pool, could reduce the integrity of the
926 SML and the availability of phytoplankton and zooplankton that graze on them, so nutrient
927 stripping by the belt is a further independent candidate explanation for the low plankton count, one
928 that a targeted phosphate and arsenate survey could test directly. The timing matters for the
929 comparison with earlier surveys: the belt was essentially absent before 2011 (Wang et al., 2019),
930 while the meridional transects of the region (Aiken et al., 2000; Woodd-Walker et al., 2002) predate
931 the belt. Part of any contrast with those surveys may therefore reflect genuine change in the tropical
932 and subtropical North Atlantic over the intervening two decades rather than sampling differences
933 alone.

934 Satellite ocean colour over the belt region shows no trend in annual mean chlorophyll-a between
935 1998 and 2025 (slope not different from zero, $p = 0.98$; Fig. 7a), so the belt has not measurably

936 reduced phytoplankton biomass. Light attenuation in the same water rose by about 5 to 6% between
 937 2003 and 2021, on the merged record and on MODIS-Aqua alone (Fig. 7b), which indicates an
 938 increased load of non-algal particles, because chlorophyll did not change over the same period. The
 939 material responsible cannot be identified from the satellite record alone: Saharan dust, coccoliths
 940 and anthropogenic particles all fall within that optical description, and although this survey resolves
 941 nothing below 20 μm , the particle composition it reports provides context for the question.



942

943 **Figure 7.** Satellite ocean colour over the north tropical Atlantic, 5 to 20° N, 20 to 50° W. (a) Annual mean
 944 chlorophyll-a from the ESA Ocean Colour CCI v6.0 merged record, 1998 to 2025, with least squares fit. (b) Annual
 945 mean diffuse attenuation coefficient K_d490 from the merged record and from MODIS-Aqua alone, 2003 to 2021, with
 946 least squares fits. Slopes and p-values corrected for first-order autocorrelation are given in the panels. Data: ESA OC
 947 CCI v6.0 served by the Plymouth Marine Laboratory THREDDS server; MODIS-Aqua K_d490 R2018.0 served by NOAA
 948 OceanWatch ERDDAP.

949 4.7 Microplastics, primary producers and ocean oxygen

950 The near-surface layer we sampled carries a high particle load and is inhabited by
 951 picocyanobacteria, although the region's productivity maximum lies at the deep chlorophyll
 952 maximum below our sampling depth. No direct link between the surface counts and
 953 *Prochlorococcus* health is claimed here, because any effect on organisms below the sampled layer
 954 would be attenuated at each step of mixing and leachate transport. The potential consequences for
 955 marine primary production are nonetheless substantial. Laboratory exposure shows that leachates

956 from common plastics impair the growth and oxygen production of *Prochlorococcus* (Tetu et al.,
957 2019). That organism is the single most abundant marine photosynthetic bacterium, of the order of
958 10^{27} cells across the world ocean, and it went undetected until Chisholm et al. (1988) because its 0.6
959 μm cells escaped detection by conventional microscopy. Together with *Synechococcus*, it is
960 responsible for roughly a quarter of marine primary production and a comparable share of the
961 ocean's oxygen supply and biological carbon fixation (Flombaum et al., 2013). A recent meta-analysis
962 estimates that microplastic pollution measurably depresses photosynthesis across aquatic and
963 terrestrial primary producers, implying substantial losses of marine primary production and oxygen
964 output (Zhu et al., 2025), and model experiments indicate that zooplankton grazing on microplastics
965 re-routes export production in a way that accelerates the ongoing global loss of ocean oxygen (Kvale
966 et al., 2021). Plastic and dark opaque particles, which occur at a much higher concentration than
967 plastic, are emerging additional stressors that compound well-quantified drivers of ocean
968 deoxygenation, warming, acidification and eutrophication.

969

970 5. Conclusions

971 **Spatial coverage.** The GOES survey constitutes a preliminary baseline for the first systematic
972 record of plastic and partially combusted carbon particles in the near-surface waters of the tropical
973 and subtropical North Atlantic's Main Development Region, the corridor in which most major
974 Atlantic hurricanes form (Goldenberg and Shapiro, 1996). The results demonstrate the utility of the
975 GOES filter as an instrument for serious citizen science investigations and the collection of data for
976 further detailed interrogation that would otherwise not be available. The programme can be greatly
977 expanded to thousands of blue-water yachts that cross all oceans, from the tropics to high latitudes,
978 including coastal zones and estuaries. Collectors do not need to be restricted to just boats; rainwater

979 samples are important as well as lakes, rivers, piers and rocky outcrops. Most pollution starts on
980 land or falls as rain, so collecting as much information as possible improves detection, accuracy and
981 resolution of the data.

982

983 **Sampling depth.** Although the ocean covers approximately 71% of the planetary surface, very few
984 oceanographic surveys sample the uppermost metre of the water column. This thin interfacial layer,
985 surmounted by the SML, is well established in the literature as a regulator of air–sea gas exchange
986 and as the principal source of biogenic aerosols that serve as marine cloud condensation nuclei
987 (Cunliffe et al., 2013). The ocean has absorbed in excess of 93% of the surplus heat accumulated
988 through rising atmospheric greenhouse gas concentrations since the 1970s (IPCC, 2013), yet this
989 critical interface, responsible for 86% of global evaporation into the atmosphere (Trenberth et al.,
990 2007), remains substantially under-investigated.

991 **Particle size range.** The GOES filter resolves particles down to a nominal diameter of 20 μm ,
992 whereas plankton net surveys typically use meshes of 200 to 330 μm (Fernández de Puelles et al.,
993 2019; Mériguet et al., 2025), notwithstanding the recognised ecological importance of the smallest
994 size fractions. The most abundant marine photosynthetic bacterium, *Prochlorococcus*, remained
995 undetected until its identification by Chisholm and colleagues in 1988 (Chisholm et al., 1988),
996 illustrating the consequences of such observational gaps. The GOES filter is therefore well positioned
997 to provide an initial, broad characterisation of this small size fraction, for which almost no open-
998 ocean data currently exist.

999 **Plastic contamination.** Both plastic fibres and microplastic granular particles, as optically
1000 classified, were recorded throughout the survey area, with fibres substantially outnumbering
1001 granular particles. Rivers are estimated to carry 0.8 to 2.7 million tonnes of plastic into the ocean

1002 each year (Meijer et al., 2021), and total leakage to the ocean was about 1.7 million tonnes in 2019
1003 (OECD, 2022). The laundering of synthetic textiles represents a major and under-appreciated
1004 pathway of fibre release, and Sect. 4.3 presents an illustrative extrapolation of the resulting fibre
1005 burden; wastewater treatment does not achieve complete fibre removal, and fibres retained within
1006 treatment systems may re-enter the environment through the land application or disposal of sewage
1007 sludge.

1008 **Dark opaque particles.** Particles of the dark class were recorded throughout the survey area, and
1009 they dominate the total anthropogenic particle load. No prior baseline exists for this region and size
1010 fraction, so these concentrations cannot yet be judged high or low against any reference condition.
1011 Carbonaceous particles are known to adsorb and concentrate lipophilic persistent organic pollutants
1012 from the surrounding water column and may transport these contaminants through the
1013 atmosphere, returning them to terrestrial and aquatic environments via wet deposition; Sect. 4.3
1014 presents an illustrative global extrapolation of this burden, representing an aspect of marine science
1015 that warrants considerably greater investigative attention.

1016 **Lessons for the next crossing.** This first crossing is offered as a preliminary study and a set of
1017 lessons rather than as a finished protocol, and the next crossing will make the following change. A
1018 subset of filters will be dried and sealed in airtight containers, after that preservation method has
1019 itself been tested, so that particles classed as dark or plastic can be checked by FTIR or Raman
1020 spectroscopy on land.

1021 Cutting carbon dioxide emissions addresses ocean acidification, but on its own this would not
1022 remove black carbon, lipophilic persistent pollutants and plastic from the ocean or restore the
1023 microlayer, because those materials act through biogeochemical and ecotoxicological pathways that
1024 are distinct from those of carbon dioxide.

1025 Marine primary producers, dominated by phytoplankton, hold only about 1 Gt of carbon as standing
1026 biomass (Bar-On et al., 2018). They replace that stock in about one day under favourable photic
1027 conditions in tropical and subtropical waters (Laws, 2013). Rapid turnover means that marine
1028 primary production is roughly equal to terrestrial primary production and that a small standing
1029 stock sustains the whole marine food web (Bar-On et al., 2018). On that basis they could be
1030 considered the life support system for marine life and, through the carbon exported to depth, for the
1031 entire planet. The same rapid turnover allows for recovery within days after relieving toxic pressure,
1032 and it also enables a similarly rapid decline when toxicant loading continues to rise.

1033 Reductions in marine pollution may yield climate-relevant co-benefits through the protection of
1034 biological productivity and may also support ecosystem recovery in a manner complementary to
1035 reducing carbon dioxide emissions.

1036 The GOES filter allows this data to be collected, upon which informed decisions and actions could be
1037 implemented to help protect marine life, nature and public health, and to test whether the surface
1038 microlayer mechanism raised in Sect. 4.4 has a climate role.

1039

1040 **6. Code availability**

1041 The data-processing and figure-generation code used to produce the figures, tables and reference list
1042 of this study is openly archived at Zenodo (<https://doi.org/10.5281/zenodo.21477681>). The particle-
1043 classification image pipeline, including the frame-curation stage, detection, sizing, classification and
1044 aggregation scripts and their complete per-image output, is deposited in the same Zenodo record;
1045 the analysis can be reproduced end to end from the archived images with no additional code. The
1046 code described here and the data described in Sect. 7 are deposited together in that single Zenodo
1047 record, so cross-references to either section point to the same deposit.

1048 **7. Data availability**

1049 The complete data set underlying this study, comprising the per-station particle counts, the
1050 individual particle-size measurements and the crew field logs, is openly archived in the Zenodo
1051 repository (<https://doi.org/10.5281/zenodo.21477681>; Dryden, 2026). The record contains the
1052 complete re-analysis package: the analysis scripts, the per-image census, the frame-curation list
1053 with a stated reason for every excluded file, the station-level table, and the original workbook
1054 (GOES_ALL_DATA.xlsx), which is retained for the record. The crew's hand-logs are included for
1055 transparency; because visual identification of small, degraded particles by non-specialists is
1056 subjective, these hand counts are provided as qualitative context only and are not used in the
1057 quantitative analysis, which rests on the deposited image pipeline and the surface net tow. The
1058 volunteer field guide describing the sampler build and protocol is available at
1059 <https://goesfoundation.com/water-sampling-field-guide-for-volunteers/>, and an archived copy has
1060 been added to the same Zenodo record so that the specification does not depend on a live URL. The
1061 MODIS-Aqua monthly chlorophyll-a product used for Fig. 6 (erdMH1chlamday) is freely available
1062 from NASA Ocean Colour and from the NOAA CoastWatch ERDDAP server. The ESA Ocean Colour
1063 CCI v6.0 chlorophyll-a and Kd490 records used for Fig. 7 are served by the Plymouth Marine
1064 Laboratory THREDDS server, and the MODIS-Aqua Kd490 R2018.0 record by the NOAA OceanWatch
1065 ERDDAP server.

1066 **8. Author contribution**

1067 H.D. conceived and led the GOES project, designed the sampling protocol, and led the analysis and
1068 writing. D.D. contributed to the study design and to the manuscript and served as the second scorer
1069 for the blind classification check. The authors skippered the sailing vessel Copepod, which provided
1070 the GPS-tagged reference crossing. The participating vessel crews collected the remaining field

1071 samples and microscope images. All authors reviewed the manuscript in full and approved the final
1072 version for submission.

1073 **9. Competing interests**

1074 The authors are associated with the GOES Foundation, a not-for-profit organisation originally based
1075 on the sailing vessel Copepod and now located at www.seahorsepoint.org in Bocas del Toro, Panama.
1076 Howard Dryden designed the GOES filter that this paper evaluates. They declare that they have no
1077 financial competing interests to report. Readers should nevertheless weigh the fact that the
1078 reputation of the GOES filter and of the Foundation that promotes it benefits from a favourable
1079 assessment.

1080 **10. Acknowledgements**

1081 We thank the volunteer skippers and crews of the participating vessels (Copepod, Emma, Misty Blue,
1082 Eleuthera, Yolo, Ya, Jiyu, Imagine, Meander, Elixir, Thetis, Sunflower and Ari), without whom this
1083 survey would not have been possible; the Viking Explorers yacht rally
1084 (www.vikingexplorersrally.com) for allowing us to work with their clients to recruit the survey
1085 yachts; Dr Jesús Ramón Barriuso Díez (Calplas, Basque Country, Spain) for help to design and
1086 manufacture the sampling filter; and the editor and reviewers for their constructive assessment,
1087 which materially improved the manuscript. A generative AI system (Anthropic's Claude) was used
1088 under the authors' direction for the image-analysis pipeline code, the curation and eye-check
1089 statistics, the inter-scorer agreement calculation, the longitudinal regressions, the figure generation,
1090 literature checks and copy editing; all data, interpretations and conclusions are the authors' own,
1091 and the authors reviewed, verified and take full responsibility for all content.

1092 **11. Financial support**

1093 This research received no specific grant from any public, commercial or not-for-profit funding
1094 agency. Volunteer citizen-science crews conducted the fieldwork, with support from the GOES
1095 Foundation.

1096 **12. References**

1097 Aeschlimann, M., Li, G., Kanji, Z. A., and Mitrano, D. M.: Potential impacts of atmospheric
1098 microplastics and nanoplastics on cloud formation processes, *Nat. Geosci.*, 15, 967–975,
1099 <https://doi.org/10.1038/s41561-022-01051-9>, 2022.

1100 Aiken, J., Rees, N., Hooker, S., Holligan, P., Bale, A., Robins, D., Moore, G., Harris, R., and Pilgrim, D.:
1101 The Atlantic Meridional Transect: overview and synthesis of data, *Prog. Oceanogr.*, 45, 257–312,
1102 [https://doi.org/10.1016/S0079-6611\(00\)00005-7](https://doi.org/10.1016/S0079-6611(00)00005-7), 2000.

1103 Al-Aidaros, A. M., El-Sherbiny, M. M., Satheesh, S., Mantha, G., Agustí, S., Carreja, B., and Duarte, C.
1104 M.: Strong sensitivity of Red Sea zooplankton to UV-B radiation, *Estuaries Coasts*, 38, 846–853,
1105 <https://doi.org/10.1007/s12237-014-9868-4>, 2015.

1106 Allen, S., Allen, D., Phoenix, V. R., Le Roux, G., Jiménez, P. D., Simonneau, A., Binet, S., and Galop, D.:
1107 Atmospheric transport and deposition of microplastics in a remote mountain catchment, *Nat.*
1108 *Geosci.*, 12, 339–344, <https://doi.org/10.1038/s41561-019-0335-5>, 2019.

1109 Aves, A. R., Revell, L. E., Gaw, S., Ruffell, H., Schuddeboom, A., Wotherspoon, N. E., LaRue, M., and
1110 McDonald, A. J.: First evidence of microplastics in Antarctic snow, *Cryosphere*, 16, 2127–2145,
1111 <https://doi.org/10.5194/tc-16-2127-2022>, 2022.

1112 Bar-On, Y. M., Phillips, R., and Milo, R.: The biomass distribution on Earth, *Proc. Natl Acad. Sci. USA*,
1113 115, 6506–6511, <https://doi.org/10.1073/pnas.1711842115>, 2018.

1114 Barbeau, K., Moffett, J. W., Caron, D. A., Croot, P. L., and Erdner, D. L.: Role of protozoan grazing in
 1115 relieving iron limitation of phytoplankton, *Nature*, 380, 61–64, <https://doi.org/10.1038/380061a0>,
 1116 1996.

1117 Bergmann, M., Mützel, S., Primpke, S., Tekman, M. B., Trachsel, J., and Gerdts, G.: White and
 1118 wonderful? Microplastics prevail in snow from the Alps to the Arctic, *Sci. Adv.*, 5, eaax1157,
 1119 <https://doi.org/10.1126/sciadv.aax1157>, 2019.

1120 Boltovskoy, D., Kling, S. A., Takahashi, K., and Bjørklund, K.: World atlas of distribution of recent
 1121 Polycystina (Radiolaria), *Palaeontol. Electron.*, 13, 13.3.18A, 2010.

1122 Bond, T. C., Doherty, S. J., Fahey, D. W., Forster, P. M., Berntsen, T., DeAngelo, B. J., Flanner, M. G.,
 1123 Ghan, S., Kärcher, B., Koch, D., Kinne, S., Kondo, Y., Quinn, P. K., Sarofim, M. C., Schultz, M. G., Schulz,
 1124 M., Venkataraman, C., Zhang, H., Zhang, S., Bellouin, N., Guttikunda, S. K., Hopke, P. K., Jacobson, M.
 1125 Z., Kaiser, J. W., Klimont, Z., Lohmann, U., Schwarz, J. P., Shindell, D., Storelvmo, T., Warren, S. G., and
 1126 Zender, C. S.: Bounding the role of black carbon in the climate system, *J. Geophys. Res. Atmos.*, 118,
 1127 5380–5552, <https://doi.org/10.1002/jgrd.50171>, 2013.

1128 Brahney, J., Mahowald, N., Prank, M., Cornwell, G., Klimont, Z., Matsui, H., and Prather, K. A.:
 1129 Constraining the atmospheric limb of the plastic cycle, *Proc. Natl Acad. Sci. USA*, 118, e2020719118,
 1130 <https://doi.org/10.1073/pnas.2020719118>, 2021.

1131 China, S., Scarnato, B., Owen, R. C., Zhang, B., Ampadu, M. T., Kumar, S., Dzepina, K., Dziobak, M. P.,
 1132 Fialho, P., Perlinger, J. A., Hueber, J., Helmig, D., Mazzoleni, L. R., and Mazzoleni, C.: Morphology and
 1133 mixing state of aged soot particles at a remote marine free troposphere site: implications for optical
 1134 properties, *Geophys. Res. Lett.*, 42, 1243–1250, <https://doi.org/10.1002/2014GL062404>, 2015.

1135 Chisholm, S. W., Olson, R. J., Zettler, E. R., Goericke, R., Waterbury, J. B., and Welschmeyer, N. A.: A
 1136 novel free-living prochlorophyte abundant in the oceanic euphotic zone, *Nature*, 334, 340–343,
 1137 <https://doi.org/10.1038/334340a0>, 1988.

1138 Cornelissen, G., Gustafsson, Ö., Bucheli, T. D., Jonker, M. T. O., Koelmans, A. A., and van Noort, P. C.
 1139 M.: Extensive sorption of organic compounds to black carbon, coal, and kerogen in sediments and
 1140 soils: mechanisms and consequences for distribution, bioaccumulation, and biodegradation,
 1141 *Environ. Sci. Technol.*, 39, 6881–6895, <https://doi.org/10.1021/es050191b>, 2005.

1142 Cózar, A., Echevarría, F., González-Gordillo, J. I., Irigoien, X., Úbeda, B., Hernández-León, S., Palma, Á.
 1143 T., Navarro, S., García-de-Lomas, J., Ruiz, A., Fernández-de-Puelles, M. L., and Duarte, C. M.: Plastic
 1144 debris in the open ocean, *Proc. Natl Acad. Sci. USA*, 111, 10239–10244,
 1145 <https://doi.org/10.1073/pnas.1314705111>, 2014.

1146 Cunliffe, M. and Murrell, J. C.: The sea-surface microlayer is a gelatinous biofilm, *ISME J.*, 3, 1001–
 1147 1003, <https://doi.org/10.1038/ismej.2009.69>, 2009.

1148 Cunliffe, M., Engel, A., Frka, S., Gašparović, B., Guitart, C., Murrell, J. C., Salter, M., Stolle, C., Upstill-
 1149 Goddard, R., and Wurl, O.: Sea surface microlayers: a unified physicochemical and biological
 1150 perspective, *Prog. Oceanogr.*, 109, 104–116, <https://doi.org/10.1016/j.pocean.2012.08.004>, 2013.

1151 De Falco, F., Di Pace, E., Cocca, M., and Avella, M.: The contribution of washing processes of synthetic
 1152 clothes to microplastic pollution, *Sci. Rep.*, 9, 6633, <https://doi.org/10.1038/s41598-019-43023-x>, 2019.

1153 Desforges, J.-P. W., Galbraith, M., and Ross, P. S.: Ingestion of microplastics by zooplankton in the NE
 1154 Pacific, *Arch. Environ. Contam. Toxicol.*, 69, 320–330, <https://doi.org/10.1007/s00244-015-0172-5>,
 1155 2015.

1156 Devault, D. A., Pierre, R., Marfaing, H., Dolique, F., and Lopez, P.-J.: Sargassum contamination and
 1157 consequences for downstream uses: a review, *J. Appl. Phycol.*, 33, 567–602,
 1158 <https://doi.org/10.1007/s10811-020-02250-w>, 2021.

1159 Dittmar, S., Weyrauch, S., Reemtsma, T., Eisentraut, P., Altmann, K., Ruhl, A. S., and Jekel, M.: Settling
 1160 velocities of tire and road wear particles: analysing finely graded density fractions of samples from a
 1161 road simulator and a highway tunnel, *Environ. Sci. Technol.*, 59, 13434–13446,
 1162 <https://doi.org/10.1021/acs.est.5c04165>, 2025.

1163 Dryden, H.: Zooplankton, phytoplankton and pervasive anthropogenic particles along a zonal North
 1164 Atlantic transect: a multi-vessel citizen-science image survey [data set], Zenodo,
 1165 <https://doi.org/10.5281/zenodo.21477681>, 2026.

1166 Ebling, A. M. and Landing, W. M.: Trace elements in the sea surface microlayer: rapid responses to
 1167 changes in aerosol deposition, *Elem. Sci. Anth.*, 5, 42, <https://doi.org/10.1525/elementa.237>, 2017.

1168 Edzwald, J. K. and Haarhoff, J.: Seawater pretreatment for reverse osmosis: chemistry, contaminants,
 1169 and coagulation, *Water Res.*, 45, 5428–5440, <https://doi.org/10.1016/j.watres.2011.08.014>, 2011.

1170 Engel, A., Bange, H. W., Cunliffe, M., Burrows, S. M., Friedrichs, G., Galgani, L., Herrmann, H.,
 1171 Hertkorn, N., Johnson, M., Liss, P. S., Quinn, P. K., Schartau, M., Soloviev, A., Stolle, C., Upstill-
 1172 Goddard, R. C., van Pinxteren, M., and Zäncker, B.: The ocean’s vital skin: toward an integrated
 1173 understanding of the sea surface microlayer, *Front. Mar. Sci.*, 4, 165,
 1174 <https://doi.org/10.3389/fmars.2017.00165>, 2017.

1175 Erni-Cassola, G., Zadjelovic, V., Gibson, M. I., and Christie-Oleza, J. A.: Distribution of plastic polymer
 1176 types in the marine environment: a meta-analysis, *J. Hazard. Mater.*, 369, 691–698,
 1177 <https://doi.org/10.1016/j.jhazmat.2019.02.067>, 2019.

1178 Evangeliou, N., Grythe, H., Klimont, Z., Heyes, C., Eckhardt, S., Lopez-Aparicio, S., and Stohl, A.:
 1179 Atmospheric transport is a major pathway of microplastics to remote regions, *Nat. Commun.*, 11,
 1180 3381, <https://doi.org/10.1038/s41467-020-17201-9>, 2020.

1181 Feinstein, A. R. and Cicchetti, D. V.: High agreement but low kappa: I. The problems of two
 1182 paradoxes, *J. Clin. Epidemiol.*, 43, 543–549, [https://doi.org/10.1016/0895-4356\(90\)90158-L](https://doi.org/10.1016/0895-4356(90)90158-L), 1990.

1183 Fernández de Puelles, M. L., Gazá, M., Cabanellas-Reboredo, M., Santandreu, M. del M., Irigoien, X.,
 1184 González-Gordillo, J. I., Duarte, C. M., and Hernández-León, S.: Zooplankton abundance and diversity
 1185 in the tropical and subtropical ocean, *Diversity*, 11, 203, <https://doi.org/10.3390/d11110203>, 2019.

1186 Flombaum, P., Gallegos, J. L., Gordillo, R. A., Rincón, J., Zabala, L. L., Jiao, N., Karl, D. M., Li, W. K. W.,
 1187 Lomas, M. W., Veneziano, D., Vera, C. S., Vrugt, J. A., and Martiny, A. C.: Present and future global
 1188 distributions of the marine Cyanobacteria *Prochlorococcus* and *Synechococcus*, *Proc. Natl Acad. Sci.*
 1189 *USA*, 110, 9824–9829, <https://doi.org/10.1073/pnas.1307701110>, 2013.

1190 Fock, H. O., Andresen, H., Bertrand, A., Farias, G. B., Carré, C., Couret, M., Díaz-Pérez, J., Dudeck, T.,
 1191 Dugenne, M., Duncan, S., Figueiredo, G. G. A. A., Frédou, T., Lucena-Frédou, F., Díaz, X. F. G., Yemane,
 1192 D., González-García, C., Kiko, R., Landeira, J. M., Lira, S. M. A., Lüskow, F., Marañón, E., de Castro
 1193 Melo, P. A. M., Neumann-Leitao, S., Eduardo, L. N., Stemmann, L., and Schwamborn, R.: Synthetic
 1194 pelagic biomass size spectra of the tropical and subtropical Atlantic, *Ecosphere*, 17, e70608,
 1195 <https://doi.org/10.1002/ecs2.70608>, 2026.

1196 Fuller, R., Landrigan, P. J., Balakrishnan, K., Bathan, G., Bose-O'Reilly, S., Brauer, M., Caravanos, J.,
 1197 Chiles, T., Cohen, A., Corra, L., Cropper, M., Ferraro, G., Hanna, J., Hanrahan, D., Hu, H., Hunter, D.,
 1198 Janata, G., Kupka, R., Lanphear, B., Lichtveld, M., Martin, K., Mustapha, A., Sanchez-Triana, E.,
 1199 Sandilya, K., Schaefli, L., Shaw, J., Seddon, J., Suk, W., Téllez-Rojo, M. M., and Yan, C.: Pollution and

1200 health: a progress update, *Lancet Planet. Health*, 6, e535–e547, <https://doi.org/10.1016/S2542->
1201 5196(22)00090-0, 2022.

1202 Gao, Z., Cizdziel, J. V., Wontor, K., Clisham, C., Focia, K., Rausch, J., and Jaramillo-Vogel, D.: On
1203 airborne tire wear particles along roads with different traffic characteristics using passive sampling
1204 and optical microscopy, single particle SEM/EDX, and μ -ATR-FTIR analyses, *Front. Environ. Sci.*, 10,
1205 1022697, <https://doi.org/10.3389/fenvs.2022.1022697>, 2022.

1206 Garrett, W. D.: The organic chemical composition of the ocean surface, *Deep-Sea Res.*, 14, 221–227,
1207 [https://doi.org/10.1016/0011-7471\(67\)90007-1](https://doi.org/10.1016/0011-7471(67)90007-1), 1967.

1208 Geyer, R., Jambeck, J. R., and Law, K. L.: Production, use, and fate of all plastics ever made, *Sci. Adv.*, 3,
1209 e1700782, <https://doi.org/10.1126/sciadv.1700782>, 2017.

1210 Gilgen, A., Adolf, C., Brugger, S. O., Ickes, L., Schwikowski, M., van Leeuwen, J. F. N., Tinner, W., and
1211 Lohmann, U.: Implementing microscopic charcoal particles into a global aerosol–climate model,
1212 *Atmos. Chem. Phys.*, 18, 11813–11829, <https://doi.org/10.5194/acp-18-11813-2018>, 2018.

1213 GOES Foundation: Water sampling field guide for volunteers, [https://goesfoundation.com/water-](https://goesfoundation.com/water-sampling-field-guide-for-volunteers/)
1214 [sampling-field-guide-for-volunteers/](https://goesfoundation.com/water-sampling-field-guide-for-volunteers/), last access: 19 August 2026, 2026.

1215 Goldenberg, S. B. and Shapiro, L. J.: Physical mechanisms for the association of El Niño and West
1216 African rainfall with Atlantic major hurricane activity, *J. Climate*, 9, 1169–1187,
1217 [https://doi.org/10.1175/1520-0442\(1996\)009<1169:PMFTA0>2.0.CO;2](https://doi.org/10.1175/1520-0442(1996)009<1169:PMFTA0>2.0.CO;2), 1996.

1218 Goßmann, I., Herzke, D., Held, A., Schulz, J., Nikiforov, V., Georgi, C., Evangeliou, N., Eckhardt, S.,
1219 Gerdt, G., Wurl, O., and Scholz-Böttcher, B. M.: Occurrence and backtracking of microplastic mass
1220 loads including tire wear particles in northern Atlantic air, *Nat. Commun.*, 14, 3707,
1221 <https://doi.org/10.1038/s41467-023-39340-5>, 2023a.

1222 Goßmann, I., Mattsson, K., Hassellöv, M., Crazzolara, C., Held, A., Robinson, T. B., Wurl, O., and
 1223 Scholz-Böttcher, B. M.: Unraveling the marine microplastic cycle: the first simultaneous data set for
 1224 air, sea surface microlayer, and underlying water, *Environ. Sci. Technol.*, 57, 16541–16551,
 1225 <https://doi.org/10.1021/acs.est.3c05002>, 2023b.

1226 Gower, J. and King, S.: Distribution of floating Sargassum in the Gulf of Mexico and the Atlantic
 1227 Ocean mapped using MERIS, *Int. J. Remote Sens.*, 32, 1917–1929,
 1228 <https://doi.org/10.1080/01431161003639660>, 2011.

1229 Han, Y. M., Cao, J., Lee, S. C., Ho, K. F., and An, Z. S.: Different characteristics of char and soot in the
 1230 atmosphere and their ratio as an indicator for source identification in Xi'an, China, *Atmos. Chem.*
 1231 *Phys.*, 10, 595–607, <https://doi.org/10.5194/acp-10-595-2010>, 2010.

1232 Held, I. M. and Soden, B. J.: Water vapor feedback and global warming, *Annu. Rev. Energy Environ.*,
 1233 25, 441–475, <https://doi.org/10.1146/annurev.energy.25.1.441>, 2000.

1234 Holdway, P. and Maddock, L.: A comparative survey of neuston: geographical and temporal
 1235 distribution patterns, *Mar. Biol.*, 76, 263–270, <https://doi.org/10.1007/BF00393027>, 1983.

1236 Hopkins, T. L.: The vertical distribution of zooplankton in the eastern Gulf of Mexico, *Deep-Sea Res.*
 1237 *Pt. A*, 29, 1069–1083, [https://doi.org/10.1016/0198-0149\(82\)90028-0](https://doi.org/10.1016/0198-0149(82)90028-0), 1982.

1238 Huang, Y., Kok, J. F., Saito, M., and Muñoz, O.: Single-scattering properties of ellipsoidal dust aerosols
 1239 constrained by measured dust shape distributions, *Atmos. Chem. Phys.*, 23, 2557–2577,
 1240 <https://doi.org/10.5194/acp-23-2557-2023>, 2023.

1241 Hunt, B. P. V. and Hosie, G. W.: Continuous Plankton Recorder flow rates revisited: clogging, ship
 1242 speed and flow meter design, *J. Plankton Res.*, 28, 847–855, <https://doi.org/10.1093/plankt/fbl020>,
 1243 2006.

1244 IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth
 1245 Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press,
 1246 Cambridge, UK and New York, NY, USA, 2013.

1247 Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W.,
 1248 Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P. S., Mahowald, N., Prospero, J.
 1249 M., Ridgwell, A. J., Tegen, I., and Torres, R.: Global iron connections between desert dust, ocean
 1250 biogeochemistry, and climate, *Science*, 308, 67–71, <https://doi.org/10.1126/science.1105959>, 2005.

1251 Johnsen, S. and Widder, E. A.: Ultraviolet absorption in transparent zooplankton and its implications
 1252 for depth distribution and visual predation, *Mar. Biol.*, 138, 717–730,
 1253 <https://doi.org/10.1007/s002270000499>, 2001.

1254 Jonas, T. D., Walne, A., Beaugrand, G., Gregory, L., and Hays, G. C.: The volume of water filtered by a
 1255 Continuous Plankton Recorder sample: the effect of ship speed, *J. Plankton Res.*, 26, 1499–1506,
 1256 <https://doi.org/10.1093/plankt/fbh137>, 2004.

1257 Kandler, K., Lieke, K., Benker, N., Emmel, C., Küpper, M., Müller-Ebert, D., Ebert, M., Scheuven, D.,
 1258 Schladitz, A., Schütz, L., and Weinbruch, S.: Electron microscopy of particles collected at Praia, Cape
 1259 Verde, during the Saharan Mineral Dust Experiment: particle chemistry, shape, mixing state and
 1260 complex refractive index, *Tellus B*, 63, 475–496, <https://doi.org/10.1111/j.1600-0889.2011.00550.x>,
 1261 2011.

1262 Kaufman, Y. J., Koren, I., Remer, L. A., Tanré, D., Ginoux, P., and Fan, S.: Dust transport and
 1263 deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS)
 1264 spacecraft over the Atlantic Ocean, *J. Geophys. Res.*, 110, D10S12,
 1265 <https://doi.org/10.1029/2003JD004436>, 2005.

1266 Koelmans, A. A., Bakir, A., Burton, G. A., and Janssen, C. R.: Microplastic as a vector for chemicals in
 1267 the aquatic environment: critical review and model-supported reinterpretation of empirical studies,
 1268 *Environ. Sci. Technol.*, 50, 3315–3326, <https://doi.org/10.1021/acs.est.5b06069>, 2016.

1269 Kole, P. J., Löhr, A. J., Van Belleghem, F. G. A. J., and Ragas, A. M. J.: Wear and tear of tyres: a stealthy
 1270 source of microplastics in the environment, *Int. J. Environ. Res. Public Health*, 14, 1265,
 1271 <https://doi.org/10.3390/ijerph14101265>, 2017.

1272 Kooi, M., van Nes, E. H., Scheffer, M., and Koelmans, A. A.: Ups and downs in the ocean: effects of
 1273 biofouling on vertical transport of microplastics, *Environ. Sci. Technol.*, 51, 7963–7971,
 1274 <https://doi.org/10.1021/acs.est.6b04702>, 2017.

1275 Kovochich, M., Liong, M., Parker, J. A., Oh, S. C., Lee, J. P., Xi, L., Kreider, M. L., and Unice, K. M.:
 1276 Chemical mapping of tire and road wear particles for single particle analysis, *Sci. Total Environ.*, 757,
 1277 144085, <https://doi.org/10.1016/j.scitotenv.2020.144085>, 2021.

1278 Kukulka, T., Proskurowski, G., Morét-Ferguson, S., Meyer, D. W., and Law, K. L.: The effect of wind
 1279 mixing on the vertical distribution of buoyant plastic debris, *Geophys. Res. Lett.*, 39, L07601,
 1280 <https://doi.org/10.1029/2012GL051116>, 2012.

1281 Kvale, K., Prowe, A. E. F., Chien, C. T., Landolfi, A., and Oschlies, A.: Zooplankton grazing of
 1282 microplastic can accelerate global loss of ocean oxygen, *Nat. Commun.*, 12, 2358,
 1283 <https://doi.org/10.1038/s41467-021-22554-w>, 2021.

1284 Landis, J. R. and Koch, G. G.: The measurement of observer agreement for categorical data,
 1285 *Biometrics*, 33, 159–174, <https://doi.org/10.2307/2529310>, 1977.

1286 Landrigan, P. J., Stegeman, J. J., Fleming, L. E., Allemand, D., Anderson, D. M., Backer, L. C., Brucker-
 1287 Davis, F., Chevalier, N., Corra, L., Czerucka, D., Bottein, M.-Y. D., Demeneix, B., Depledge, M., Deheyn,

1288 D. D., Dorman, C. J., Fénichel, P., Fisher, S., Gaill, F., Galgani, F., Gaze, W. H., Giuliano, L., Grandjean, P.,
 1289 Hahn, M. E., Hamdoun, A., Hess, P., Judson, B., Laborde, A., McGlade, J., Mu, J., Mustapha, A., Neira,
 1290 M., Noble, R. T., Pedrotti, M. L., Reddy, C., Rocklöv, J., Scharler, U. M., Shanmugam, H., Taghian, G.,
 1291 van de Water, J. A. J. M., Vezzulli, L., Weihe, P., Zeka, A., Raps, H., and Rampal, P.: Human health and
 1292 ocean pollution, *Ann. Glob. Health*, 86, 151, <https://doi.org/10.5334/aogh.2831>, 2020.

1293 Lapointe, B. E., Brewton, R. A., Herren, L. W., Wang, M., Hu, C., McGillicuddy, D. J., Lindell, S.,
 1294 Hernandez, F. J., and Morton, P. L.: Nutrient content and stoichiometry of pelagic Sargassum reflects
 1295 increasing nitrogen availability in the Atlantic Basin, *Nat. Commun.*, 12, 3060,
 1296 <https://doi.org/10.1038/s41467-021-23135-7>, 2021.

1297 Larsen, P. S. and Riisgård, H. U.: Viscosity and not biological mechanisms often controls the effects of
 1298 temperature on ciliary activity and swimming velocity of small aquatic organisms, *J. Exp. Mar. Biol.*
 1299 *Ecol.*, 381, 67–73, <https://doi.org/10.1016/j.jembe.2009.09.021>, 2009.

1300 Law, K. L., Morét-Ferguson, S., Maximenko, N. A., Proskurowski, G., Peacock, E. E., Hafner, J., and
 1301 Reddy, C. M.: Plastic accumulation in the North Atlantic subtropical gyre, *Science*, 329, 1185–1188,
 1302 <https://doi.org/10.1126/science.1192321>, 2010.

1303 Laws, E. A.: Evaluation of in situ phytoplankton growth rates: a synthesis of data from varied
 1304 approaches, *Annu. Rev. Mar. Sci.*, 5, 247–268, [https://doi.org/10.1146/annurev-marine-121211-](https://doi.org/10.1146/annurev-marine-121211-172258)
 1305 [172258](https://doi.org/10.1146/annurev-marine-121211-172258), 2013.

1306 Lee, W.-K., Sim, Y., Ju, S.-J., Kim, D., Jeong, J., and Kim, S.-J.: Oceanic determinants of microplastic
 1307 bioaccumulation in fauna of deep-sea hydrothermal vents: comparative study of the southwestern
 1308 Pacific and Indian Oceans, *Water Res.*, 303, 126245, <https://doi.org/10.1016/j.watres.2026.126245>,
 1309 2026.

1310 Li, L., Chen, C., Li, D., Breivik, K., Abbasi, G., and Li, Y.-F.: What do we know about the production and
 1311 release of persistent organic pollutants in the global environment?, *Environ. Sci.: Adv.*, 2, 55–68,
 1312 <https://doi.org/10.1039/d2va00145d>, 2023.

1313 Löder, M. G. J. and Gerdts, G.: Methodology used for the detection and identification of microplastics:
 1314 a critical appraisal, in: *Marine Anthropogenic Litter*, edited by: Bergmann, M., Gutow, L., and Klages,
 1315 M., Springer, Cham, 201–227, https://doi.org/10.1007/978-3-319-16510-3_8, 2015.

1316 Ma, H., Pu, S., Liu, S., Bai, Y., Mandal, S., and Xing, B.: Microplastics in aquatic environments: toxicity
 1317 to trigger ecological consequences, *Environ. Pollut.*, 261, 114089,
 1318 <https://doi.org/10.1016/j.envpol.2020.114089>, 2020.

1319 Mato, Y., Isobe, T., Takada, H., Kanehiro, H., Ohtake, C., and Kaminuma, T.: Plastic resin pellets as a
 1320 transport medium for toxic chemicals in the marine environment, *Environ. Sci. Technol.*, 35, 318–
 1321 324, <https://doi.org/10.1021/es0010498>, 2001.

1322 McGillicuddy, D. J., Morton, P. L., Brewton, R. A., Hu, C., Kelly, T. B., Solow, A. R., and Lapointe, B. E.:
 1323 Nutrient and arsenic biogeochemistry of Sargassum in the western Atlantic, *Nat. Commun.*, 14, 6205,
 1324 <https://doi.org/10.1038/s41467-023-41904-4>, 2023.

1325 McQuatters-Gollop, A., Holland, M. M., Artigas, L. F., Louchart, A. P., Atkinson, A., Aubert, A., Best, M.,
 1326 Blauw, A., Bresnan, E., Devlin, M., Enserink, L., Faith, M. P., Goberville, E., Heyden, B., Jakobsen, H. H.,
 1327 Johansen, M., Johns, D. G., Ostle, C., Rombouts, I., Schilder, J., Tett, P., and Vincent, D.: Integrating
 1328 plankton indicators to assess the state of pelagic habitats in the Northeast Atlantic, *Ecol. Indic.*, 189,
 1329 115005, <https://doi.org/10.1016/j.ecolind.2026.115005>, 2026.

1330 Meijer, L. J. J., van Emmerik, T., van der Ent, R., Schmidt, C., and Lebreton, L.: More than 1000 rivers
 1331 account for 80% of global riverine plastic emissions into the ocean, *Sci. Adv.*, 7, eaaz5803,
 1332 <https://doi.org/10.1126/sciadv.aaz5803>, 2021.

1333 Mériquet, Z., Bourdin, G., Jalabert, L., Bun, O., Caray-Counil, L., Elineau, A., Gorsky, G., and Lombard,
 1334 F.: Global scale surface meso-plankton dataset collected with High-Speed Net and imaged with
 1335 ZooScan during the Tara Pacific Expedition, SEANOE [data set], <https://doi.org/10.17882/102336>,
 1336 2024.

1337 Mériquet, Z., Bourdin, G., Kristan, N., Jalabert, L., Bun, O., Picheral, M., Caray-Counil, L., Maury, J.,
 1338 Pedrotti, M.-L., Elineau, A., Paz-Garcia, D. A., Karp-Boss, L., Gorsky, G., Lombard, F., and the Tara
 1339 Pacific Consortium Coordinators team: Quantitative imaging datasets of surface micro- to
 1340 mesoplankton communities and microplastic across the Pacific and North Atlantic oceans from the
 1341 Tara Pacific expedition, *Earth Syst. Sci. Data*, 17, 2761–2792, <https://doi.org/10.5194/essd-17-2761->
 1342 2025, 2025.

1343 Mills, M. M., Ridame, C., Davey, M., La Roche, J., and Geider, R. J.: Iron and phosphorus co-limit
 1344 nitrogen fixation in the eastern tropical North Atlantic, *Nature*, 429, 292–294,
 1345 <https://doi.org/10.1038/nature02550>, 2004.

1346 Moore, C. M., Mills, M. M., Arrigo, K. R., Berman-Frank, I., Bopp, L., Boyd, P. W., Galbraith, E. D.,
 1347 Geider, R. J., Guieu, C., Jaccard, S. L., Jickells, T. D., La Roche, J., Lenton, T. M., Mahowald, N. M.,
 1348 Marañón, E., Marinov, I., Moore, J. K., Nakatsuka, T., Oschlies, A., Saito, M. A., Thingstad, T. F., Tsuda,
 1349 A., and Ulloa, O.: Processes and patterns of oceanic nutrient limitation, *Nat. Geosci.*, 6, 701–710,
 1350 <https://doi.org/10.1038/ngeo1765>, 2013.

1351 Murphy, E. L., Baechler, B. R., Roman, L., Leonard, G. H., Mallos, N. J., Santos, R. G., and Rochman, C.
 1352 M.: A quantitative risk assessment framework for mortality due to macroplastic ingestion in

1353 seabirds, marine mammals, and sea turtles, *Proc. Natl Acad. Sci. USA*, 122, e2415492122,
 1354 <https://doi.org/10.1073/pnas.2415492122>, 2025.

1355 Mustaffa, N. I. H., Ribas-Ribas, M., Banko-Kubis, H. M., and Wurl, O.: Global reduction of in situ CO₂
 1356 transfer velocity by natural surfactants in the sea-surface microlayer, *Proc. R. Soc. A*, 476, 20190763,
 1357 <https://doi.org/10.1098/rspa.2019.0763>, 2020.

1358 O'Dowd, C. D., Smith, M. H., Consterdine, I. E., and Lowe, J. A.: Marine aerosol, sea-salt and the
 1359 marine sulphur cycle, *Atmos. Environ.*, 31, 73–80, [https://doi.org/10.1016/S1352-2310\(96\)00106-9](https://doi.org/10.1016/S1352-2310(96)00106-9),
 1360 1997.

1361 O'Dowd, C. D., Facchini, M. C., Cavalli, F., Ceburnis, D., Mircea, M., Decesari, S., Fuzzi, S., Yoon, Y. J.,
 1362 and Putaud, J.-P.: Biogenically driven organic contribution to marine aerosol, *Nature*, 431, 676–680,
 1363 <https://doi.org/10.1038/nature02959>, 2004.

1364 OECD: Global Plastics Outlook: Economic Drivers, Environmental Impacts and Policy Options, OECD
 1365 Publishing, Paris, <https://doi.org/10.1787/de747aef-en>, 2022.

1366 Pabortsava, K. and Lampitt, R. S.: High concentrations of plastic hidden beneath the surface of the
 1367 Atlantic Ocean, *Nat. Commun.*, 11, 4073, <https://doi.org/10.1038/s41467-020-17932-9>, 2020.

1368 Pereira, R., Ashton, I., Sabbaghzadeh, B., Shutler, J. D., and Upstill-Goddard, R. C.: Reduced air–sea
 1369 CO₂ exchange in the Atlantic Ocean due to biological surfactants, *Nat. Geosci.*, 11, 492–496,
 1370 <https://doi.org/10.1038/s41561-018-0136-2>, 2018.

1371 Purcell, E. M.: Life at low Reynolds number, *Am. J. Phys.*, 45, 3–11, <https://doi.org/10.1119/1.10903>,
 1372 1977.

1373 Rahlff, J., Ribas-Ribas, M., Brown, S. M., Mustaffa, N. I. H., Renz, J., Peck, M. A., Bird, K., Cunliffe, M.,
 1374 Melkonian, K., and Zappa, C. J.: Blue pigmentation of neustonic copepods benefits exploitation of a

1375 prey-rich niche at the air–sea boundary, *Sci. Rep.*, 8, 11510, <https://doi.org/10.1038/s41598-018->
 1376 29869-7, 2018.

1377 Reisser, J., Slat, B., Noble, K., du Plessis, K., Epp, M., Proietti, M., de Sonnevile, J., Becker, T., and
 1378 Pattiaratchi, C.: The vertical distribution of buoyant plastics at sea: an observational study in the
 1379 North Atlantic Gyre, *Biogeosciences*, 12, 1249–1256, <https://doi.org/10.5194/bg-12-1249-2015>, 2015.

1380 Rodríguez-Martínez, R. E., Roy, P. D., Torrescano-Valle, N., Cabanillas-Terán, N., Carrillo-Domínguez,
 1381 S., Collado-Vides, L., García-Sánchez, M., and van Tussenbroek, B. I.: Element concentrations in
 1382 pelagic Sargassum along the Mexican Caribbean coast in 2018–2019, *PeerJ*, 8, e8667,
 1383 <https://doi.org/10.7717/peerj.8667>, 2020.

1384 Schmidt, G. A., Ruedy, R. A., Miller, R. L., and Lacis, A. A.: Attribution of the present-day total
 1385 greenhouse effect, *J. Geophys. Res. Atmos.*, 115, D20106, <https://doi.org/10.1029/2010JD014287>, 2010.

1386 Silva, A., Nikzad, S., Barthelmeß, T., Engel, A., Herrmann, H., van Pinxteren, M., Wirtz, K., Wurl, O.,
 1387 and Schartau, M.: Meta-analytical insights into organic matter enrichment in the surface
 1388 microlayer, *Biogeosciences*, 23, 1697–1718, <https://doi.org/10.5194/bg-23-1697-2026>, 2026.

1389 Swindles, G. T., Watson, E., Turner, T. E., Galloway, J. M., Hadlari, T., Wheeler, J., and Bacon, K. L.:
 1390 Spheroidal carbonaceous particles are a defining stratigraphic marker for the Anthropocene, *Sci.*
 1391 *Rep.*, 5, 10264, <https://doi.org/10.1038/srep10264>, 2015.

1392 Tedetti, M. and Sempéré, R.: Penetration of ultraviolet radiation in the marine environment. A
 1393 review, *Photochem. Photobiol.*, 82, 389–397, <https://doi.org/10.1562/2005-11-09-IR-733>, 2006.

1394 Tetu, S. G., Sarker, I., Schrameyer, V., Pickford, R., Elbourne, L. D. H., Moore, L. R., and Paulsen, I. T.:
 1395 Plastic leachates impair growth and oxygen production in *Prochlorococcus*, *Commun. Biol.*, 2, 184,
 1396 <https://doi.org/10.1038/s42003-019-0410-x>, 2019.

1397 Textile Exchange: Materials Market Report 2025,
 1398 <https://textileexchange.org/knowledge-center/reports/materials-market-report-2025/>, last access:
 1399 23 August 2026, 2025.

1400 Tilstone, G. H., Lange, P. K., Misra, A., Brewin, R. J. W., and Cain, T.: Micro-phytoplankton
 1401 photosynthesis, primary production and potential export production in the Atlantic Ocean, *Prog.*
 1402 *Oceanogr.*, 158, 109–129, <https://doi.org/10.1016/j.pocean.2017.01.006>, 2017.

1403 Tovar-Sánchez, A., Rodríguez-Romero, A., Engel, A., Zäncker, B., Fu, F., Marañón, E., Pérez-Lorenzo,
 1404 M., Bressac, M., Wagener, T., Triquet, S., Siour, G., Desboeufs, K., and Guieu, C.: Characterizing the
 1405 surface microlayer in the Mediterranean Sea: trace metal concentrations and microbial plankton
 1406 abundance, *Biogeosciences*, 17, 2349–2364, <https://doi.org/10.5194/bg-17-2349-2020>, 2020.

1407 Trainic, M., Flores, J. M., Pinkas, I., Pedrotti, M. L., Lombard, F., Bourdin, G., Gorsky, G., Boss, E.,
 1408 Rudich, Y., Vardi, A., and Koren, I.: Airborne microplastic particles detected in the remote marine
 1409 atmosphere, *Commun. Earth Environ.*, 1, 64, <https://doi.org/10.1038/s43247-020-00061-y>, 2020.

1410 Tréguer, P. and De La Rocha, C. L.: The World Ocean Silica Cycle, *Annu. Rev. Mar. Sci.*, 5, 477–501,
 1411 <https://doi.org/10.1146/annurev-marine-121211-172346>, 2013.

1412 Trenberth, K. E., Smith, L., Qian, T., Dai, A., and Fasullo, J.: Estimates of the Global Water Budget and
 1413 Its Annual Cycle Using Observational and Model Data, *J. Hydrometeorol.*, 8, 758–769,
 1414 <https://doi.org/10.1175/JHM600.1>, 2007.

1415 Turner, A.: Marine pollution from antifouling paint particles, *Mar. Pollut. Bull.*, 60, 159–171,
 1416 <https://doi.org/10.1016/j.marpolbul.2009.12.004>, 2010.

1417 Tyrrell, T., Merico, A., Waniek, J. J., Wong, C. S., Metzl, N., and Whitney, F.: Effect of seafloor depth on
 1418 phytoplankton blooms in HNLC regions, *J. Geophys. Res. Biogeosci.*, 110, G02007,
 1419 <https://doi.org/10.1029/2005JG000041>, 2005.

1420 van der Does, M., Korte, L. F., Munday, C. I., Brummer, G.-J. A., and Stuut, J.-B. W.: Particle size traces
 1421 modern Saharan dust transport and deposition across the equatorial North Atlantic, *Atmos. Chem.*
 1422 *Phys.*, 16, 13697–13710, <https://doi.org/10.5194/acp-16-13697-2016>, 2016.

1423 van der Jagt, H., Friese, C., Stuut, J.-B. W., Fischer, G., and Iversen, M. H.: The ballasting effect of
 1424 Saharan dust deposition on aggregate dynamics and carbon export: Aggregation, settling, and
 1425 scavenging potential of marine snow, *Limnol. Oceanogr.*, 63, 1386–1394,
 1426 <https://doi.org/10.1002/lno.10779>, 2018.

1427 Vereshchaka, A. L., Abyzova, G., Lunina, A., and Musaeva, E.: The deep-sea zooplankton of the North,
 1428 Central, and South Atlantic: Biomass, abundance, diversity, *Deep-Sea Res. II*, 137, 89–101,
 1429 <https://doi.org/10.1016/j.dsr2.2016.06.017>, 2017.

1430 Wang, M., Hu, C., Barnes, B. B., Mitchum, G., Lapointe, B., and Montoya, J. P.: The great Atlantic
 1431 Sargassum belt, *Science*, 365, 83–87, <https://doi.org/10.1126/science.aaw7912>, 2019.

1432 Williams, P. M., Carlucci, A. F., Henrichs, S. M., Van Vleet, E. S., Horrigan, S. G., Reid, F. M. H., and
 1433 Robertson, K. J.: Chemical and microbiological studies of sea-surface films, *Mar. Chem.*, 19, 17–98,
 1434 [https://doi.org/10.1016/0304-4203\(86\)90033-2](https://doi.org/10.1016/0304-4203(86)90033-2), 1986.

1435 Woodd-Walker, R. S., Ward, P., and Clarke, A.: Large-scale patterns in diversity and community
 1436 structure of surface water copepods from the Atlantic Ocean, *Mar. Ecol. Prog. Ser.*, 236, 189–203,
 1437 <https://doi.org/10.3354/meps236189>, 2002.

1438 Wurl, O. and Obbard, J. P.: A review of pollutants in the sea-surface microlayer (SML): a unique
 1439 habitat for marine organisms, *Mar. Pollut. Bull.*, 48, 1016–1030,
 1440 <https://doi.org/10.1016/j.marpolbul.2004.03.016>, 2004.

1441 Wurl, O., Ekau, W., Landing, W. M., and Zappa, C. J.: Sea surface microlayer in a changing ocean, a
 1442 perspective, *Elem. Sci. Anth.*, 5, 31, <https://doi.org/10.1525/elementa.228>, 2017.

1443 Wurl, O., Bird, K., Cunliffe, M., Landing, W. M., Miller, U. K., Mustaffa, N. I. H., Ribas-Ribas, M., Witte,
 1444 C. R., and Zappa, C. J.: Warming and inhibition of salinization at the ocean's surface by
 1445 cyanobacteria, *Geophys. Res. Lett.*, 45, 4230–4237, <https://doi.org/10.1029/2018GL077946>, 2018.

1446 Yebra, D. M., Kiil, S., and Dam-Johansen, K.: Antifouling technology—past, present and future steps
 1447 towards efficient and environmentally friendly antifouling coatings, *Prog. Org. Coat.*, 50, 75–104,
 1448 <https://doi.org/10.1016/j.porgcoat.2003.06.001>, 2004.

1449 Yu, H., Chin, M., Bian, H., Yuan, T., Prospero, J. M., Omar, A. H., Remer, L. A., Winker, D. M., Yang, Y.,
 1450 Zhang, Y., and Zhang, Z.: Quantification of trans-Atlantic dust transport from seven-year (2007–
 1451 2013) record of CALIPSO lidar measurements, *Remote Sens. Environ.*, 159, 232–249,
 1452 <https://doi.org/10.1016/j.rse.2014.12.010>, 2015.

1453 Zhang, Z., Cai, W., Liu, L., Liu, C., and Chen, F.: Direct determination of thickness of sea surface
 1454 microlayer using a pH microelectrode at original location, *Sci. China Ser. B*, 46, 339–351,
 1455 <https://doi.org/10.1360/02yb0192>, 2003.

1456 Zhou, X., Novi, L., Hay, M. E., Montoya, J. P., Aliu, A., Realff, M. J., and Bracco, A.: Changing drivers of
 1457 the Great Atlantic Sargassum Belt from physical forcing to ecological control, *Nat. Commun.*, 17,
 1458 4600, <https://doi.org/10.1038/s41467-026-72183-4>, 2026.

1459 Zhu, R., Zhang, Z., Zhang, N., Zhong, H., Zhou, F., Zhang, X., Liu, C., Huang, Y., Yuan, Y., Wang, Y., Li, C.,
1460 Shi, H., Rillig, M. C., Dang, F., Ren, H., Zhang, Y., and Xing, B.: A global estimate of multiecosystem
1461 photosynthesis losses under microplastic pollution, *Proc. Natl Acad. Sci. USA*, 122, e2423957122,
1462 <https://doi.org/10.1073/pnas.2423957122>, 2025.

1463 Ziccardi, L., Edgington, A., Hentz, K., Kulacki, K., and Driscoll, S.: Microplastics as vectors for
1464 bioaccumulation of hydrophobic organic chemicals in the marine environment: a state-of-the-
1465 science review, *Environ. Toxicol. Chem.*, 35, 1667–1676, <https://doi.org/10.1002/etc.3461>, 2016.