nature portfolio

https://doi.org/10.1038/s43017-022-00292-x

Supplementary information

Microplastics and nanoplastics in the marine-atmosphere environment

In the format provided by the authors and unedited

Title: The Atmospheric Cycle of Microplastics in the Marine Environment

Supplementary Note 1: The importance of atmospheric micro(nano)plastic transport to remote and polar regions

The remote and polar regions are natural reserve areas relatively untouched by human activity. They provide the last bastions of natural ecosystems and biodiversity. If human activities and resource exploitation results in catastrophic ecosystem collapse and biodiversity loss, these natural reserve areas provide the potential for future natural regeneration.

It is possible the microplastic and nanoplastic are not transported solely by either atmospheric transport or aquatic (ocean) transport to these remote areas and poles. Plastic particles may undergo re-entrainment multiple times in terrestrial and marine environments, resulting in long-distance transport via a cyclic entrainment-deposition-re-entrainment process. This may allow for plastic pollution to reach areas that do not have air or ocean currents feeding directly into them from polluted areas.

There is significant evidence of microplastic in the Arctic and Antarctic seas, suggesting that oceanic currents are one key source of Arctic plastic pollution[1,2] in the polar marine environment. However, while polar ice acts as a sponge, collecting marine plastic during its ice formation[3,4], the microplastic found on the surface of ice flows and snow are not directly attributable to marine conveyance. Notable microplastic quantities have been found on Arctic surfaces[5], and early studies have identified microplastic in the Antarctic atmosphere. It is suggested that these particles were either transported long-distance through the atmosphere prior to polar deposition, or were conveyed via marine currents then emitted during ocean turbulence (e.g. through the bubble burst ejection process) and atmospherically transported to the polar surface (land, glaciers or sea ice). Characterising and quantifying the atmospheric transport contribution to remote area and polar micro(nano)plastic is therefore necessary to both understand the remote areas transport processes and to model plastic pollution influx (and future scenarios) to these relatively pristine and remote locations.

Supplementary Note 2: Atmospheric microplastics and climate change

Research on micro(nano)plastic in the context of climate change is extremely limited to date. Life cycle and greenhouse gas (GHG) emission analyses show micro(nano)plastic to contribute to GHG, climate change/global warming potential and photochemical ozone formation/ozone formation[6,7]. Micro(nano)plastic lost to the environment release GHG and interfere with ocean carbon fixation. Early model estimations suggest current GHG from plastic from cradle to grave (incorporating material extraction, production, manufacture, transport and waste management) of 1.34 gigatons CO_2 equivalent $year^{-1}$ by 2030, and by 2050 may consume 10-13% of the remaining carbon budget[7].

It has been hypothesised that deposition of brake wear and tyre wear particles on ice and snow may accelerate warming of the cryosphere[8]. Micro(nano)plastic particles, particularly black coloured particles, may function as cryoconites, increasing the snow and ice melt in polar and high elevation locations. Given their hydrophobic nature, microplastic and nanoplastic may act as cloud ice nuclei[9]. Certain regions may therefore be particularly sensitive to the presence of airborne micro(nano)plastic, such

as the Southern Ocean, where cloud albedo is strongly linked to the concentration of ice-nucleating particles[10]. Southern high latitudes have experienced enhanced UV fluxes in recent decades owing to the Antarctic ozone hole; this is thought to enhance the formation of micro(nano)plastics in surface waters and terrestrial environments at southern high latitudes[11].

Airborne particulate matter influences surface climate by absorbing and scattering solar and terrestrial radiation. While total aerosol number concentrations range between 1×10^9 – 1×10^{10} per m^3 over Europe and East Asia[12], the concentrations of airborne micro(nano)plastics in the same regions are much lower; between 0.01 – 5000 MP m^{-3}.[13,14] Airborne microplastics therefore make only a small contribution to total aerosol abundances in the present-day atmosphere. Electromagnetic scattering and absorption calculations indicate that non-pigmented microplastics are efficient at scattering solar (shortwave) radiation, and at absorbing terrestrial (longwave) radiation[15]. Global climate model simulations show that the balance between shortwave effects (which imply a cooling influence on Earth's surface) and longwave effects (i.e., the greenhouse effect) depends strongly on the assumed vertical distribution of airborne microplastics[15]. The effective radiative forcing (ERF), assuming direct aerosol-radiation interactions only (that is, neglecting aerosol-cloud interactions) is calculated to be on the order of -0.746 – 0.044 mW m^{-2} assuming a surface concentration of 1 MP m^{-3}. Compared with the total aerosol effective radiative forcing of -0.71 to -0.14 W m^{-2} due to aerosol-radiation interactions[16], the microplastic ERF is small in the present-day atmosphere.

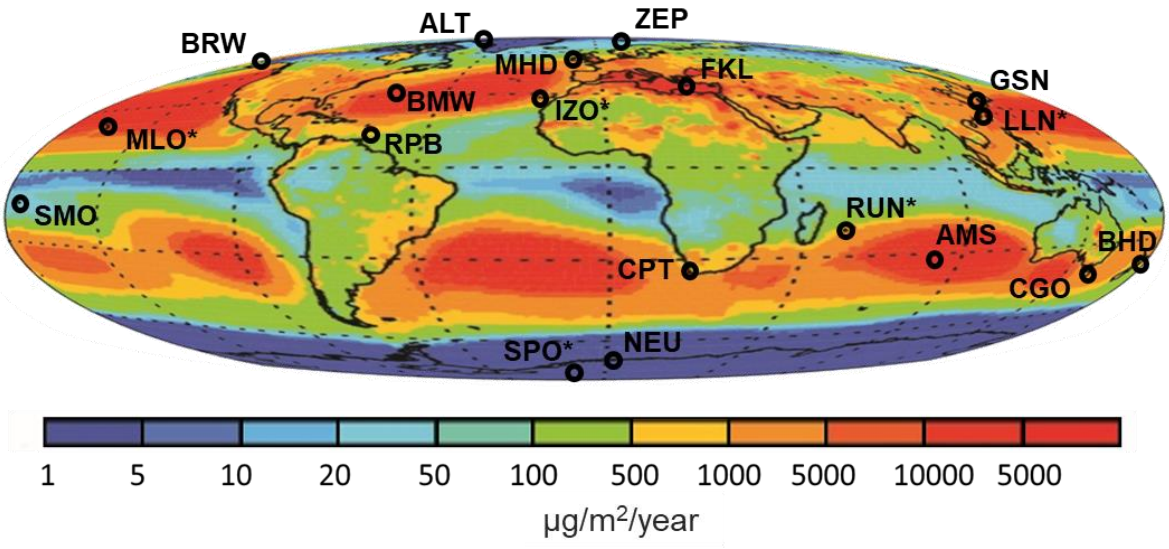
The expected increase in atmospheric micro(nano)plastic abundances due to increasing global plastic use and mismanaged plastic waste will increase microplastic ERF in future, and may influence local and regional climate in regions where airborne micro(nano)plastic concentrations are particularly large. Furthermore, emissions of anthropogenic aerosols are projected to decrease in future, which is linked to expected improvements in air quality[17]. Micro(nano)plastics will therefore make a larger relative contribution to total aerosol ERF in future.

Supplementary Note 3: CAM model global gross microplastic deposition and the global monitoring network

The Community Atmospheric Model (CAM) model has been used to estimate gross microplastic deposition across the globe[18]. The results presented in Figure C3.1 highlight the high deposition of atmospheric microplastic across both northern and southern hemisphere oceans (especially over the Pacific and Mediterranean Oceans)[18] as well as key terrestrial deposition areas in Europe, China, India, the middle east, central and northern Africa eastern south America and the USA. The CAM model results provided an interesting backdrop to the marine microplastic flux question, providing an early insight into the gross deposition over the marine environment (microplastic atmospherically transport from the terrestrial environment as well as marine (secondary) sourced microplastic emission and (re)deposition. These early global atmospheric microplastic model findings are important as it is the first tentative assessment of total atmospheric microplastic transport, considering all plastic polymer types and incorporating marine microplastic atmospheric emission.

The results of the CAM model are notably different from those presented for FLEXPART modelled tyre and brake wear global *net* deposition[8]. This is partly due to the inclusion of marine emission in the CAM model whereas Figure 4**Error! Reference source not found.** FLEXPART models net deposition to the marine environment (no marine emission) therefore providing an insight into the terrestrial net influx of microplastic to the marine environment. The microplastic particle size included in the CAM model also differs from that used in the FLEXPART model, with the CAM model particle size extending from 250µm to 4µm while the FLEXPART model considered particles of either <10µm or <2.5µm (PM10 or PM2.5). As presented Figure C3.1 the quantity of microplastic particles increases significantly with decreasing particle size. Thus the FLEXPART model may incorporate a significantly greater number and mass of smaller, more easily atmospherically transported microplastic particles than the CAM model. It is also important to note the CAM model adopts a global road microplastic emission rate (all polymers in road dust, not just tyre and brake wear) of 96Mt/yr rather than the 284MT yr^{-1} used in the FLEXPART model[18]. These highlighted differences illustrate the need for better harmonization and compatible parameterisation and field work to characterise atmospheric micro(nano)plastic particles and transport dynamics to enable advancement of atmospheric micro(nano)plastic modelling.

The proposed GAW/WMO long-term monitoring stations have been overlaid onto the global *gross* atmospheric microplastic deposition results from the CAM model analysis to illustrate that the proposed stations incorporate locations appropriate to analyse marine microplastic (re)emission and recycling as well as net marine microplastic deposition. The proposed GAW/WMO sampling sites extend onto high marine atmospheric microplastic gross deposition areas of the Atlantic, Mediterranean and Pacific as well as the low deposition zones of the Arctic and Antarctic. The proposed fixed platform network would therefore be effective in providing both an understanding of net marine micro(nano)plastic deposition and gross marine micro(nano)plastic cycling, advancing the early estimation of the terrestrially sourced atmospheric micro(nano)plastic flux to the marine environment and quantification of the marine atmospheric micro(nano)plastic cycle.



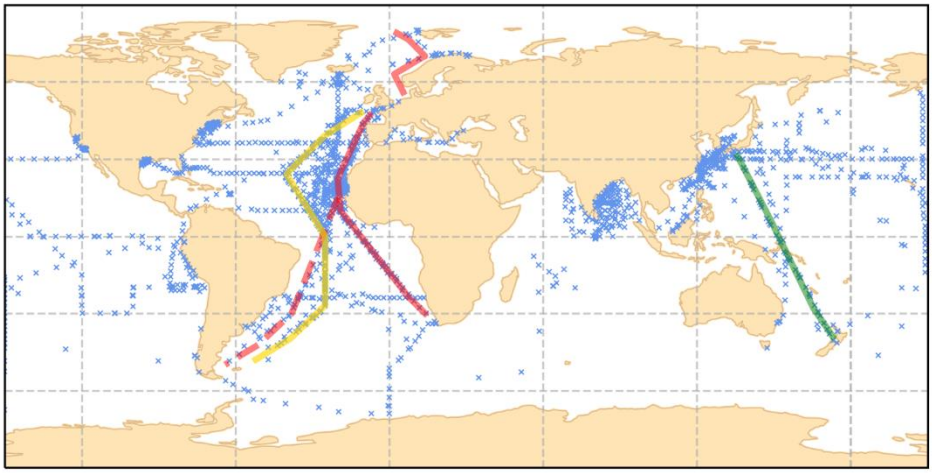
Supplementary Figure 3 Possible sampling sites illustrated on maps of CAM modelling of the total atmospheric microplastic deposition (all polymer types)[18]. Locations identified with * are high altitude

(tropospheric) sites, all other locations are coastal monitoring sites. Sites are as follows: ALT Alert (Canada); AMS Amsterdam Island (France); BHD Baring Head (NZ); BMW Tudor Hill (Bermuda); BRW (Barrow, USA); CGO Cape Grim (Australia); CPT Cape Point (South Africa); FKL Finokalia (Greece); GSN Gosan (Korea); IZO Izana (Spain, 2373 m); LLN Lulin (Taiwan, China 2862 m); MHD Mace Head (Ireland); MLO Mauna Loa (USA, 3397 m); NEU Neumayer (Antarctica); RPB Ragged Point (Barbados); RUN La Reunion (France, 2160m); SMO American Samoa (USA); SPO South Pole (Antarctica, 2841 m); ZEP Zeppelin (Norway).

Supplementary Note 4: Marine atmospheric sampling platforms

Marine Research Vessels

Ships provide access to regions of the ocean that are otherwise inaccessible, functioning with a typical campaign of 20-40 days. While ship-based research (primarily research vessels) can provide sampling from currently unmonitored marine atmospheric locations, the individual voyages result in a dataset that may be spatially and temporally patchy[19] and therefore climatologically less representative. Longer-term monitoring research campaigns such as GEOTRACES[20], the Atlantic Meridional Transect Programme[21] and Alfred Wegener Institute ship-based research program (e.g. RV Polarstern research campaigns)[22] can however provide vital offshore marine atmospheric information and be a valuable monitoring platform when employed multi-annually (potentially also seasonally) over a specific transect. To date only pumped aerosol samplers have been used on vessels, providing data of atmospheric composition (only three marine cruises have sampled and published marine atmospheric microplastic to date (Figure 2, Figure C4.1) across the Atlantic, Pacific Antarctic and Arctic oceans primarily[13,23,24]. In general, rainfall and dry deposition is grossly under-sampled over the oceans considering its importance to the air-to-sea transfer of material to the global ocean, with no precipitation or dry deposition yet undertaken specifically for micro(nano)plastic analysis.



Supplementary Figure 4. Locations of aerosol samples collected from UK, French, German, Dutch, New Zealand, Australian and Japanese ships and analysed at UEA from 2000 to 2019 (n = ~2070) (blue)[19]. Atlantic Meridional Transect cruises are shown in yellow, *Polarstern* inter-hemisphere transfers and Arctic campaigns in red and *Transfuture5* voyages in green.

To advance marine shipping research programmes, it is recommended both atmospheric deposition and air concentration (pumped air sampling) be undertaken on research cruises, and that these cruises occur across the range of seasonal conditions and over multiple years (long-term monitoring). This would result in illustration of seasonal and annual trends in marine atmospheric micro(nano)plastic

composition and provide information of the deposition rate of atmospheric micro(nano)plastic to the ocean. With quantitatively characterised marine atmospheric micro(nano)plastic deposition information, back trajectory location specific models can identify the potential marine or terrestrial source of these particles, improving the early estimations of marine atmospheric micro(nano)plastic flux. Once a substantive marine atmospheric MP database is available, global flux modelling (such as undertaken by Brahney et al. and Evangeliou et al.[8,18]) to quantify the overall marine atmospheric micro(nano)plastic flux can be executed with greater accuracy (both terrestrial provisioning of micro(nano)plastic to the oceans and marine micro(nano)plastic contribution to the terrestrial atmospheric micro(nano)plastic burden). Furthermore, vessels transects can be designed to follow major continental outflows to examine the trend in micro(nano)plastic atmospheric transport along established meteorological conveyance pathways. Such micro(nano)plastic specific vessel based sampling help document gradients in continental-sourced micro(nano)plastic concentrations and potentially opposing gradients in sea surface microlayer sourced micro(nano)plastic, demonstrating the spatial atmospheric micro(nano)plastic burden and influence of terrestrial or offshore marine conditions.

Fixed coastal or island platforms

Two notable fixed platform networks have been used to analyse the continental aerosol contribution to the marine environment over the past four decades. The SEAREX Ocean Aerosol Sampling Network was designed to characterise marine atmospheric chemistry and the role of continental to marine (ocean) transport within the (western) Pacific Ocean[25]. The AEROCE Network (interlinked with several World Meteorological Organisation observatories and Global Atmosphere Watch Programme(GAW)) undertook similar research extending along the east and west of the central to north Atlantic Ocean. The SEAREX and AEROCE networks used 17-20m walk-up scaffold sampling towers equipped with elevated atmospheric samplers supported by temporary or permanent field laboratories located on both continental coast and islands at the terrestrial-marine interface. Long-term monitoring occurred, including year-round measurements linked to the specific synoptic meteorological conditions, in conjunction with short-term intensive research activities that addressed focused research questions (e.g. sea salt aerosol bubble burst emission quantification).

The SEAREX and AEROCE networks long-term monitoring has paved the way for marine atmospheric science breakthroughs over the past four decades[26–29]. The sampling strategy and network design was shown to be effective in capturing the continental atmospheric contribution and influence to the marine environment and helped to establish protocols and field campaign design for global marine atmospheric monitoring strategies. During the SEAREX and AEROCE long-term monitoring campaigns key results illustrated the needs for meteorological consideration in the efforts to minimise sample contamination, the island effect (especially on condensation nuclei concentrations) and the importance of sampling times steps of <24 hours to ensure synoptic situations to be attributed to individual samples and back-trajectory analysis can be undertaken with greater certainty. The SEAREX and AEROCE networks provide a proven global network strategy that could be effectively utilised to collect representative samples and undertake analyse consistent and comparable analysis of global marine atmospheric micro(nano)plastic.

Aircraft, UAV, buoys

Manned aircraft have been used to collect atmospheric samples for short term or snap shot monitoring of atmospheric composition[30–32]. Recently, one campaign has used manned aircraft to sample for micro(nano)plastic (over a populated terrestrial area)[33]. Manned aircraft can provide access to spatial locations and elevations which are difficult to reach, operating at a variety of altitudes (PBL, troposphere and stratosphere) over terrestrial or marine environments. Similar to constraints identified with ship sampling, manned aircraft sampling occurs over a spatial extent rather than single location and has campaign duration constraints (limited by flight times). Furthermore, micro(nano)plastic (specifically environmentally weathered and degraded particles) are very fragile and shatter under notable impact (such as sampling at high wind speeds or at significant velocity). Therefore, significant further research is necessary to quantify the efficiency of traditional research aircraft for atmospheric micro(nano)plastic sampling. Studies are needed to ensure particle integrity is retained and to quantify the micro(nano)plastic loss due to filter inlet pressure (preventing particles from entering the sampling chamber due to aircraft speed and inlet design) and by/through pass (particles by-passing or being sucked through the filter due to pressure differential or excessive vacuum).

Unmanned aircraft systems (UAVs) have recently emerged as an effective low altitude (PBL, troposphere) sampling platforms[34–36]. While UAVs have not yet been used to sample atmospheric MP, their low airspeed coupled with elevation range and access to remote or difficult to sample locations suggests they may be an effective platform for atmospheric micro(nano)plastic sampling. The low operational cost and easy availability of UAV make them very attractive. Significant recent advances allow for a complete automatic flight from launch to landing following a predetermined flight path. However, these UAV have payload and/or duration limitations, requiring sampling equipment to be minimalist (and battery powered active sampling is required). There are also spatial and elevation limitations as under air law in most countries, the UAV must stay within visual line of sight (VLOS) and have an altitude restriction of 400 feet above ground level (~120m). These restrictions can be overcome under special permits requiring substantial investment in both equipment and training. Larger long range UAV such as the Global Hawk UAV, one of the largest available, has a 680kg payload, an 8500 nautical-mile range and a 24-hour endurance. Unfortunately, this aircrafts cruising speed is of a similar nature to the standard research aircraft.

Fixed wing and vertical take-off and landing (VTOL) fixed wing, a more commonly available UAV, can have a 5kg payload, 100km flight range (within VLOS) and 5-hour endurance. These may create opportunities for micro(nano)plastic research due to their ability to fly very close to potential sources in complete safety whilst staying within aircraft regulations. Many heavy lift multirotor UAV are available with up to 20kg payload, however very few have a longer than 20 min flight duration severely limiting their applicability to micro(nano)plastic research due to small sample size. For coastal operations, low elevations and remote locations (marine launched UAVs) UAVs could provide an effective sampling platform for marine and terrestrial atmospheric MP.

Buoys have been successfully used for marine atmospheric sampling, monitoring dust and atmospheric composition in static marine locations at low (near sea surface) elevations[37]. Buoys may provide a complementary long-term static marine sampling

network complementary to fixed platforms and shipping vessel sampling, providing near surface air concentration or depositional data. Power supply on buoys can be limited, constraining sampling methodology to passive or low power consumption activities. Sample collection via buoys includes complexity due to their isolation (accessing buoy samples by ship may be difficult at regular intervals) resulting in potentially irregular sampling times and longer sample durations. Despite these limitations, use of buoys to undertake specific research intensive field assessment may be effective where low elevation sampling is required, and buoys may form part of a long-term monitoring network when combined with other global initiatives.

Supplementary Table 1. Tabulated summary of sampling platforms and the advantages and disadvantages of their use in atmospheric micro(nano)plastic studies

Platform Type	Advantages	Disadvantages
Ships	• Unlimited marine locations • Can have trained personnel and appropriate technical capacity (i.e. clean labs) • Potential of ocean-atmosphere exchange sampling • Long-term monitoring through repeated visitation of selected offshore stations over multiple years (e.g. GEOTRACES program)	• Short-term (days or weeks to several months) temporal snapshots • Very dirty environment • May travel at speeds resulting in spatially ranging sample representation
Sailing vessels	• Unlimited marine locations • Can accommodate trained personnel • Functional in mild to moderate weather conditions • Slow passage speed supporting effective spatial sampling • Potential for ocean-atmosphere exchange sampling • Relatively low cost	• Short to moderate temporal snapshots • Fewer personnel accommodated than ships • Limited on-board analysis
Island/coastal sites *WMO/GAW permanent sites*	• Synoptic, seasonal and annual variability • Trained personnel • Supporting chemical/ meteorological measurements • Multiple elevations	• Limited geographical locations
Island/coastal sites *Other permanent sites*	• Synoptic, seasonal and annual variability • Possible supporting chemical/ meteorological measurements	• Limited trained personnel • Limited geographical locations
Island/coastal sites *Non-permanent sites*	• Synoptic and possibly seasonal scale variability • Possible supporting chemical/meteorological	• Limited/untrained personnel • Limited geographical locations

	measurements (in some cases)	
Aircraft	• Unlimited marine locations • Trained personnel • Multiple elevations	• Very short-term temporal snapshots • Limited sampling intervals • Very expensive
Drones & UAVs	• Multiple elevations • Relatively Low cost	• Limited marine locations unless launched from ships • Very short-term temporal snapshots • Limited sampling intervals • Limited power availability and payload
Tethered or remotely controlled balloons	• Full range of elevation (surface-PBL-troposphere) • Generally limited to terrestrial release but potentially possible from ships	• Limited access due to expense, licensing • Snapshot sampling rather than continuous • Potential for constraints in spatial control • Limited sampling equipment payload (when considering multiple elevation sampling)
Buoys	• Synoptic, seasonal and annual variability • Possible wide geographical coverage	• Difficult to service • Possible limited power • Excessive sea spray

References

1. Cincinelli, A. *et al.* Microplastic in the surface waters of the Ross Sea (Antarctica): Occurrence, distribution and characterization by FTIR. *Chemosphere* **175**, 391–400 (2017).
2. Tekman, M. B. *et al.* Tying up Loose Ends of Microplastic Pollution in the Arctic: Distribution from the Sea Surface through the Water Column to Deep-Sea Sediments at the HAUSGARTEN Observatory. *Environ. Sci. Technol.* **54**, 4079–4090 (2020).
3. Kelly, A., Lannuzel, D., Rodemann, T., Meiners, K. M. & Auman, H. J. Microplastic contamination in east Antarctic sea ice. *Mar. Pollut. Bull.* **154**, 111130 (2020).
4. Peeken, I. *et al.* Arctic sea ice is an important temporal sink and means of transport for microplastic. *Nat. Commun.* **9**, 1505 (2018).
5. Bergmann, M. *et al.* White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. *Sci. Adv.* **5**, eaax1157 (2019).
6. Vega, G. C., Gross, A. & Birkved, M. The impacts of plastic products on air pollution - a simulation study for advanced life cycle inventories of plastics covering secondary microplastic production. *Sustain. Prod. Consum.* **28**, 848–865 (2021).
7. Shen, M. *et al.* (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. *J. Clean. Prod.* **254**, 120138 (2020).

8. Evangeliou, N. *et al.* Atmospheric transport, a major pathway of microplastics to remote regions. *Nat. Commun.* **11**, 3381 (2020).
9. Ganguly, M. & Ariya, P. A. Ice Nucleation of Model Nano-Micro Plastics: A Novel Synthetic Protocol and the Influence of Particle Capping at Diverse Atmospheric Environments. *ACS Earth Sp. Chem.* (2019) doi:10.1021/acsearthspacechem.9b00132.
10. Vergara-Temprado, J. *et al.* Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. *Proc. Natl. Acad. Sci. U. S. A.* **115**, 2687–2692 (2018).
11. Williamson, C. E. *et al.* The interactive effects of stratospheric ozone depletion, UV radiation, and climate change on aquatic ecosystems. *Photochem. Photobiol. Sci.* **18**, 717–746 (2019).
12. Spracklen, D. V. *et al.* Explaining global surface aerosol number concentrations in terms of primary emissions and particle formation. *Atmos. Chem. Phys.* **10**, 4775–4793 (2010).
13. Liu, K. *et al.* Consistent transport of terrestrial microplastics to the ocean through atmosphere. *Environ. Sci. Technol.* **53**, 10612–10619 (2019).
14. Li, Y. *et al.* Airborne fiber particles: Types, size and concentration observed in Beijing. *Sci. Total Environ.* **705**, 135967 (2020).
15. Revell, L., Kuma, P., Ru, E. C. Le, Somerville, W. R. C. & Gaw, S. K. Direct radiative effects of airborne microplastics. *Nature* **598**, 462–467 (2021).
16. Bellouin, N. *et al.* Bounding Global Aerosol Radiative Forcing of Climate Change. *Rev. Geophys.* **58**, 1–45 (2020).
17. Riahi, K. *et al.* The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Glob. Environ. Chang.* **42**, 153–168 (2017).
18. Brahney, J. *et al.* Constraining the atmospheric limb of the plastic cycle. *PNAS* **118**, e2020719118 (2021).
19. Baker, A. R. *et al.* Observation- and Model-Based Estimates of Particulate Dry Nitrogen Deposition to the Oceans. *Atmos. Chem. Phys.* **17**, 8189–8210 (2017).
20. He, Y. & Mason, R. P. Comparison of reactive gaseous mercury measured by KCl-coated denuders and cation exchange membranes during the Pacific GEOTRACES GP15 expedition. *Atmos. Environ.* **244**, 117973 (2021).
21. Baker, A. R. & Jickells, T. D. Atmospheric deposition of soluble trace elements along the Atlantic Meridional Transect (AMT). *Prog. Oceanogr.* **158**, 41–51 (2017).
22. Kanitz, T., Ansmann, A., Engelmann, R. & Althausen, D. North-south cross sections of the vertical aerosol distribution over the Atlantic Ocean from multiwavelength Raman/polarization lidar during Polarstern cruises. *J. Geophys. Res. Atmos.* **118**, 2643–2655 (2013).
23. Trainic, M. *et al.* Airborne microplastic particles detected in the remote marine atmosphere. *Commun. Earth Environ.* **1**, 1–9 (2020).
24. Wang, X. *et al.* Atmospheric microplastic over the South China Sea and East Indian Ocean : abundance , distribution and source. *J. Hazard. Mater.* **389**, 121846 (2020).
25. Duce, R. A. SEAREX: the sea/air exchange program. in *Chemical Oceanography* vol. 10 (Academic Press, 1989).
26. Prospero, J. M., Savoie, D. L. & Duce, R. A. Particulate nitrate and non-sea-salt sulfate in the boundary layer over the Pacific Ocean. *Atmos. Environ.*

2074–2075 (1986).
27. Gagosian, R. B., Peltzer, E. T. & Zafiriou, O. C. Atmospheric transport of continentally derived lipids to the tropical North Pacific. *Nature* **291**, 312–314 (1981).
28. Uematsu, M. *et al.* Transport of mineral aerosol from Asia over the North Pacific ocean. *J. Geophys. Res.* **88**, 5343–5352 (1983).
29. Uematsu, M., Duce, R. A. & Prospero, J. M. Deposition of atmospheric mineral particles in the North Pacific Ocean. *J. Atmos. Chem.* **3**, 123–138 (1985).
30. Smith, D. J. *et al.* Airborne bacteria in earth's lower stratosphere resemble taxa detected in the troposphere: Results from a new NASA Aircraft Bioaerosol Collector (ABC). *Front. Microbiol.* **9**, 1–20 (2018).
31. Bakwin, P. S. *et al.* Strategies for measurement of atmospheric column means of carbon dioxide from aircraft using discrete sampling. *J. Geophys. Res. Atmos.* **108**, 1–7 (2003).
32. Stith, J. L. *et al.* An overview of aircraft observations from the Pacific Dust Experiment campaign. *J. Geophys. Res. Atmos.* **114**, 1–16 (2009).
33. González-Pleiter, M. *et al.* Occurrence and transport of microplastics sampled within and above the planetary boundary layer. *Sci. Total Environ.* **761**, 143213 (2020).
34. Powers, C. W. *et al.* Coordinated Sampling of microorganisms over freshwater and saltwater environments using an unmanned surface vehicle (USV) and a small unmanned aircraft system (sUAS). *Front. Microbiol.* **9**, 1–12 (2018).
35. Andersen, T., Scheeren, B., Peters, W. & Chen, H. A UAV-based active AirCore system for measurements of greenhouse gases. *Atmos. Meas. Tech.* **11**, 2683–2699 (2018).
36. Chang, C. C. *et al.* An optimized multicopter UAV sounding technique (MUST) for probing comprehensive atmospheric variables. *Chemosphere* **254**, 126867 (2020).
37. van der Does, M., Knippertz, P., Zschenderlein, P., Giles Harrison, R. & Stuut, J.-B. W. The mysterious long-range transport of giant mineral dust particles. *Sci. Adv.* **4**, (2018).