Description and evaluation of airborne microplastics in the United Kingdom Earth System Model (UKESM1.1) using GLOMAP-mode

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Abstract. Airborne microplastics are a recently identified atmospheric aerosol species with potential air quality and climate impacts, yet they are not currently represented in global climate models. Here, we describe the addition of microplastics to the aerosol scheme of the UK Earth System Model (UKESM1.1): the Global Model of Aerosol Processes (GLOMAP). Microplastics are included as both fragments and fibres across a range of aerosol size modes, enabling interaction with existing aerosol processes such as ageing and wet and dry deposition. Simulated microplastics have higher concentrations over land, but can be transported into remote regions including Antarctica despite no assumed emissions from these regions. Lifetimes range between ∼17 days to ∼1 hour, with smaller, ~~soluble~~ hydrophilic microplastics having longer lifetimes. Microplastics are ~~well-mixed~~ present throughout the troposphere, and the smallest particles are simulated to reach the lower stratosphere in small numbers. Dry deposition is the dominant microplastic removal pathway, but greater wet deposition occurs for smaller ~~soluble~~ hydrophilic microplastic, due to interactions with clouds. Although microplastics currently contribute a minor fraction of the total aerosol burden, their concentration is expected to increase in future if plastic production continues to increase, and as existing plastic waste in the environment degrades to form new microplastic. Incorporating microplastics into UKESM1.1 is a key step toward quantifying their current atmospheric impact and offers a framework for simulating future emission scenarios for an assessment of their long term impacts on air quality and climate.

1 Introduction

Since large-scale plastic production began over the 20$^{\text{th}}$ century, plastics have become the most used synthetic material in the world due to their versatility and durability. However, plastics become brittle as they age and break down through exposure to sunlight and other environmental factors (Gewert et al., 2015). This degradation forms microplastics (plastic particles 1-5000 μm) and nanoplastics (particles smaller than 1 μm), which have the potential to cause ecological damage (MacLeod et al., 2021). Microplastics can also be released through burning (Luo et al., 2023) and washing (Šaravanja et al., 2022). It is estimated that 5 Gt of plastic waste has accumulated in landfills and the natural environment since the 1950s, and that unless serious changes are made to curb global plastic production and ~~management~~ plastic waste management, the abundance of plas-

tic litter will double over the next 30 years (Geyer et al., 2017).

Microplastics have long been studied in the marine environment (Carpenter et al., 1972; Carpenter and Smith, 1972), where they are ingested by marine organisms, causing physical harm and disrupting feeding behaviour (Kvale et al., 2021). Since the first study of microplastics in atmospheric fallout (Dris et al., 2015), many further reports of airborne microplastics have been published (e.g. Allen et al., 2022, and references therein). Due to their small size and low densities, microplastics are transported throughout the atmosphere (Evangeliou et al., 2020). In particular, studies carried out in the Arctic (Bergmann et al., 2019), Antarctic (Aves et al., 2022) and other remote locations (Brahney et al., 2020; Allen et al., 2021; Materić et al., 2021) indicate that airborne microplastics are ubiquitous.

As a form of atmospheric aerosol, microplastics ~~can~~ could contribute to climate change by interacting with incoming solar and outgoing thermal radiation. ~~This in turn has an impact on the radiative balance of the atmosphere (Revell et al., 2021). Aerosols such as microplastics can also have indirect effects on radiative balance through cloud interactions and by acting as cloud condensation nuclei (CCN) (Aeschlimann et al., 2022). Clouds play an important role in the climate system (Forster et al., 2021) by reflecting sunlight to space (which has a cooling effect on Earth's surface) and trapping thermal radiation emitted by the Earth (which has a warming effect). In general, clouds that have been perturbed by aerosols consist of more numerous and smaller cloud droplets, so that they reflect more sunlight and are longer lived (Twomey, 1977; Albrecht, 1989).~~

~~Although the field of airborne microplastic-climate interactions is in its infancy, several lines of evidence from field and lab studies demonstrate that microplastic-cloud interactions occur. Microplastics are present throughout the lower atmosphere at cloud-forming altitudes, having been found as high as 3500 m above sea level (Allen et al., 2021; González-Pleiter et al., 2021) . Microplastics have also been collected in cloud water (Xu et al., 2024c; Wang et al., 2023), indicating their uptake into clouds occurs and that microplastics potentially act as cloud condensation nuclei (CCN). Studies have also determined that microplastics can act as~~ Revell et al. (2021) demonstrated that airborne microplastics exert a very small negative radiative forcing, given limited assumptions about microplastic size distribution, colour, surface concentration and vertical profile. Recent studies have shown that airborne microplastics may contribute to radiative forcing via their role as ice nucleating particles (INP~~) when pristine and when aged through environmental processes such as exposure to ultraviolet light and ozone. (Ganguly and Ariya, 2019; Busse et al., 2024; Brahana et al., 2024; Seifried et al., 2024). If present in high enough concentration, this indicates~~ ; Ganguly and Ariya 2019; Busse et al. 2024; Brahana et al. 2024; Seifried et al. 2024), indicating that microplastics can potentially seed cloud formation. Research remains conflicted about how ~~the~~ ageing impacts the nucleation ability of microplastics, with studies indicating both increases (Brahana et al., 2024) and decreases (Busse et al., 2024; Seifried et al., 2024) in the ice nucleation activity of microplastics due to ageing. ~~Tatsii et al. (2025) found when~~ When modelling atmospheric microplastics~~under high emissions scenarios they can potentially contribute significantly to INP concentrations~~, Tatsii et al. (2025) found they contribute to INP concentrations. This impact was greatest under high microplastic emissions scenarios, and in pristine regions where other INP particles are scarce, such as Antarctic and the Southern Ocean. Microplastics have also been collected in cloud water (Xu et al., 2024c; Wang et al., 2023), indicating that their uptake into clouds occurs and

that microplastics potentially act as cloud condensation nuclei (CCN). However, the present-day concentration of microplastics is unlikely to make them a significant source of CCN.

~~The contribution of airborne microplastics to global aerosol loading and implications for climate change are not well understood, since global climate models do not include microplastics in their aerosol schemes~~As an emerging aerosol species, microplastics emissions are highly uncertain due to limited spatial and temporal coverage of observations. The differences in sample collection and analysis methods make comparisons between studies difficult. Because these methods are not yet standardized, variation within individual techniques further hinders comparisons between studies. While drawing firm conclusions about the atmospheric behaviour of microplastics is difficult given a lack of empirical data (for example their lifetime, transport and deposition pathways), models are useful tools to help interpret observations, and to inform future sampling and laboratory studies (e.g. identifying the most uncertain processes or emissions regions), thereby advancing the field as a whole. Here we describe the addition of microplastics as a new aerosol species ~~to~~ in the United Kingdom Earth System Model. The model and ~~the~~ microplastics scheme are described in Section 2. In Section 3 we present simulations of the global airborne microplastics loading and deposition to ~~the~~ marine and terrestrial environments. We also evaluate the model against current observational data. Given the limitations described above, the model will inevitably need to be updated as new empirical studies or emission inventories emerge. Nonetheless, we anticipate this model to be a useful tool for airborne microplastics research.

2 Methods

2.1 Model description

Model simulations were performed using the UK Earth System Model at version 1.1 (UKESM1.1). UKESM1.1 is built on component models which each simulate a domain of the Earth system including the physical atmosphere, atmospheric composition and chemistry, ocean, sea ice and the land surface. Additional Earth system processes included in UKESM1.1 are ocean biogeochemistry and terrestrial biogeochemistry. The UKESM1.1 component models are coupled together to capture the climate impact of interactions and feedbacks within the Earth system. UKESM1.1 operates on a grid with a resolution of 1.25° latitude × 1.85° longitude, and the atmosphere contains 85 unevenly spaced levels extending to 85 km above the surface. The fully coupled configuration of UKESM1.1 (and the earlier UKESM1 version) is described in Sellar et al. (2019); Mulcahy et al. (2023).

Here we use the atmosphere only UKESM1.1 configuration, UKESM1.1-AMIP, as we are primarily interested in the atmospheric transport of microplastics. Like the fully coupled configuration, the physical atmosphere component of UKESM1.1 is the Global Atmosphere 7.1 (GA7.1) science configuration of the Unified Model (Walters et al., 2019; Mulcahy et al., 2018). Atmospheric composition, chemistry and aerosols are simulated by the United Kingdom Chemistry and Aerosols (UKCA) model (Archibald et al., 2020) coupled with the two-moment modal aerosol microphysics scheme, the Global Model of Aerosol Pro-

cesses (GLOMAP; Mulcahy et al. 2020). In UKESM1.1-AMIP the physical atmosphere and the atmospheric composition are coupled, but sea surface temperature, ocean biogeochemistry, sea ice, land surface, terrestrial biogeochemistry are prescribed from a fully coupled UKESM1.1 simulation.

In UKESM1.1, UKCA uses a combined stratospheric and tropospheric chemistry scheme within. The 'StratTrop' scheme simulates interactive chemistry from the surface to the top of the model and describes the chemistry of 81 species through 291 thermal and photolytic reactions (Archibald et al., 2020). GLOMAP currently simulates the number and mass balances across six aerosol species, modelling their sources, sinks and evolution. Aerosol species in GLOMAP include sulfate (SO_4), black carbon (BC), organic matter (OM), sea salt, dust, and nitrate (Mann et al., 2010; Jones et al., 2021). The organic carbon (OC) component of OM is included using a $1:4$ OC:OM mass ratio. OM encompasses all organic compounds, including elements such as hydrogen and oxygen, whereas OC is solely the carbon component of those compounds. Aerosol species are represented in eight log-normal size modes: nucleation soluble mode, Aitken soluble mode, accumulation soluble mode, coarse soluble mode, Aitken insoluble mode, accumulation insoluble mode, coarse insoluble mode and super-coarse insoluble mode (Mulcahy et al., 2020). These modes, their sizes ranges and represented aerosol species in each mode are summarised in Table 1. Aerosols in the soluble modes are hydrophilic, and can be incorporated into cloud droplets and affect the formation of clouds; Typically aerosols with a radius of ≥ 25 nm are activated into CCN and cloud droplets (Abdul-Razzak and Ghan, 2000; Walters et al., 2019). Aerosols in the insoluble modes are hydrophobic, and do not act as CCN. Aerosol species can settle out of the atmosphere through dry deposition and wet deposition processes such as nucleation scavenging (rainout), impaction scavenging (washout), and convective plume scavenging.

The UKESM1.1 radiative transfer scheme uses the Suite of Community Radiative Transfer codes based on Edwards and Slingo (SOCRATES; Edwards and Slingo, 1996). The shortwave part of the spectrum between 200 nm and 10 µm is divided into six spectral bands and the longwave part between 3.3 µm and 1 cm into nine spectral bands. Direct aerosol-radiation interactions are calculated in UKCA by the RADAER component of GLOMAP (Bellouin, 2010). This determines aerosol optical properties via Mie theory which are passed to the model radiation scheme to interactively calculate scattering and absorption of radiation by aerosol species. This requires tabulations of the complex refractive index of each aerosol species across the model spectral bands.

2.2 Microplastic emissions

Microplastic emissions are difficult to estimate globally due to a lack of consistent measurements with good ~~spatial~~ spatiotemporal coverages. Microplastics are emitted into UKESM1.1 using an updated version of the observationally-derived inventory from Evangeliou et al. (2022)~~. Microplastics~~ , and are emitted in two different shapes of fragments and fibres. Microplastic fragments are small pieces of plastic, often created through the deterioration of larger plastic pieces (macroplastics), whereas microplastic fibres are thread like plastics primarily produced from ~~clothing~~ the shedding of clothing, textiles and other fabrics.

Mode name	Diameter range	Represented Aerosols
Nucleation Soluble	< 5 nm	SO_4, OC
Aitken Soluble	$5 - 50$ nm	SO_4, BC, OC, NO_3, *MP*
Aitken Insoluble	$5 - 50$ nm	BC, OC, *MP*
Accumulation Soluble	$50 - 250$ nm	SO_4, BC, OC, SS, DU, NO_3, *MP*
Accumulation Insoluble	$50 - 500$ nm	DU, MP
Coarse Soluble	> 250 nm	SO_4, BC, OC, SS, DU, NH_4, NO_3, *MP*
Coarse Insoluble	> 500 nm	DU, *MP*
Super-coarse Insoluble	> 2500 nm	DU, *MP*

Table 1. Description of the eight log-normal size modes in GLOMAP and aerosol species represented in each mode. Aerosols in UKESM1.1 soluble modes are hydrophilic, and aerosol in UKESM1.1 insoluble modes are hydrophobic. Current species are sulphate (SO_4) in the form of sulphuric acid, black carbon (BC), organic carbon (OC) in the form of organic matter (OM) with an OM:OC ratio of 1 : 4, sea salt (SS), nitrate (NO_3; in the form of ammonium nitrate in the Aitken and accumulation soluble modes, and in the form of sodium nitrate in the accumulation and coarse soluble modes), dust (DU). The new microplastic aerosol species (*MP*) is represented in all modes except the nucleation mode, (see Section 2.4).

In the original emissions inventory of Evangeliou et al. (2022), ~~microplastic fragments are represented in five size bins between~~ microplastics were assumed to be spheres with diameters of 5 – 250 µm ~~, and microplastic fibres are represented in nine size binswith lengths~~ represented in five size bins, and microplastic fibres with diameters between 10 – 3000 µm ~~and widths between 1 – 10 m~~in nine size bins.

The updated microplastic inventory is based on airborne microplastic deposition measurements collected across 11 National Park and Wilderness sites between 2017 and 2019 in the Western USA (Brahney et al., 2020). ~~Sources of the fallout measurements were determined using the FLEXPART~~ So far, this is the only consistent measurement dataset suitable for top-down estimates, because it comprises weekly to bi-weekly samples from background sites over a long period. The dataset is limited by its small spatial coverage, as well as the analysis method used for identification of microplastics, which restricts the size range of observed microplastics to 4 µm. The updated emissions inventory used a new version of the Lagrangian particle dispersion model ~~running in retroplume mode to calculate back trajectories. These sources were combined with a robust Bayesian inverse modelling algorithm to determine microplastic emissions , and~~ FLEXPART, version 11 (Bakels et al., 2024) . FLEXPART version 11 uses an updated settling scheme that, unlike other models, differentiates between spherical and non-spherical shapes (e.g fragments and fibres), that have been reported to disperse differently (Tatsii et al., 2024). The optimization procedure of measurements from Brahney et al. (2020) and source-receptor matrices were based on the Gibbs sampling method

(Gelfand, 2000). We constructed a hierarchical Bayesian model, whose parameters are optimized using the Gibbs sampler. Gibbs sampling is beneficial for optimization in high-dimensional or complex problems where traditional methods struggle. It simplifies the process by sampling from conditional distributions, avoiding full joint evaluations. This makes it especially effective for Bayesian models and correlated parameters. Unlike gradient-based methods, it handles multimodality well. Its modularity also allows easy integration with other sampling strategies. This method was used to estimate microplastics emissions in the form of samples from posterior distributions, quantifying effectively uncertainties of estimated mean and median values. The respective posterior emissions estimated at a domain that cover most of the US (yet unpublished) were then extrapolated globally using ~~inventories of other emissions. Sea salt, agriculture , mineral dust~~ emission patterns of other sectors. Sea spray, agriculture (plastic nets), resuspension from mineral dust in bare soil and road dust were ~~used as~~ assumed to be the main sources of microplastic fragments. For the microplastic fibres, their main source was assumed to be largely from clothing and linked to the distribution of the global population. Thus, fibre emissions are absent from the ocean. Yang et al. (2025) assessed the oceanic emission potential of microplastics and found that 100 µm long microplastic fibres of various widths did not produce an oceanic emissions flux due to size, density and shape.

~~Since~~ In the original publication, ~~updates have been made to~~ emissions of microplastics were estimated to be equal to 0.82 Tg y^{-1} for sizes between 5 – 25 µm, while fibres were 6.5 Tg y^{-1} for all sizes (10 – 3000 µm). In the updated inventory, microplastic emissions at the smallest and most highly dispersed size bin (5-25 µm) were 0.74 Tg y^{-1}, in contrast to 0.82 Tg y^{-1} in the original inventory, with greater differences at the largest sizes. Microfibre emissions are kept the same. The difference in the updated inventory is that the ~~emissions inventory, which are accounted for in this study. The updated inventory now considers the~~ positions of ocean gyres ('great garbage patches') are now considered alongside the sea spray inventory when determining oceanic ~~microplastic emissions (Isobe et al., 2021). The~~ emissions for microplastic fragments (Isobe et al., 2021) , as well as the shape-oriented dispersion that is obtained using the newer model version of FLEXPART v11. Furthermore, the high emissions observed across polar regions in Evangeliou et al. (2022) have been reduced ~~, and emissions over land have been increased~~in the upgraded version, using the sea-ice extent adopted from the fifth generation ECMWF (European Centre for Medium-range Weather Forecasts) atmospheric reanalysis produced by the Copernicus Climate Change Service (C3S; Hersbach et al., 2020). The new emission inventory is more realistic and in line with the latest knowledge, such as new insights into low oceanic microplastic emissions (Yang et al., 2025). To create emissions data files for UKESM1.1-AMIP the updated inventory was re-gridded with a resolution of 1.25° latitude × 1.85° longitude. One year of emissions data is available for 2018, based on when the airborne microplastic deposition measurements were collected (Brahney et al., 2020). Figure 1 shows microplastics emissions for both fragments and fibres using the updated emissions inventory.

2.3 Extrapolation of microplastic emissions

As indicated by the size ranges of the insoluble GLOMAP modes in Table 1, all of the microplastics emissions from Evangeliou et al. (2022), i.e. sizes greater than 5 µm, correspond to the super-coarse insoluble mode which has a lower bound of 2.5 µm di-

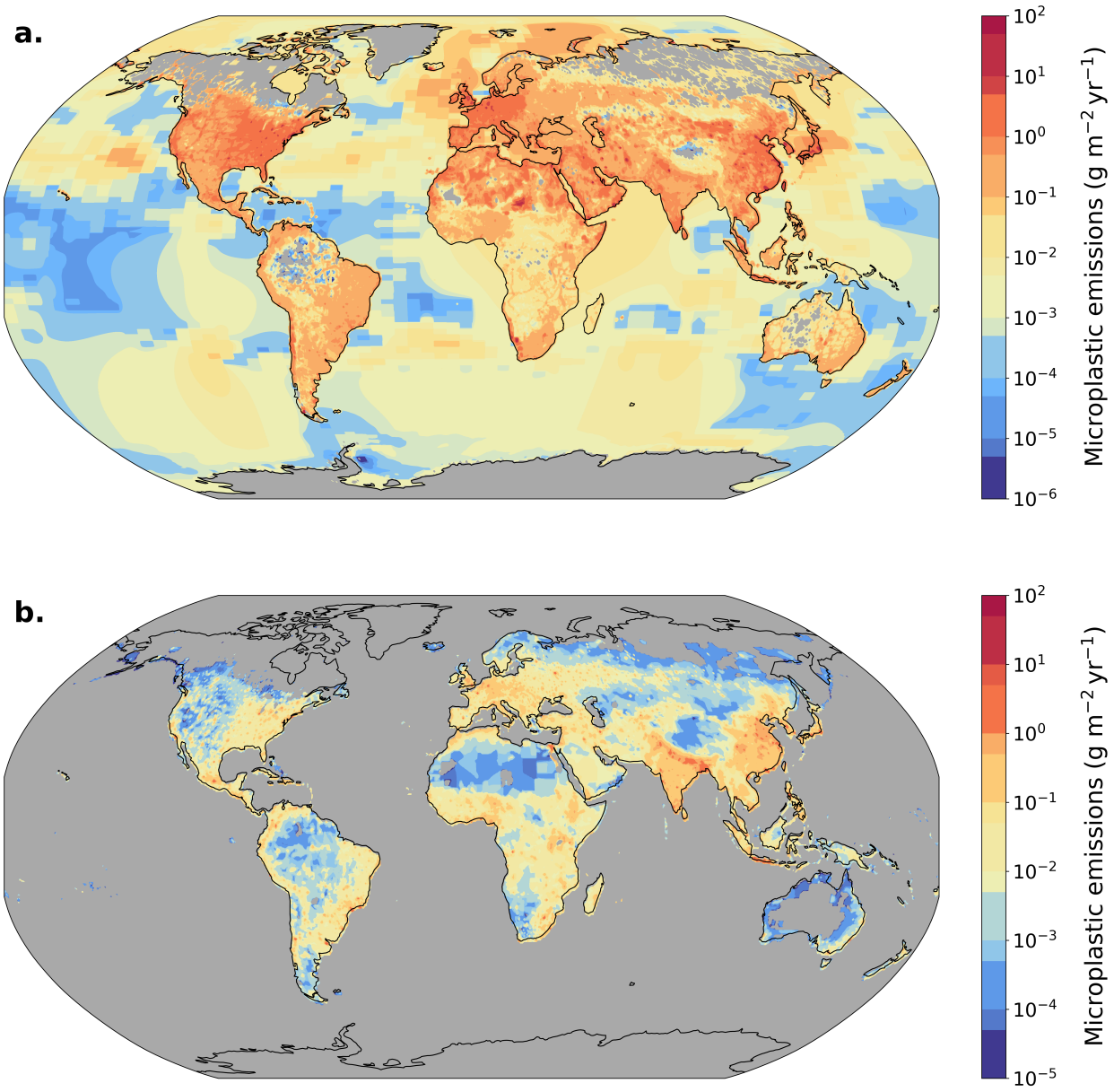

Figure 1. The microplastic emissions inventory for (a) microplastic fragments and (b) microplastic fibres, updated from Evangeliou et al (2022). Grey shading indicates that emissions are zero.

175 ameter and no upper bound. Studies indicate that plastic particles smaller than 5 μm have been detected (Materić et al., 2021, 2022; ten Hietl across land, ocean and atmosphere. To input emissions into the smaller Aitken, accumulation and coarse insoluble modes, microplastic fragment emissions were extrapolated. This extrapolation was based on methodology described by Leusch et al. (2023), which surveyed more than 120 published studies reporting microplastic size distributions and identified a power law

distribution which was common across several matrices (air, water, soil); exponentially larger numbers of particles are found at smaller sizes. When log-transformed, Leusch et al. (2023) demonstrate a linear increase in particle number with decreasing size. Leusch et al. (2023) further demonstrated that if the concentration of microplastics in a particular size bin is known, then the concentration in a different size bin can be estimated using Equation 1:

$$n_{pred} = n_{ref} \times \left(\frac{x_{UB.pred} - x_{LB.pred}}{x_{UB.ref} - x_{LB.ref}}\right) \times \left(\frac{x_{UB.pred} \times x_{LB.pred}}{x_{UB.ref} \times x_{LB.ref}}\right)^{-\alpha/2} \quad (1)$$

Where n_{pred} is the number of microplastics predicted in a size bin with upper and lower bounds $x_{UB.pred}$ and $x_{LB.pred}$, respectively. n_{ref} is the number of microplastics in the reference bin with upper and lower bounds $x_{UB.ref}$ and $x_{LB.ref}$, respectively. α is the slope of the linear regression of the log-logistic fit.

Microplastic fragments were extrapolated using the 10 – 25 µm ~~m~~ m size bin as a reference~~because~~ , as it contained the largest number of microplastics ~~.~~ within the emissions inventory. Using a single size bin to extrapolate provided four remaining bins in the emissions dataset to validate the extrapolated microplastic concentrations against. The value of α from Equation 1 was tuned to provide the best match between the extrapolated data and the ~~remaining four bins for microplastics fragments with emissions data~~four emissions bins. α was chosen to be 1.81 which matches the reference values of 1.44 ± 0.37 given for airborne microplastics in Leusch et al. (2023).

Supplementary Figure A1 shows the results of the extrapolation, for both the number and mass concentration of microplastics. Extrapolation for the lower limit of $\alpha = 1.07$ is also shown to indicate uncertainty. The extrapolated estimates of microplastic fragments are only used across the size bins where observationally-derived microplastic data is absent. Extrapolation of the microplastic fragments to the GLOMAP size modes indicated in Table 2 extends their representation into the nanometre size range. While these particles fall within the definition of nanoplastics, they are referred to as microplastics throughout this study for clarity. Microplastic fibres were not extrapolated due to their thread like shape; Once the length of microplastic fibres approaches the nanometre range their aspect ratios (length/diameter) become small enough they essentially behave more as microplastic fragments.

The Leusch et al. (2023) study demonstrated a linear increase in log-transformed microplastic number with decreasing size, but only for microplastics down to 25 µm. This is a common lower size limit in studies using μFTIR spectroscopy (e.g. Liu et al. 2019a; Chen et al. 2023; Abbasi et al. 2024), which has been a widely-used analysis to date. In this study, we extrapolate down to 5 nm under the assumption that this relation remains valid at smaller sizes of microplastics. This introduces uncertainty, particularly in the absence of robust observational data below 1 µm to validate against: to the best of our knowledge, no one has yet published a comprehensive size distribution for microplastics smaller than 10 μm. We acknowledge that differing

values of α, or a different relation than assumed in Equation 1, could lead to significantly different extrapolated microplastic concentrations. As such, our extrapolation should be treated as speculative. Adjusting the value of α to better represent these smaller-sized particles will be straightforward as and when new data become available. Nonetheless, the chosen value of $\alpha = 1.81$ indicates strong agreement between the extrapolated estimation and the emissions dataset, while the lower limit of $\alpha = 1.07$ provides a poorer match (Supplementary Figure A1).

2.4 Implementation of microplastics into GLOMAP

Microplastics have been added to GLOMAP in a new aerosol configuration that also includes sulfate, black carbon, organic matter, sea salt and dust. This allows interactions between microplastics and the other aerosol species. Microplastics are emitted as hydrophobic aerosol into the insoluble Aitken, accumulation, coarse and super-coarse modes. However, microplastics can be transferred to the ~~soluble modes through an ageing process of aerosol species previously existing within GLOMAP~~model's soluble modes and become hydrophilic through the existing aerosol ageing within GLOMAP which also applies to existing aerosol species such as black carbon and dust. This ageing occurs due to a build-up of soluble material such as sulfate on the surface of the aerosol (Mulcahy et al., 2018). Once the soluble material builds up to a size of 10 monolayers, the aerosol particles are transferred to the corresponding soluble mode. ~~This effectively~~ Because microplastics in the soluble modes are hydrophilic, it allows them to act as CCN within UKESM1.1 as they remain aloft in the atmosphere. ~~Because~~ As the model does not contain a super-coarse soluble mode, ~~there is no transfer of~~ microplastics from the super-coarse insoluble mode ~~to a corresponding soluble mode .~~ age into the coarse soluble mode instead, while retaining their larger mass. While Wang et al. (2023) identified microplastics bearing hydrophilic groups in cloud water, we acknowledge that representing microplastics as hydrophilic aerosol is uncertain. Similar to other aerosol species in GLOMAP, microplastics ~~are also able to~~ can undergo wet and dry deposition ~~, and are able to coagulate~~ and coagulate with other microplastics into larger size modes.

Atmospheric transport and lifetime of microplastic fibres is influenced by their shapes (Tatsii et al., 2024; Xiao et al., 2023). Because of their non-spherical shape, microplastic fibres may be transported higher into the atmosphere than microplastic fragments. Tatsii et al. (2024) concluded that on average, microplastic fibres have settling velocities ~~up to 76~~60% lower when compared to spheres of an equivalent volume. ~~This suggests microplastic fibres need to be treated differently within the model, however they currently have the same spherical shape and settling velocities as the microplastic fragments~~To represent this behaviour within UKESM1.1, microplastic fibres are first modelled as volume-equivalent spheres based on their length and width from the emissions dataset. This changes the size distribution of fibres from having lengths between 10 – 3000 µm and widths between 1 – 10 µm, to spheres with diameters between 2.4 - 77 µm. This represents microplastic fibres in three modes, super-coarse insoluble, coarse insoluble, and coarse soluble through the GLOMAP ageing process. Secondly, the settling velocities of volume-equivalent spherical fibres is reduced within UKESM1.1 by 60% based on the work of Tatsii et al. (2024) .

Microplastic fragments and fibres can be switched off separately, allowing for model runs with both, one or neither of the two types enabled. ~~While current representation of microplastic fibres may not be realistic, the~~ The partitioning between fragment and fibre emissions creates a separate framework for microplastic ~~fibres that future iterations of the microplastic scheme can improve upon~~shape to assess their relative importance separately. The direct radiative effects of microplastics are included via RADAER. We use the complex refractive index of Revell et al. (2021) for ~~colourless~~ non-pigmented plastics, such that all plastics are treated as colourless. Note that, as RADAER calculates aerosol radiative effects using Mie theory, all microplastic particles are assumed to be spherical and homogeneous in composition. Microplastic in UKESM1.1 have a density of 1000 kg/m^3. This is an average plastic density similar to those used in previous studies (Brahney et al., 2020; Evangeliou et al., 2022; Tatsii et al., 2024) and agrees with the work of Stride et al. (2024), who found most microplastics have densities between 940 kg/m^3 and 1320 kg/m^3. The molar mass of microplastics was set to 0.12 kg/mol, corresponding to the molar mass of carbon.

2.5 UKESM1.1 model simulations

Simulations were performed with the atmosphere-only configuration of the model (UKESM1.1-AMIP) and run for a period of 11 years, from January 2004 to December 2014. The first 12 months were discarded as spin-up and we focus our analysis on the 10 years from January 2005 to December 2014. Microplastic emissions for the 12 months of available data have been repeated for each year of the simulations. While this predates atmospheric microplastic observations and the emissions inventory~~it provides a well tested simulation period for analysis~~ , it corresponds to the historical period of UKESM1.1-AMIP where ancillary data such as greenhouse gas emissions are well constrained (Mulcahy et al., 2023). Three simulations were performed: A control with no microplastic emissions, one with microplastic fragment emissions and one with microplastic fibre emissions.

2.6 Microplastic observations for model evaluation

An examination of existing studies reporting atmospheric microplastic concentrations was undertaken to provide a comparison with model output. Published airborne microplastic data was gathered through a Scopus search using the following criteria: (1) search by ~~'~~'Article Title', (2) search documents ~~'~~'microplastics AND airborne OR atmospheric OR atmosphere' (3) including all available years. All papers were screened for relevance by reviewing abstracts, with studies excluded if they did not directly measure airborne microplastics and report results in either ~~'~~'particles m^{-3}' or ~~'~~'particles m^{-2} day^{-1}'. Relevant studies were then examined in detail to extract key information. While this approach aimed to compile a comprehensive dataset of airborne microplastics to date, it is acknowledged that some relevant studies may not have been captured due to the specific search terms used. Brahney et al. (2020), which wasn't identified in the Scopus search because it doesn't have the word 'microplastics' in the title, has been added to the collated observational dataset, as our microplastic emissions are derived from their deposition measurements. In addition, we also include two studies reporting atmospheric nanoplastics (Kau et al., 2024; Materić et al., 2021), that were not identified by the Scopus search. Table A1 displays the author, name and

year of studies used for comparison with the UKESM1.1 model. A complete table with concentration and latitude/longitude data is available at McErlich (2025).

3 Results and discussion

3.1 Microplastic surface concentrations

Figure 2 shows the annual mean surface concentration from UKESM1.1-AMIP output (2005–2014) for microplastic fragments and fibres. The surface height is defined as the lowest vertical level in UKESM1.1-AMIP and reaches up to ~33 m above the land surface. Figure 2a-b shows the microplastic surface number concentration and Figure 2c-d shows the microplastic surface mass concentration. Microplastics have greater number and mass concentrations over land than the ocean, which matches well with the emissions profile (Figure 1). Model output shows that microplastic fragments do not stay localised to their point of emissions, but are advected around the atmosphere such that they are ubiquitous across the globe. For example, over Antarctica small amounts of microplastic are present despite a lack of emissions there for both fragments and fibres. Microplastic fibres (Figure 2b,d) display high concentrations close to areas of population where they are emitted. ~~Fibres display some~~ Despite having no emissions over the oceans, microplastic fibres display atmospheric transport into ~~other~~ oceanic regions, particularly over coastal regions which are ~~close~~ closer to emission sources.

Figure 2 indicates differences between microplastic fragments and fibres in terms of their surface number and mass concentrations. Microplastic fragments (Figure 2a,c) exhibit a significantly higher surface number concentration (~~1.3×10^4~~6.7×10^5 m^{-3}) compared to microplastic fibres (~~3.4~~1187.8 m^{-3}). This difference arises because fibres are only represented in the largest ~~size mode (~~two size modes (coarse and super-coarse~~insoluble), which contains~~), where emissions have the fewest microplastic particles. Microplastic fibres ~~contribute slightly more to the~~ also have a slightly smaller surface mass concentration (~~2.8×10^{-2}~~1.4×10^{-1} µg m
~~than~~ compared to microplastic fragments (~~1.0×10^{-2}~~1.4×10^{-1} µg m^{-3}).

Table 2 presents the average number and mass concentrations of microplastic fragments and fibres across individual size modes, indicating their relative contributions to the total concentrations on Figure 2. The spatial distribution of these concentrations is shown in Supplementary Figures A2-A5. Table 2 indicates that fewer microplastics are present at the surface in the soluble modes as compared to the insoluble ones, as microplastics only enter the soluble modes via the build up of soluble material on their surfaces as they age. Ageing does not occur in the super-coarse insoluble mode in the model as there is no corresponding soluble mode.

Microplastic surface number and mass concentrations vary substantially across size modes, as expected from the prescribed size distribution of emissions (Supplementary Figure A1). The highest number concentrations are observed in the Aitken mode and the highest mass concentrations are observed in the super-coarse insoluble mode. Fragments are present in all

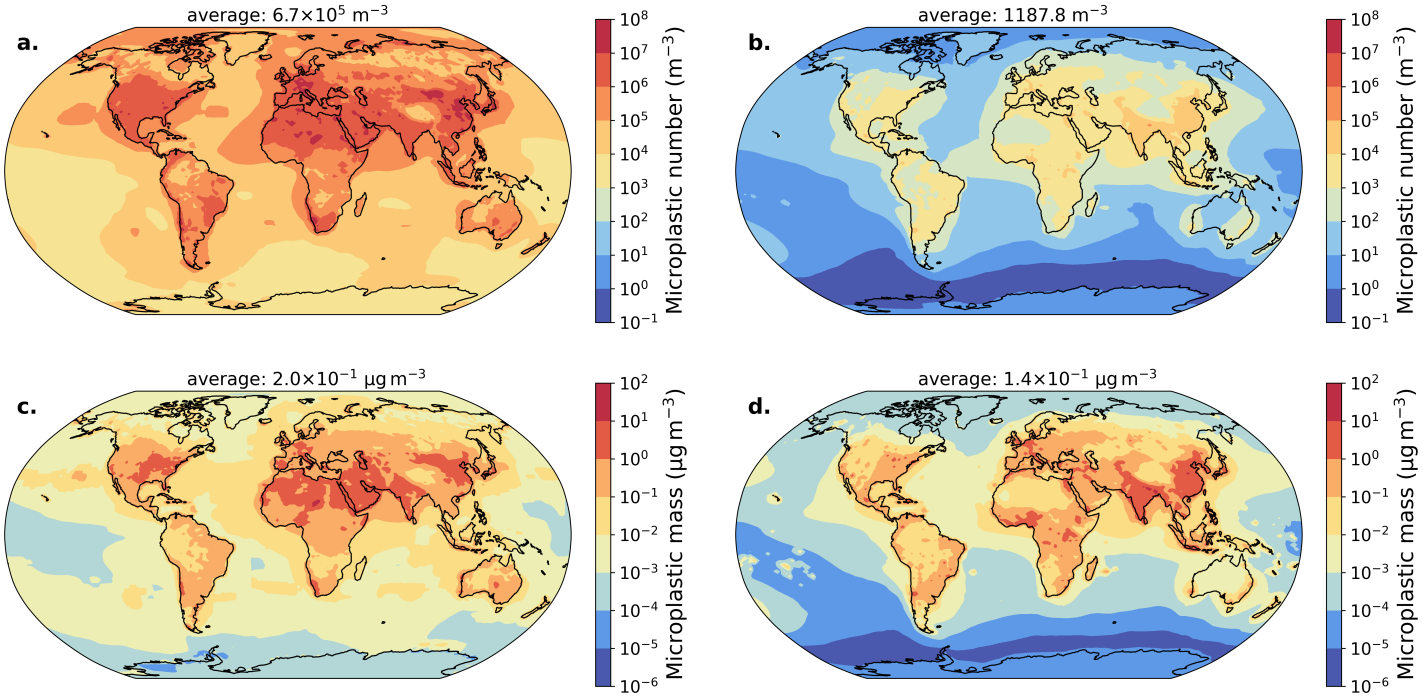

Figure 2. Annual-mean surface concentration of microplastics in UKESM1.1-AMIP (2005–2014) for (a) fragment number concentration, (b) fibre number concentration, (c) fragment mass concentration, and (d) fibre mass concentration. The area weighted average is displayed on each subplot.

Size Mode	**Fragments**		**Fibres**	
	number (m^{-3})	**mass** (µg m^{-3})	**number** (m^{-3})	**mass** (µg m^{-3})
Aitken Insoluble	381786.5	7.9×10^{-7}	-	-
Aitken Soluble	158009.0	3.3×10^{-7}	-	-
Accumulation Insoluble	63588.5	1.3×10^{-4}	-	-
Accumulation Soluble	57206.6	1.4×10^{-4}	-	-
Coarse Insoluble	8259.0	6.0×10^{-3}	387.2	2.8×10^{-4}
Coarse Soluble	1486.8	3.4×10^{-2}	786.0	1.8×10^{-2}
Super-Coarse Insoluble	19.1	1.6×10^{-1}	14.6	1.2×10^{-1}
Total	6.7×10^{5}	2.0×10^{-1}	1187.8	1.4×10^{-2}

Table 2. Global annual mean surface number and mass concentrations of microplastic fragments and microplastic fibres across GLOMAP aerosol size modes in UKESM1.1-AMIP.

size modes, with the majority of number concentration in the Aitken insoluble (~~7410.9~~381786.5 m^{-3}) and Aitken soluble (~~3083.6~~158009.0 m^{-3}) modes, highlighting their abundance at the smallest aerosol size of 5 - 50 nm. ~~Fragment~~ Microplastic fragment surface mass concentration is dominated by the super-coarse insoluble mode (~~9.9×10^{-3}~~1.6×10^{-1} µg m^{-3}), despite its small number concentration (~~1.2~~19.1 m^{-3}). Fibres, which are only allowed in the coarse soluble, coarse insoluble, super-coarse insoluble mode, show ~~greater number (3.4 m^{-3}) and mass (2.8×10^{-2} g m^{-3})~~ smaller number concentrations compared to microplastic fragments across equivalent size modes.

~~Supplementary Figures A2-A4 indicate that soluble modesshow a better atmospheric mixing of microplastics compared to the insoluble modes. Supplementary Figure A4 displays a narrower range of microplastic concentrations and smoother spatial distributions observed for soluble particles. In contrast, Supplementary Figures A2,A3 for insoluble microplastics have more varied spatial patterns, with localized regions of elevated concentrations from features such as orography more pronounced.~~

A previous microplastic modelling study by Revell et al. (2021) assumed a uniform surface microplastic concentration of 1 m^{-3}, based on previously reported airborne microplastic concentrations. These studies focused on particle sizes down to 5 µm corresponding to the supercoarse mode used in our study. We show that modelled microplastic surface concentrations for supercoarse-mode particles are ~~1.2~~19.1 m^{-3} for fragments and ~~3.4~~14.6 m^{-3} for fibres (Table 2). These concentrations are ~~in the same order of magnitude as~~ similar in magnitude to the assumption of Revell et al. (2021), and ~~suggests~~ suggest that emissions based on Evangeliou et al. (2022) and our modelling approach is consistent with previous research.

3.2 Microplastic vertical distributions

Figure 3 shows the vertical profile of microplastic fragments, for each of the four hydrophobic, insoluble modes. Microplastic number concentration is averaged over time and longitude to determine the annual zonal mean. Number concentrations ~~of less than 1~~less than or equal 1×10^{-7} m^{-3} are ~~masked out to remove unrealistic~~ shown using the same colour scale as negligible values. Microplastics in the Aitken insoluble mode (Figure 3a) show the greatest vertical extent as they are the lightest~~. They potentially reach altitudes of up to~~ , being present throughout the troposphere. A few microplastics are also present in the stratosphere, but concentrations decrease below 1 m^{-3} around ~~17~~20 km at the equator, and ~~11~~13 km at the poles. ~~This indicates the lightest insoluble microplastics are well-mixed in the troposphere. A few microplastics are also present in the stratosphere, but do not enter in any great number.~~ The vertical distribution of microplastic influences their radiative effects, as particles suspended higher in the atmosphere have a greater potential to interact with incoming and outgoing radiation. Revell et al. (2021) show that longwave radiative heating by microplastics ~~are~~ is larger when microplastics are distributed throughout the troposphere compared to when they are confined to the boundary layer (lowermost 2 km of the atmosphere). Figures 3b-d for the accumulation, coarse, and super-coarse modes show microplastics in these modes are both less numerous and have a lesser vertical extent than the Aitken insoluble mode. The super-coarse insoluble microplastics are mostly confined to the near-surface atmosphere, though vertical uplift may be possible in small concentrations.

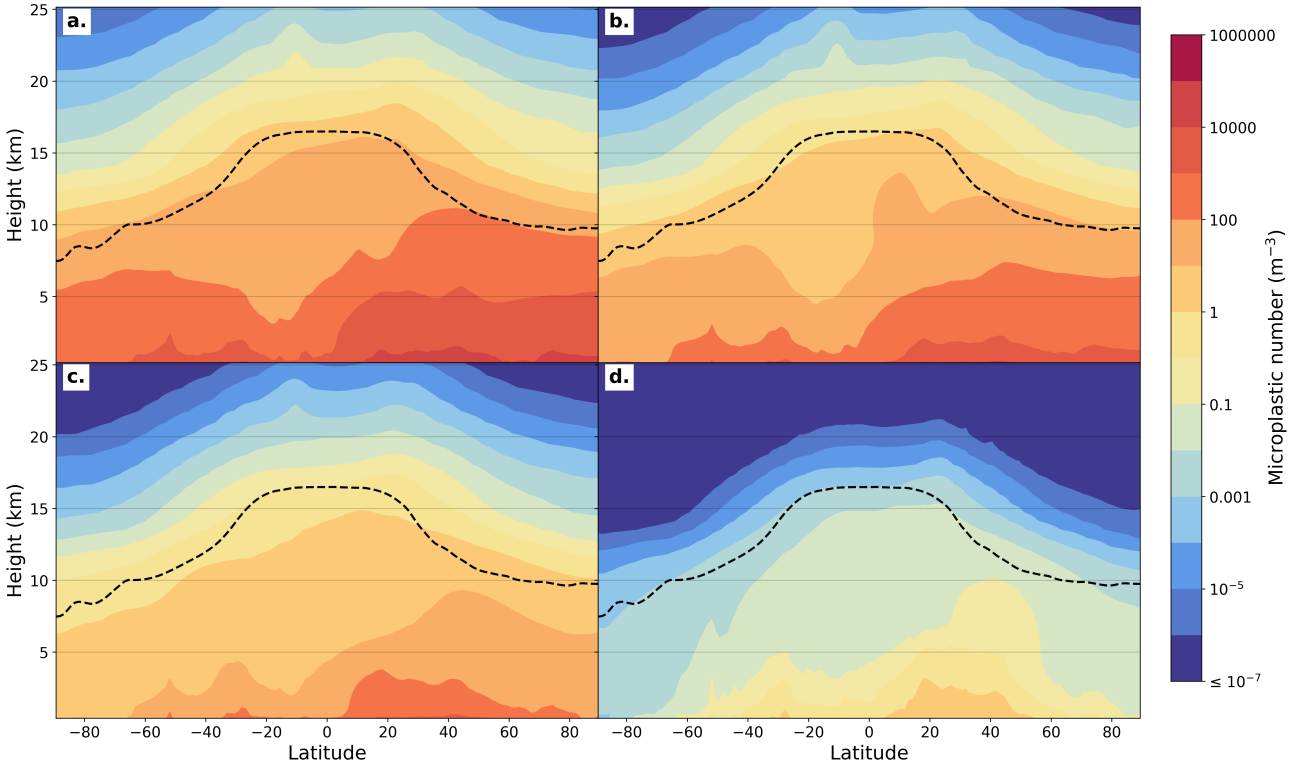

Figure 3. Vertical profile of annual zonal mean microplastic fragment concentration (2005–2014) for (a) Aitken insoluble, (b) accumulation insoluble, (c) coarse insoluble, and (d) super-coarse insoluble modes. ~~Grey shading indicates number~~ Number concentrations ~~smaller~~ less than ~~l~~or equal 1×10^{-7} m^{-3} are shown using the same colour scale as negligible values. The dashed line indicates the model's annual-mean tropopause height.

Zonal mean microplastic fragment number concentrations at UKESM1.1-AMIP vertical levels for the three microplastic-enabled soluble modes ~~and microplastic fibres~~ are shown on Figure 4. ~~Soluble~~ Hydrophilic, soluble microplastics show greater vertical extent and higher concentrations than their insoluble mode counterparts (Figure 3), even though the surface number concentration of soluble mode microplastics is less than insoluble mode microplastics (Supplementary Figure A3 and Supplementary Figure A4a,c,e). Figure 4a,b indicates that Aitken/accumulation soluble mode microplastics can be transported to even higher altitudes than insoluble mode microplastics ~~– over 19~~. Concentrations drop below 1 m^{-3} around 25 km at the equator, ~~reducing~~ and decrease towards the poles. This suggests that Aitken and accumulation soluble microplastic fragments are ~~well-mixed in~~ present throughout the troposphere and have ~~greater~~ more significant concentrations in the stratosphere than the small insoluble microplastics. They also reach cloud forming altitudes where they may impact cloud formation through their role as hydrophilic CCN (and potentially INP, although this is not yet enabled in the model). Coarse mode soluble microplastics undergo less vertical transport, ~~reaching altitudes of up to ~12.5 km. Figure 4d~~ with concentrations dropping below

1 m^{-3} around 17 km.

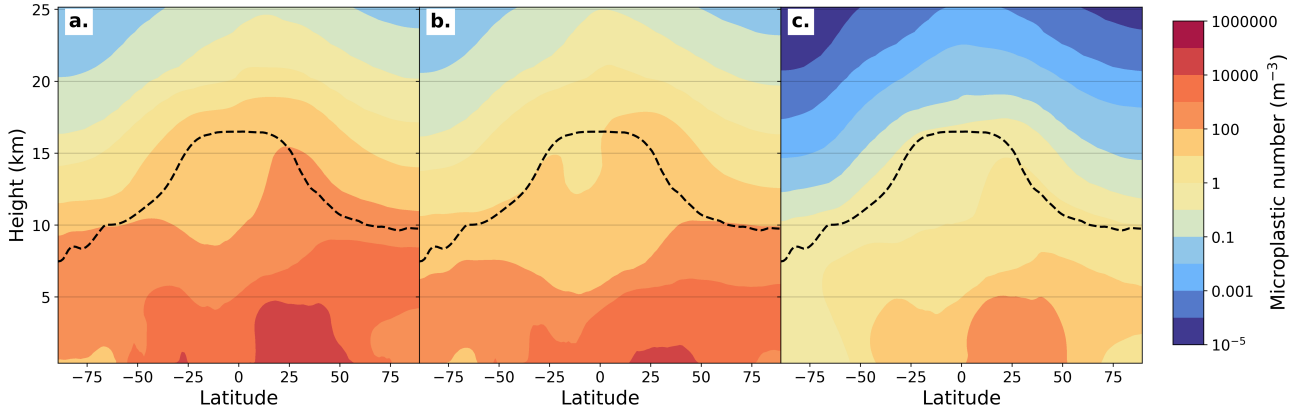

Figure 4. Vertical profile of annual zonal mean microplastic fragment concentrations (2005–2014) for (a) Aitken soluble, (b) accumulation soluble, (c) coarse soluble modes. The dashed line indicates the model's annual-mean tropopause height.

Figure 5 shows vertical profiles of number concentration for microplastic fibres for the coarse soluble, coarse insoluble and super-coarse insoluble modes. Hydrophilic, coarse soluble mode fibres are present throughout the troposphere. They also reach the stratosphere in small concentrations, decreasing below a concentration of 1 m^{-3} around 16 km. ~~Due to their large size they do not reach heights greater than 3 kmand~~ Super-coarse insoluble mode fibres are mostly contained near the surface ~~, which can be explained due to their shape being assumed as spherical.The limitations of this approach are discussed below.~~ in large concentrations.

Results shown ~~across~~ in Figures 3, 4 and 5 agree with previous work (Tatsii et al., 2024; Bucci et al., 2024) modelling the vertical transport of microplastics, which also found that microplastics reach into the stratosphere. Tatsii et al. (2024) suggested that due to their reduced settling velocities, microplastic fibres ascend higher in the atmosphere and have increased global atmospheric transport than equivalent sized microplastic fragments. ~~As~~ Even though microplastic fibres are ~~currently treated as spherical within the model, this vertical uplift is not seen in Figure 4d and highlights the need for improvements in the representation of microplastic fibres in future iterations of the microplastic scheme~~modelled as volume-equivalent spheres with 40% reduced settling velocities, they show lesser maximum vertical extents than for the corresponding size modes for fragments. This is likely due to the smaller emissions of microplastics fibres than fragments from the source dataset (Figure 1). UKESM1.1 testing shows that microplastic fibres with 60% reduced settling velocities have greater vertical ascent than those with normal settling velocities (not shown).

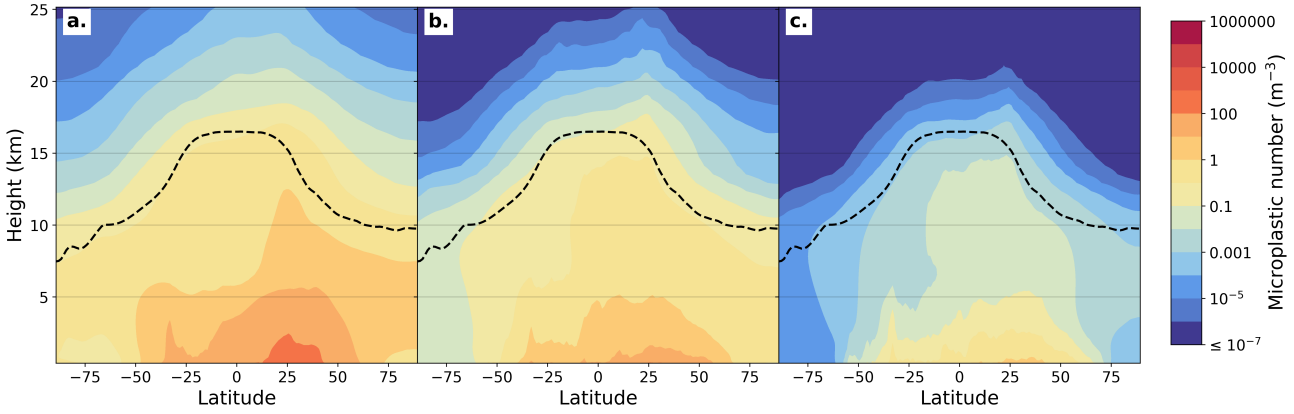

Figure 5. Vertical profile of annual zonal mean microplastic ~~fragment~~ fibres concentrations (2005–2014) for (a) ~~Aitken~~ coarse soluble, (b) ~~accumulation soluble~~coarse insoluble, (c) ~~coarse soluble modes, and (d)~~ super-coarse insoluble ~~microplastic fibres~~modes. ~~Grey shading indicates number~~ Number concentrations ~~smaller~~ less than ~~1~~ or equal 1×10^{-7} m^{-3} are shown using the same colour scale as negligible values. The dashed line indicates the model's annual-mean tropopause height.

3.3 Microplastic burden, loss and lifetime

Table 3 shows the global mean microplastic atmospheric burden, deposition processes, and estimated atmospheric lifetime across GLOMAP aerosol size modes in UKESM1.1-AMIP. The total atmospheric burden of microplastic is ~~600~~1.36×10^4 tonnes, with an estimated mean lifetime of ~~0.05~~0.07 days (~~1.2~~ 1.9 hours) before deposition. The burden and lifetime varies substantially across size modes, with the total global microplastic deposition and burden strongly weighted towards the largest super-coarse mode microplastics, which deposit out rapidly.

~~Microplastic removal is dominated by dry deposition~~ The predominant microplastic removal pathway across all size modes ~~, though wet~~ is dry deposition, with an average of 61% microplastic removal through this pathway. Wet deposition pathways indicate some interactions with cloud processes. Soluble mode hydrophilic microplastics show greater loss through ~~wet deposition processes~~ nucleation scavenging (rainout) compared to the insoluble size modes with hydrophobic microplastics. Accumulation soluble mode microplastics show the greatest loss ~~through wet deposition~~(52%) through nucleation scavenging. This reflects the ability of hydrophilic accumulation soluble mode microplastics to become incorporated into cloud droplets as CCN before wet deposition removes them. The coarse insoluble mode for both fragments and fibres shows the greatest loss through impaction scavenging (washout), of 51% and 70% of total removal through this pathway respectively. The removal of microplastics within UKESM1.1 is subject to inbuilt assumptions in the model such as their ability to act as hydrophilic CCN. Further observational studies are needed to constrain the relative importance of wet and dry deposition processes for microplastics.

Size Mode	Loss (tonnes/year)			Burden (tonnes)	Lifetime (days)
	Dry Deposition	Impaction Scavenging	Nucleation Scavenging		
Aitken Insoluble Fragments	1.08 (93.7%)	0.053 (4.6%)	0.02 (1.7%)	0.01	3.13
Aitken Soluble Fragments	0.54 (76.8%)	0.082 (11.8%)	0.8 (11.4%)	0.03	16.9
Accumulation Insoluble Fragments	125 (78.0%)	35 (22.0%)	0 (0%)	1.77	4.0
Accumulation Soluble Fragments	138 (38.1%)	37 (10.3%)	187 (51.6%)	10.4	10.5
Coarse Insoluble Fragments	1.1×10^4 (48.9%)	1.1×10^4 (51.1%)	0 (0%)	112	1.9
Coarse Soluble Fragments	2.1×10^5 (70.7%)	4.2×10^4 (13.9%)	4.7×10^4 (15.4%)	4650	5.6
Coarse Insoluble Fibres	207 (30.4%)	473 (69.6%)	0 (0%)	4.1	2.2
Coarse Soluble Fibres	4.7×10^4 (61.7%)	1.3×10^4 (17.3%)	1.6×10^4 (21.0%)	1164	5.5
Super-Coarse Insoluble Fragments	4.0×10^7 (60.5%)	2.6×10^7 (39.5%)	0.00 (0%)	6422	0.04
Super-Coarse Insoluble Fibres	4.2×10^6 (61.0%)	2.7×10^6 (39.0%)	0.00 (0%)	1260	0.7
Total	4.4×10^7 (60.58%)	2.9×10^7 (39.33%)	6.2×10^4 (0.09%)	1.36×10^4	0.07

Table 3. Global annual mean microplastic (fragments and fibres) aerosol budget showing deposition processes, burden in tonnes (1 tonne = 1000 kg), and lifetime across GLOMAP aerosol size modes in UKESM1.1-AMIP. Wet deposition can be calculated here as the sum of impaction scavenging (washout) and nucleation scavenging (rainout). Percentages indicate the total fraction of loss that each pathway is responsible for within each size mode. Fibres are only present in the coarse soluble, coarse insoluble, and super-coarse insoluble ~~mode~~modes.

Atmospheric lifetimes are longer for smaller particles as expected (Seinfeld and Pandis, 2016), with the greatest atmospheric lifetime occurring in the Aitken soluble mode (~~17.15~~16.9 days). Atmospheric lifetimes are also longer for hydrophilic microplastics. Greater atmospheric lifetimes of hydrophilic microplastics (Table 3) potentially highlighting their ability to be incorporated into clouds and water vapour, after which they are carried with the subsequent atmospheric movement. This enables them to travel longer distances, especially if they are embedded in large weather systems like cyclones or fronts (Ryan et al., 2023).

Supplementary Table A2 presents the deposition fluxes of microplastics across different size modes as in Table 3, but partitioned between land and ocean. For smaller microplastics, deposition occurs preferentially over land, with Aitken and accumulation mode microplastics exhibiting the highest land-to-ocean deposition ratios. In contrast, larger microplastic modes show greater deposition occurring over the ocean~~.~~, up to 43% for coarse mode fibres. Microplastic fibres show greater deposition over the ocean than microplastic fragments.

~~The more diffuse spatial patterns and better atmospheric mixing for soluble microplastics~~ Table 4 compares the estimated emissions, burden, lifetimes, and deposition of microplastics within UKESM1.1 to previous microplastic modelling studies (Brahney et al., 2021; Evangeliou et al., 2022; Fu et al., 2023; Yang et al., 2025), as well as the size ranges modelled. Emissions (73.4 Tg/year) and deposition fluxes (73.26 Tg/year) in this study are greater than those modelled previously and are around 4.5x greater than the previous version of the emissions modelled in Evangeliou et al. (2022). However, most of this burden

corresponds to microplastics in the 100 - 250 µm size bin from the emissions dataset, which are not included in any of the other microplastic modelling studies, and are not atmospherically relevant. When this size bin is excluded, the emissions decrease to 16 Tg/year. Despite large emissions and deposition rates, the observed microplastic burden (0.0136 Tg) is smaller than the burden reported in Yang et al. (2025), who see significantly longer microplastic lifetimes. Brahney et al. (2021) estimate microplastic lifetimes from 0.04 to 6.5 days when assessing microplastics of sizes between 0.3 and 70 µm. This matches well with the results seen for the coarse (1.9 - 5.6 days) and super-coarse (~~Figures A2~~0.04 - ~~A4) and greater atmospheric lifetimes (Table 3) potentially highlights the ability of soluble microplastics to be incorporated into clouds and water vapour, after which they are carried with the subsequent atmospheric movement. This enables them to travel longer distances, especially if they are embedded in large weather systems like cyclones or fronts (Ryan et al., 2023).~~ 0.7 days) modes that align with their modelled size ranges.

Study	Emissions (Tg/yr)	Burden (Tg)	Lifetime (days)	Deposition (Tg/year)	Sizes (µm)	
This study	73.4	0.0136	0.04 - 16.9	73.26	0.005 - 250 (fragments)	10 - 3000 (fibres)
Yang et al. (2025)	10	0.03	0.9 - 365	10	0.5 - 70	
Brahney et al. (2021)	8.6	*	0.04 - 6.5	*	0.3 - 70	
Evangeliou et al. (2022)	16.1	*	2.5 - 8.3	16	10 – 250 (fragments),	10 – 3000 (fibres)
Fu et al. (2023)	0.324	0.0006	10.68	0.000322	0.3 - 70	

Table 4. Estimated emissions, burden, lifetime and deposition of microplastics, comparing this study with previous microplastic modelling studies. Entries with a asterisk denote values not reported in that study. High emissions in our study mostly correspond to the 100 - 250 µm size bin and drop to 16 Tg/year when this bin is excluded.

3.4 Comparison with total aerosol concentration

Table 5 compares present-day microplastic concentrations relative to the total aerosol concentrations within UKESM1.1-AMIP. Across all size modes, microplastics represent a minor percentage of the total aerosol number concentration, with total microplastic particles comprising ~~0.0005~~0.02% of the total atmospheric aerosol number concentration. The greatest relative contribution occurs within the super-coarse insoluble mode, where microplastics account for ~~0.0407~~0.61% of total aerosol particles. ~~This higher percentage likely reflects the number of other represented super-coarse mode aerosols in GLOMAP, which is currently limited to super-coarse insoluble mode dust (see Table 1).~~

The ~~insoluble percentage of~~ percentage of insoluble Aitken, accumulation, and coarse mode microplastics display ~~slightly~~ higher relative contributions to total aerosol than their soluble counterparts. This results from the lower number of aerosol species represented in the insoluble modes (see Table 1) and leads to a greater proportional influence of microplastic particles, which are only emitted into the insoluble modes. However, even in these cases, microplastic number concentrations remain orders of magnitude lower than the total aerosol concentration, suggesting that their direct influence on aerosol number concentrations and CCN formation is likely minimal at current concentrations. This is reinforced by Supplementary Figure A6,

Size Mode	Microplastics (m^{-3})	Total Aerosol (m^{-3})	Percent (%)
Aitken Insoluble	1.84×10^4	1.40×10^7	0.13
Aitken Soluble	3.26×10^4	2.22×10^8	0.014
Accumulation Insoluble	3218	9.15×10^5	0.35
Accumulation Soluble	11052	4.43×10^7	0.025
Coarse Insoluble	517	1.56×10^5	0.33
Coarse Soluble	512	2.76×10^5	0.19
Super-Coarse Insoluble	2.95	486	0.61
Total	$\sim 6.6 \times 10^4$	$\sim 2.8 \times 10^8$	0.02

Table 5. Global annual-mean number concentrations of microplastic (fragments and fibres combined) and total aerosol particles (m^{-3}) across GLOMAP aerosol size modes in UKESM1.1-AMIP. The percentage that microplastic contribute to total aerosol is also displayed.

which shows spatial patterns and differences between microplastic and the control simulations for aerosol optical depth (AOD), CCN, and cloud droplet number concentration (CDNC). ~~Spatial patterns~~ For microplastic fragments, spatial patterns mostly remain consistent across the simulations, with only minor regional variations compared to the control. Only a few isolated regions exhibit statistically significant changes, which are inconsistent across the spatial patterns for AOD, CCN and CDNC. For microplastic fibres, the trend is similar, except that the AOD indicates statistically significant differences up to 30% over the ocean.

3.5 Comparison with observations

To evaluate model performance, the observational dataset described in Section 2.6 is divided into two categories: active sampling studies reporting atmospheric microplastic number concentrations, and deposition studies reporting microplastic deposition fluxes. We note some difficulties with this approach due to both the limited observations and the lack of standardisation across current observation methods; for sample collection, sample preparation and sample analysis. Observations are compared to the corresponding UKESM1.1-AMIP output by selecting the nearest model grid cell in both latitude and longitude to allow for the best comparison. Because many of the observation studies have detection limits down to ~~2~~2-10 µm, only model output corresponding to the super-coarse mode (fragments and fibres with diameter greater than 2.5 µm combined) is assessed. We also compare UKESM1.1-AMIP coarse insoluble mode output with two studies reporting nanoplastic concentrations (Materić et al., 2021; Kau et al., 2024). Figure 6 shows a spatial map of the available observational data for both active sampling and deposition, and a comparison with UKESM1.1-AMIP output. The comparison between the observations and model output is separated between land and ocean, although reported correlation coefficient (r) values and root mean

square error (RMSE) values are for land and ocean combined. The two nanoplastic studies are denoted as stars, and have units of ng m^{-3} for active sampling and kg km^{-2} yr^{-1} for deposition.

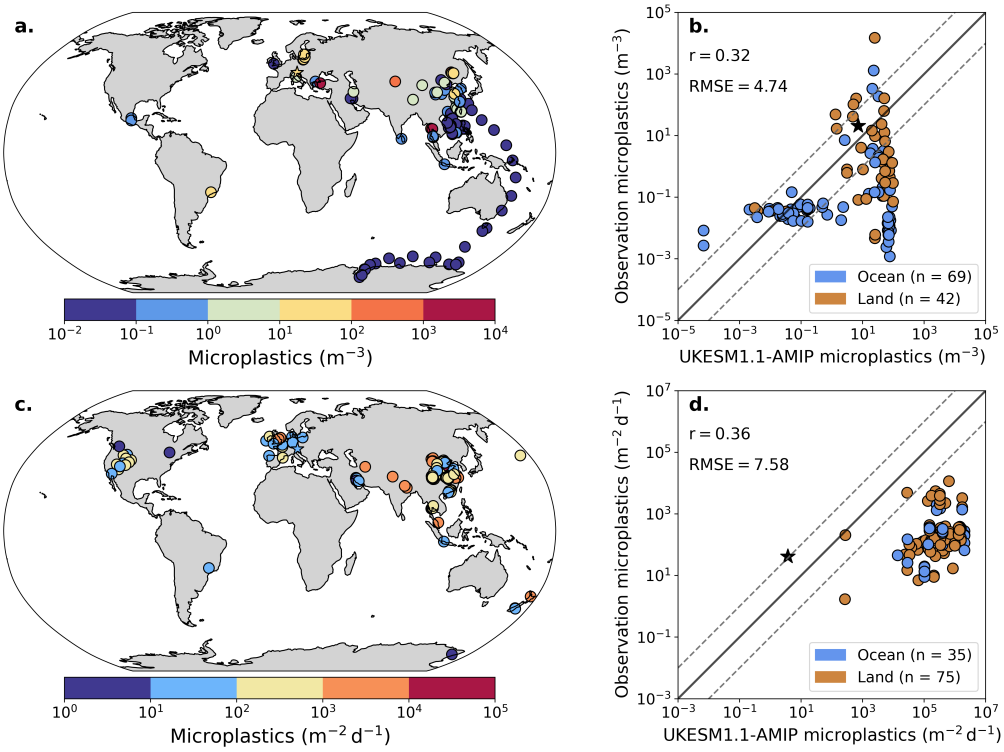

Figure 6. (a) Available observational microplastic number concentrations from active sampling studies (b) Comparison of observed concentrations from (a) with UKESM1.1-AMIP surface microplastic number concentrations at the nearest model grid cell (c) Available observational microplastic deposition fluxes from deposition studies (d) Comparison of observed deposition fluxes from (c) with UKESM1.1-AMIP microplastic deposition rates (combined wet and dry) at the nearest model grid cell. The correlation coefficients (r) and root mean square errors (RMSE) across (b) and (d) are calculated in log space, for the ocean and land measurements combined. The 1:1 (solid) and 1:10/10:1 (dashed) lines are plotted on (b) and (d) for reference. The star markers represent the two nanoplastics studies and related UKESM1.1-AMIP values, with units of ng m^{-3} for active sampling and kg km^{-2} yr^{-1} for deposition.

For active sampling studies, Figure 6a shows a regional bias with most studies undertaken in Europe and Asia. The model generally simulates greater microplastic concentrations than the observations, often by a few orders of magnitude, and with a poor correlation coefficient of r ~~= 0.35~~ = 0.32 and RMSE of ~~5.09~~ 4.74 (Figure 6b). ~~This is particularly evident across studies reporting low observed concentrations , where the model simulates~~ The separation between ocean and land shows two distinct behaviours. Over land the model simulates narrow range of concentrations (10^0 to 10^2 m^{-3}), while the observations show a wide range of concentrations (10^{-3} to 10^4 m^{-3}) Over the oceans, the model shows a large range ~~of microplastic~~

~~concentrations . However the majority of these studies are~~ in concentrations (10^{-4} to 10^{2} m^{-3}) while the observations show a narrower range (10^{-3} to 10^{-1} m^{-3}). Many points sampled over the ocean ~~during~~ correspond to a single observational study by Chen et al. (2023), which had a lower detection limit of 20 µm, and may not be representative of the microplastic ~~concentration~~concentrations in these regions. Figure 6c also shows that the observations of microplastic deposition are biased towards European and Asian locations. UKESM1.1-AMIP simulates greater deposition fluxes as compared to observations at almost all data points. Comparisons with the model shows slightly ~~lower~~ higher correlation coefficient of r ~~= 0.28, but a reduced RMSE of 3.85~~ = 0.36, but an increased RMSE of 7.58 (Figure 6d).

The general disagreement between the model and observations is unsurprising, as ~~observations represent~~ the microplastic emissions going into the model have high levels of uncertainty. Physical processes that are relevant for microplastics such as wet deposition, CCN/INP capabilities, and impacts of ageing on microplastics are also poorly constrained, so may not be accurately represented within UKESM1.1 currently. Additional difficulty in comparing the model with observations arises from observations representing a point source while the model output is the average over each latitude/longitude grid cell. Regions of high spatial variability such as around urban population centres would be most impacted by this discrepancy. Furthermore, many of the observational studies to date used micro-Fourier Transform Infrared Spectroscopy (µFTIR), which can only analyse microplastics of diameter 11 µm and larger (Allen et al., 2022), i.e. it cannot resolve microplastics down to the 2.5 µm threshold of the UKESM1.1 super-coarse mode (Table ~~2~~1). This also accounts for some of the differences between the observations and the model. The observations themselves are also uncertain due to variability in sampling and analysis methodologies and experimental setups. For example, deposition studies are sensitive to the sampled period microplastics are collected for (Aves et al., 2024).

The two nanoplastic studies show relatively good agreement with UKESM1.1-AMIP output, although the model simulates lower concentrations than those observed. Agreement with the current best estimates of microplastic observations at this size range provides some support for the extrapolated emissions methodology. However, the comparison remains highly uncertain due to the limited number of available studies and the estimated nature of modelled values at the nanoplastic scale.

4 Conclusions

In this study, we introduced atmospheric microplastic as an aerosol species into UKESM1.1, then presented results of global microplastic concentration and deposition by running UKESM1.1 in an atmosphere only configuration. Assessing the vertical transport of microplastics indicates that the smaller microplastics are ~~well mixed in the~~ present throughout troposphere, with some microplastics also reaching the stratosphere~~in small numbers (Figures 3, 4).~~ . Compared to total aerosol number concentrations, microplastics currently contribute a minor fraction. With global plastic production projected to increase substantially over the coming decades (Geyer et al., 2017), microplastic emissions and consequently their contribution to total atmospheric

aerosol concentrations are expected to grow. This is particularly relevant in regions influenced by strong sources of microplastics such as population centres which contribute through tyre-wear particles and microplastic fibres from textiles.

The representation of microplastics in UKESM1.1 has high levels of uncertainty, largely due to the limited ~~available~~ availability of observational data, both going into the emissions used in the model and for comparison with model output. The input of microplastics into climate models will require constant updating as our understanding of airborne microplastics increases, through both increased sampling with good global coverage and the standardisation of collection and ~~and~~ analysis methodology. ~~Another large source of model uncertainty is the currently representation of microplastic fibres which are assumed to be spherical. Fibres need to be treated as non-spherical particles with different settling velocities to microplastic fragments due to their shape (Tatsii et al., 2024). Future iterations of the microplastics scheme will seek to incorporate better emissions estimates and improve the representation of microplastic fibres.~~ The microplastic modelling framework can easily be updated with new emissions as future observational efforts help constrain microplastic concentrations and reduce uncertainties.

~~Compared to total aerosol number concentrations , microplastics currently contribute a minor fraction (Table 5). With global plastic production projected to increase substantially over the coming decades (Geyer et al., 2017), microplastic emissions and consequently their contribution to atmospheric aerosol concentrations are expected to grow. This is particularly relevant in regions influenced by strong sources of microplastics such as population centres which contribute through tyre-wear particles and microplastic fibres from textiles.~~

The incorporation of microplastics into UKESM1.1 provides a crucial step toward quantifying their present atmospheric burdens and understanding their impact on the climate. It also paves the way for future studies assessing human exposure to microplastics. The ability to simulate future emission scenarios of microplastics with UKESM1.1 allows for assessment of long-term impacts, highlighting the importance of including microplastics in Earth system models as plastic pollution continues to escalate.

Code and data availability. Due to intellectual property rights restrictions, we cannot provide either the source code or documentation papers for the UM. The data used to produce the figures and tables is available at https://doi.org/10.5281/zenodo.15127661 (McErlich, 2025).

Appendix A

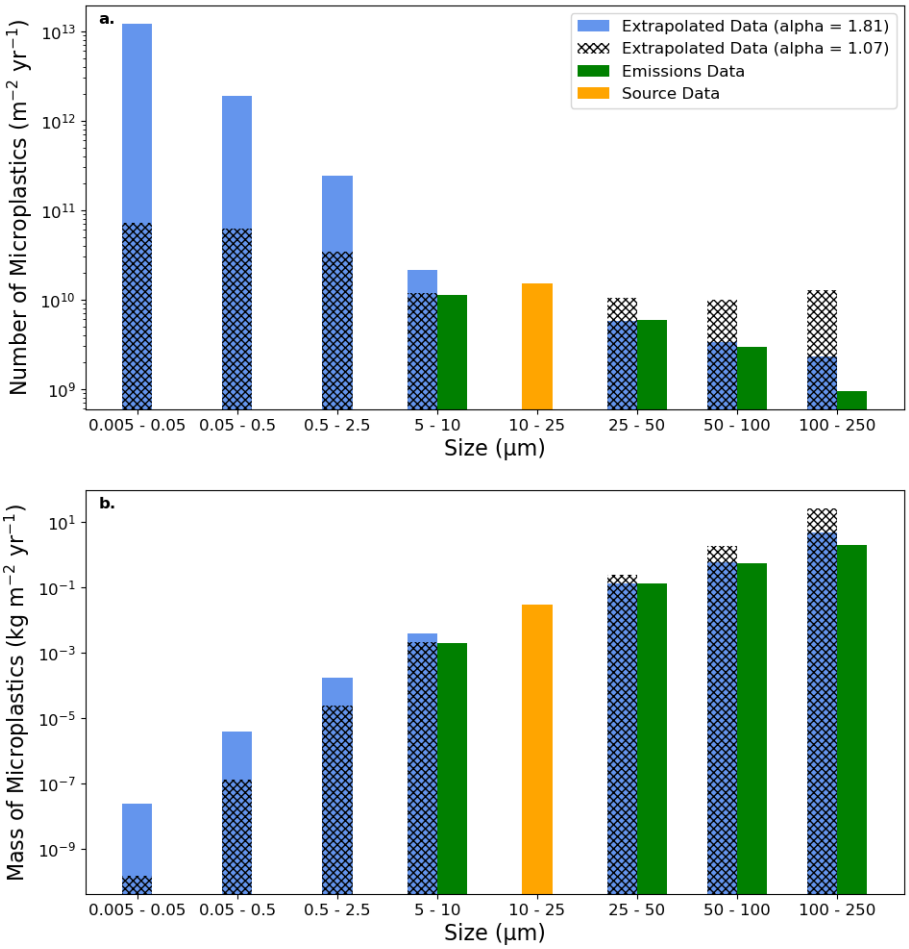

Figure A1. Microplastic emissions extrapolated across varying size bins for (a) number concentration and (b) mass concentration. Green bars represent reference emissions data from (Evangeliou et al., 2022). The orange bar indicates the bin from which emissions were extrapolated for input to the model (blue bars, alpha = 1.81). The hatching indicates the lower range of the extrapolation uncertainty (alpha = 1.07).

Author	Title	Year
Dris et al.	Synthetic fibers in atmospheric fallout: A source of microplastics in the environment?	2016
Cai et al.	Characteristic of microplastics in the atmospheric fallout from Dongguan city, China: preliminary research and first evidence	2017
Liu et al.	Source and potential risk assessment of suspended atmospheric microplastics in Shanghai	2019
Liu et al.	Accurate quantification and transport estimation of suspended atmospheric microplastics in megacities: Implications for human health	2019
Allen et al.	Atmospheric transport and deposition of microplastics in a remote mountain catchment	2019
Liu et al.	Consistent Transport of Terrestrial Microplastics to the Ocean through Atmosphere	2019
Liu et al.	Global inventory of atmospheric fibrous microplastics input into the ocean: An implication from the indoor origin	2020
Allen et al.	Examination of the ocean as a source for atmospheric microplastics	2020
Roblin et al.	Ambient Atmospheric Deposition of Anthropogenic Microfibers and Microplastics on the Western Periphery of Europe (Ireland)	2020
Knobloch et al.	Comparison of Deposition Sampling Methods to Collect Airborne Microplastics in Christchurch, New Zealand	2021
Dong et al.	Microplastics in a Remote Lake Basin of the Tibetan Plateau: Impacts of Atmospheric Transport and Glacial Melting	2021
Szewc et al.	Atmospheric deposition of microplastics in the coastal zone: Characteristics and relationship with meteorological factors	2021
Liao et al.	Airborne microplastics in indoor and outdoor environments of a coastal city in Eastern China	2021
Huang et al.	Atmospheric transport and deposition of microplastics in a subtropical urban environment	2021
Materić et al.	Nanoplastics transport to the remote, high-altitude Alps	2021
Jenner et al.	Outdoor Atmospheric Microplastics within the Humber Region (United Kingdom): Quantification and Chemical Characterisation of Deposited Particles Present	2022
Ferrero et al.	Airborne and marine microplastics from an oceanographic survey at the Baltic Sea: An emerging role of air-sea interaction?	2022
Huang et al.	Are we ignoring the role of urban forests in intercepting atmospheric microplastics?	2022
Hu et al.	Emission of airborne microplastics from municipal solid waste transfer stations in downtown	2022
Perera et al.	Airborne Microplastics in Indoor and Outdoor Environments of a Developing Country in South Asia: Abundance, Distribution, Morphology, and Possible Sources	2022
Shruti et al.	Occurrence and characteristics of atmospheric microplastics in Mexico City	2022
Fan et al.	Evidence and Mass Quantification of Atmospheric Microplastics in a Coastal New Zealand City	2022

Author	Title	Year
Amato-Lourenço et al.	Airborne microplastics and SARS-CoV-2 in total suspended particles in the area surrounding the largest medical centre in Latin America	2022
Ding et al.	Atmospheric microplastics in the Northwestern Pacific Ocean: Distribution, source, and deposition	2022
Jia et al.	Atmospheric deposition of microplastics in the megalopolis (Shanghai) during rainy season: Characteristics, influence factors, and source	2022
Welsh et al.	Atmospheric deposition of anthropogenic particles and microplastics in south-central Ontario, Canada	2022
Sarathana and Winijkul	Concentrations of Airborne Microplastics during the Dry Season at Five Locations in Bangkok Metropolitan Region, Thailand	2022
Romarate et al.	Breathing plastics in Metro Manila, Philippines: presence of suspended atmospheric microplastics in ambient air	2023
Celik-Saglam et al.	Evaluation of levels and sources of microplastics and phthalic acid esters and their relationships in the atmosphere of highly industrialized and urbanized Gebze, Türkiye	2023
Huang et al.	Mitigating airborne microplastics pollution from perspectives of precipitation and underlying surface types	2023
Kyriakoudes and Turner	Suspended and deposited microplastics in the coastal atmosphere of southwest England	2023
Yuan et al.	Atmospheric microplastics at a southern China metropolis: Occurrence, deposition flux, exposure risk and washout effect of rainfall	2023
Yuan et al.	Vertical distribution and transport of microplastics in the urban atmosphere: New insights from field observations	2023
Li et al.	Atmospheric deposition of microplastics in a rural region of North China Plain	2023
Zhang et al.	Characteristics, sources and influencing factors of atmospheric deposition of microplastics in three different ecosystems of Beijing, China	2023
Liu et al.	Occurrence of microplastics in the seawater and atmosphere of the South China Sea: Pollution patterns and interrelationship	2023
Chen et al.	Long-range atmospheric transport of microplastics across the southern hemisphere	2023
Parashar and Hait	Plastic rain - Atmospheric microplastics deposition in urban and peri-urban areas of Patna City, Bihar, India: Distribution, characteristics, transport, and source analysis	2023
Abbasi et al.	Microplastics in the atmosphere of Ahvaz City, Iran	2023
Klein et al.	Spatial distribution of atmospheric microplastics in bulk-deposition of urban and rural environments - A one-year follow-up study in northern Germany	2023
Dehhaghi and Pardakhti	Characterization of microplastics in the atmosphere of megacity Tehran (Iran)	2023

Author	Title	Year
Chang et al.	First quantification and chemical characterization of atmospheric microplastics observed in Seoul, South Korea	2023
Zhao et al.	Occurrence, characteristics, and factors influencing the atmospheric microplastics around Jiaozhou Bay, the Yellow Sea	2023
Limsiriwong and Winijkul	Evaluating Personal Exposure to Airborne Microplastics across Various Work Environments in Pathum Thani Province, Thailand	2023
Chandrakanthan et al.	Airborne microplastics in a suburban location in the desert southwest: Occurrence and identification challenges	2023
Zhu et al.	Atmospheric deposition is an important pathway for inputting microplastics: Insight into the spatiotemporal distribution and deposition flux in a mega city	2024
Ferraz et al.	Atmospheric microplastics deposition assessment in a countryside municipality in Southeastern Brazil: A case study at a state elementary school	2024
Jiang et al.	Pollution characteristics and potential health effects of airborne microplastics and culturable microorganisms during urban haze in Harbin, China	2024
Wang et al.	An important source of terrestrial microplastics-atmospheric deposition: A microplastics survey based on Shaanxi, China	2024
Xu et al.	Microplastics in the atmospheric of the eastern coast of China: different function areas reflecting various sources and transport	2024
Jung et al.	Spatial and seasonal variations of atmospheric microplastics in high and low population density areas at the intersection of tropical and subtropical regions	2024
Rao et al.	New insights into the long-term dynamics and deposition-suspension distribution of atmospheric microplastics in an urban area	2024
Winijkul et al.	Depositions of airborne microplastics during the wet and dry seasons in Pathum Thani, Thailand	2024
Liu et al.	Comparative study on physicochemical characteristics of atmospheric microplastics in winter in inland and coastal megacities: A case of Beijing and Shanghai, China	2024
Chen et al.	Atmospheric deposition of microplastics at a western China metropolis: Relationship with underlying surface types and human exposure	2024
Abbasi et al.	Atmospheric deposition of microplastics in Shiraz, Iran	2024
Aves et al.	Modelled sources of airborne microplastics collected at a remote Southern Hemisphere site	2024
Guo et al.	Characteristics, sources and potential ecological risk of atmospheric microplastics in Lhasa city	2024
Dahal and Babel	Abundance and characteristics of atmospheric microplastics deposition in indoor and outdoor environments in Bangkok, Thailand	2024

Author	Title	Year
Mandal et al.	Quantification and characterization of airborne microplastics and their possible hazards: a case study from an urban sprawl in eastern India	2024
López-Rosales et al.	A reliable method to determine airborne microplastics using quantum cascade laser infrared spectrometry	2024
Xu et al.	Characterization of atmospheric microplastics in Hangzhou, a megacity of the Yangtze river delta, China	2024
Long et al.	Atmospheric Microplastics Emission Source Potentials and Deposition Patterns in Semi-Arid Croplands of Northern China	2024
Lu et al.	Occurrence, influencing factors and sources of atmospheric microplastics in peri-urban farmland ecosystems of Beijing, China	2024
Myat et al.	Airborne microplastics in the roadside and residential areas of Southern Thailand	2024
Du et al.	Distribution Characteristics of Atmospheric Microplastics in Typical Desert Agricultural Regions	2024
Illuminati et al.	Microplastics in bulk atmospheric deposition along the coastal region of Victoria Land, Antarctica	2024
Wang et al.	Characteristics of microplastics in the atmosphere of Anyang City	2024
Ankit et al.	Atmospheric deposition of microplastics in an urban conglomerate near to the foothills of Indian Himalayas: Investigating the quantity, chemical character, possible sources and transport mechanisms	2024
Wei et al.	Remote Mountainous Area Inevitably Becomes Temporal Sink for Microplastics Driven by Atmospheric Transport	2024
Adhikari et al.	Accumulation of microplastics in soil after long-term application of biosolids and atmospheric deposition	2024
Kernchen et al.	Atmospheric deposition studies of microplastics in Central Germany	2024
Chenappan et al.	Quantification and characterization of airborne microplastics in the coastal area of Terengganu, Malaysia	2024
Kau et al.	Fine micro- and nanoplastics concentrations in particulate matter samples from the high alpine site Sonnblick, Austria	2024
Jung et al.	Assessing the impact of marine litter hotspot on atmospheric microplastics: A study of a coastal village	2025
Mokammel et al.	Airborne microplastics pollution in municipal solid waste processing and disposal complex: Concentration, characterization, and composition	2025
Liu et al.	Physicochemical characteristics of airborne microplastics of a typical coastal city in the Yangtze River Delta Region, China	2025

Author	Title	Year

Table A1. Summary of collated studies reporting airborne microplastics. A full table with reported microplastic concentrations and latitude/-longitude information is available at McErlich (2025).

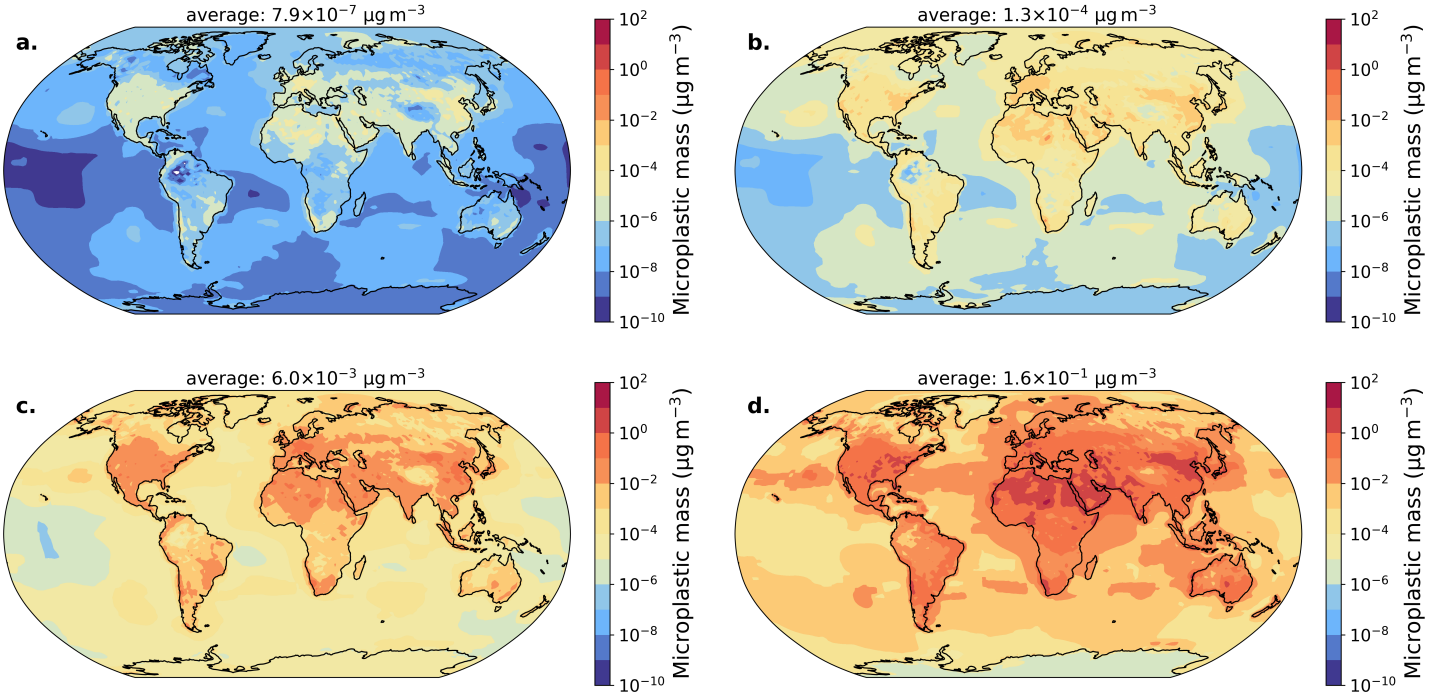

Figure A2. Annual-mean surface mass concentration of microplastic fragments in UKESM1.1-AMIP (2005–2014) for (a) Aitken, (b) accumulation, (c) coarse, and (d) super-coarse insoluble modes. The global-, area weighted average is displayed on each subplot.

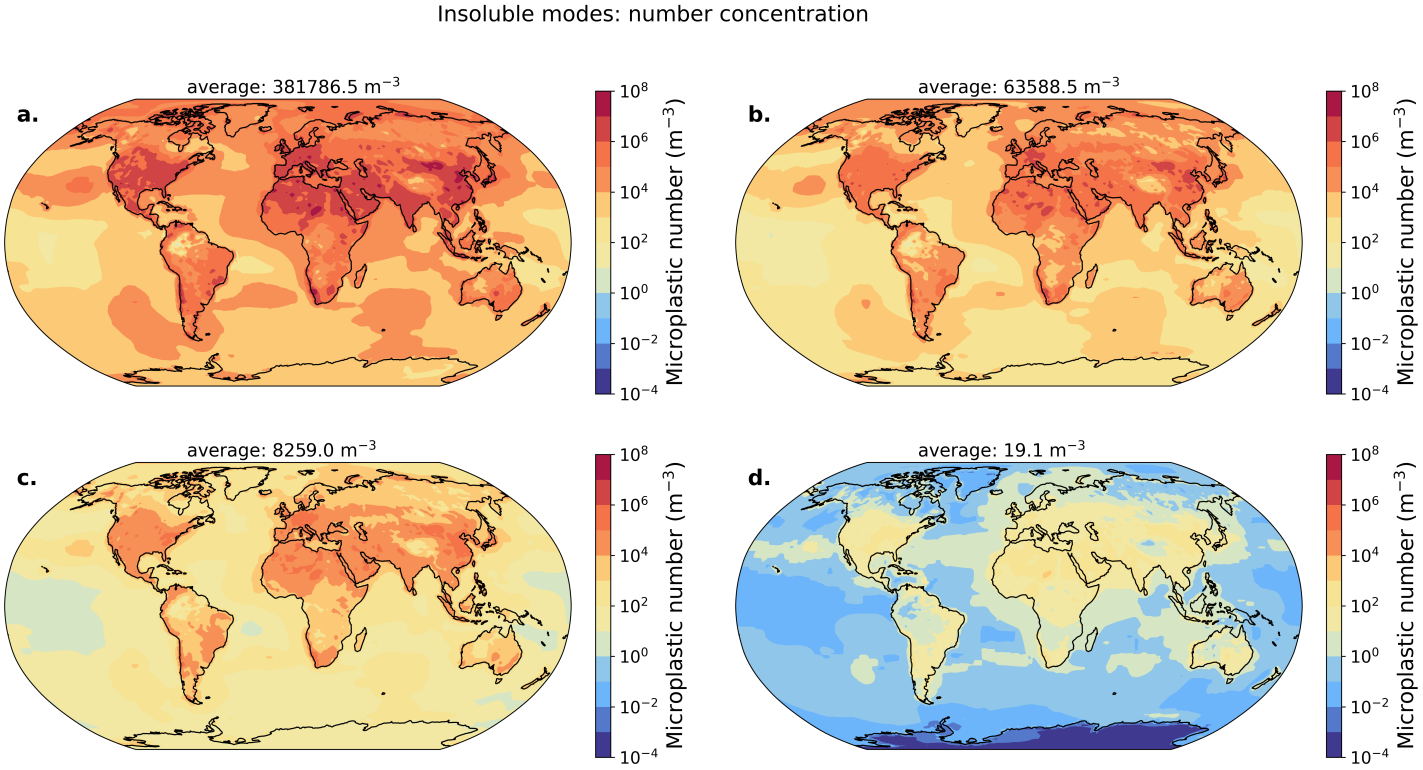

Figure A3. As for Figure A2, but showing microplastic number concentrations.

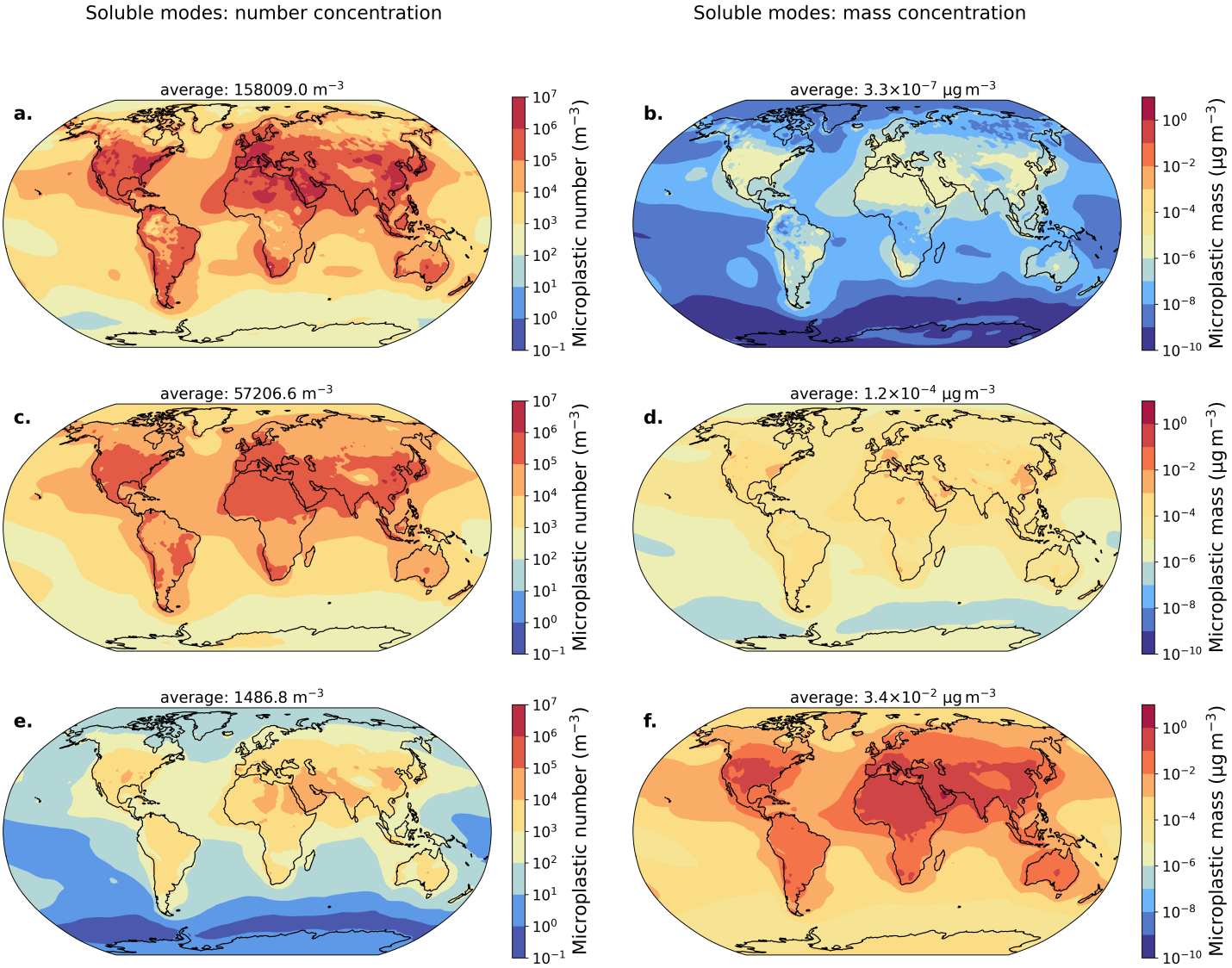

Figure A4. Annual-mean surface number concentration of microplastic fragments in UKESM1.1-AMIP (2005–2014) for (a) Aitken soluble mode number (b) Aitken soluble mode mass (c) accumulation soluble mode number (d) accumulation soluble mode mass (e) coarse soluble mode number (f) coarse soluble mode mass. The global-, area weighted average is displayed on each subplot.

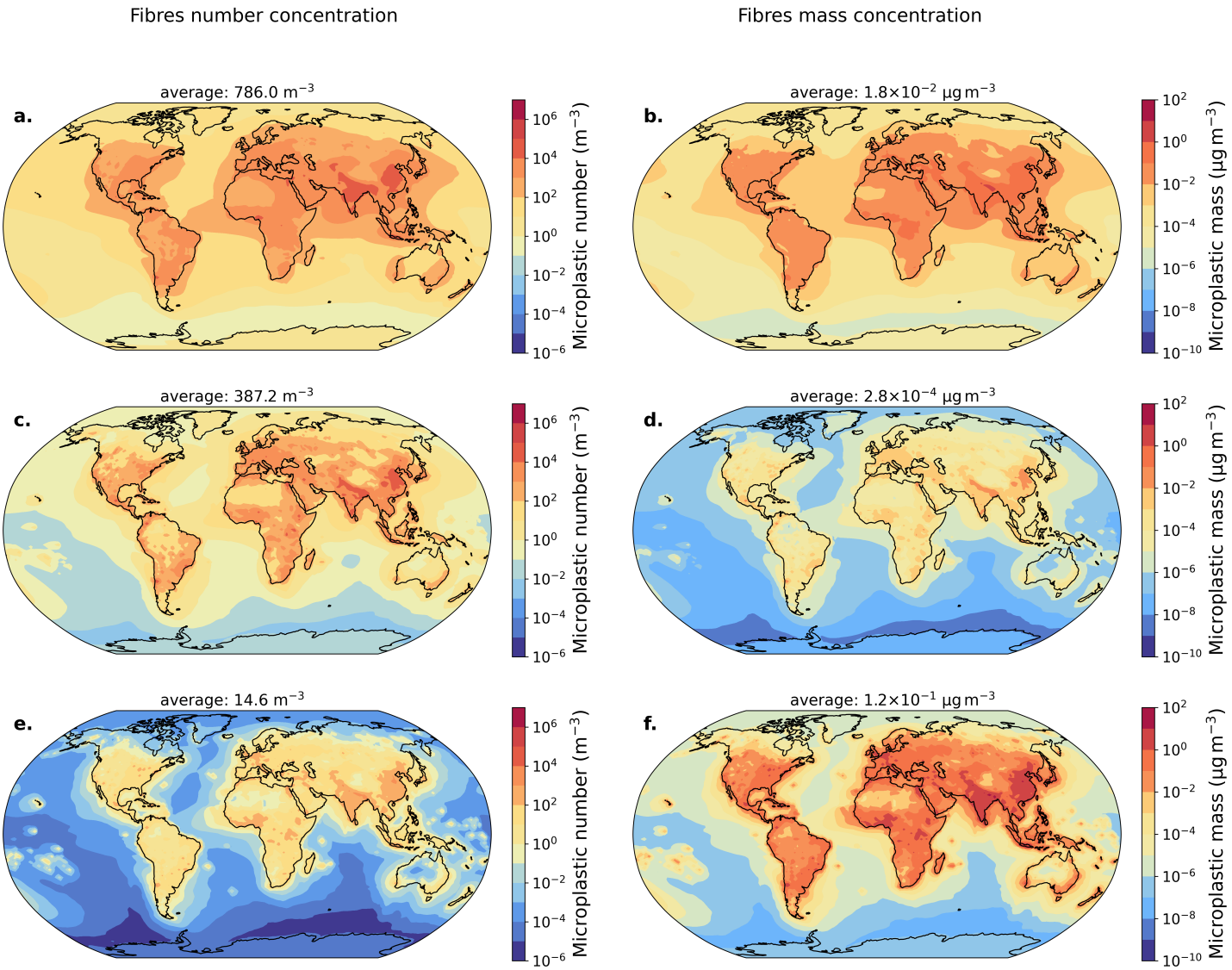

Figure A5. Annual surface concentrations of microplastic fibres in UKESM1.1-AMIP (2005–2014) for (a) coarse soluble mode number (b) coarse soluble mode mass (c) coarse insoluble mode number (d) coarse insoluble mode mass (e) super-coarse insoluble mode number and (~~b~~f) super-coarse insoluble mode mass. The global, area-weighted average is displayed on each subplot.

Size Mode	**Dry Deposition** (tonnes/yr)		**Impaction Scavenging** (tonnes/yr)		**Nucleation Scavenging** (tonnes/yr)		**Total Deposition** (tonnes/yr)	
	Land	**Ocean**	**Land**	**Ocean**	**Land**	**Ocean**	**Land**	**Ocean**
Aitken Fragments	1.19 (73.4%)	0.42 (26.6%)	0.11 (78.5%)	0.03 (22.5%)	0.075 (75.3%)	0.025 (24.7%)	1.37 (73.8%)	0.49 (26.2%)
Accumulation Fragments	194 (73.6%)	69 (26.4%)	56 (77.8%)	16 (22.2%)	146 (78.1%)	41 (21.9%)	396 (75.8%)	126 (24.1%)
Coarse Fragments	1.2×10^5 (54.2%)	1.0×10^5 (45.8%)	4.1×10^4 (77.5%)	1.2×10^4 (22.5%)	3.2×10^4 (68.5%)	1.5×10^4 (31.5%)	1.9×10^5 (60.1%)	1.3×10^5 (39.9%)
Super-coarse Fragments	2.7×10^7 (68.8%)	1.2×10^7 (31.2%)	2.0×10^6 (75.6%)	0.6×10^6 (24.4%)	0.00 (0.0%)	0.00 (0.0%)	4.7×10^7 (71.5%)	1.8×10^7 (28.5%)
Coarse Fibres	2.5×10^4 (53.5%)	2.2×10^4 (46.5%)	8772 (63.8%)	4973 (36.2%)	9609 (59.5%)	6546 (40.5%)	4.4×10^4 (56.6%)	3.4×10^4 (43.4%)
Super-coarse Fibres	2.4×10^6 (57.1%)	1.8×10^6 (42.9%)	1.6×10^6 (59.0%)	1.1×10^6 (41.0%)	0.00 (0.0%)	0.00 (0.0%)	4.0×10^6 (57.8%)	2.9×10^6 (42.2%)
Total	3.0×10^7 (67.6%)	1.4×10^7 (32.4%)	2.1×10^{67} (74.0%)	0.75×10^7 (26.0%)	4.2×10^4 (66.2%)	2.1×10^4 (33.8%)	5.1×10^7 (70.1%)	2.2×10^7 (29.9%)

Table A2. Deposition fluxes of microplastic (tonnes/year) for each deposition process and size mode, masked over land and ocean. Percentages indicate the fraction of each process occurring over land and ocean.

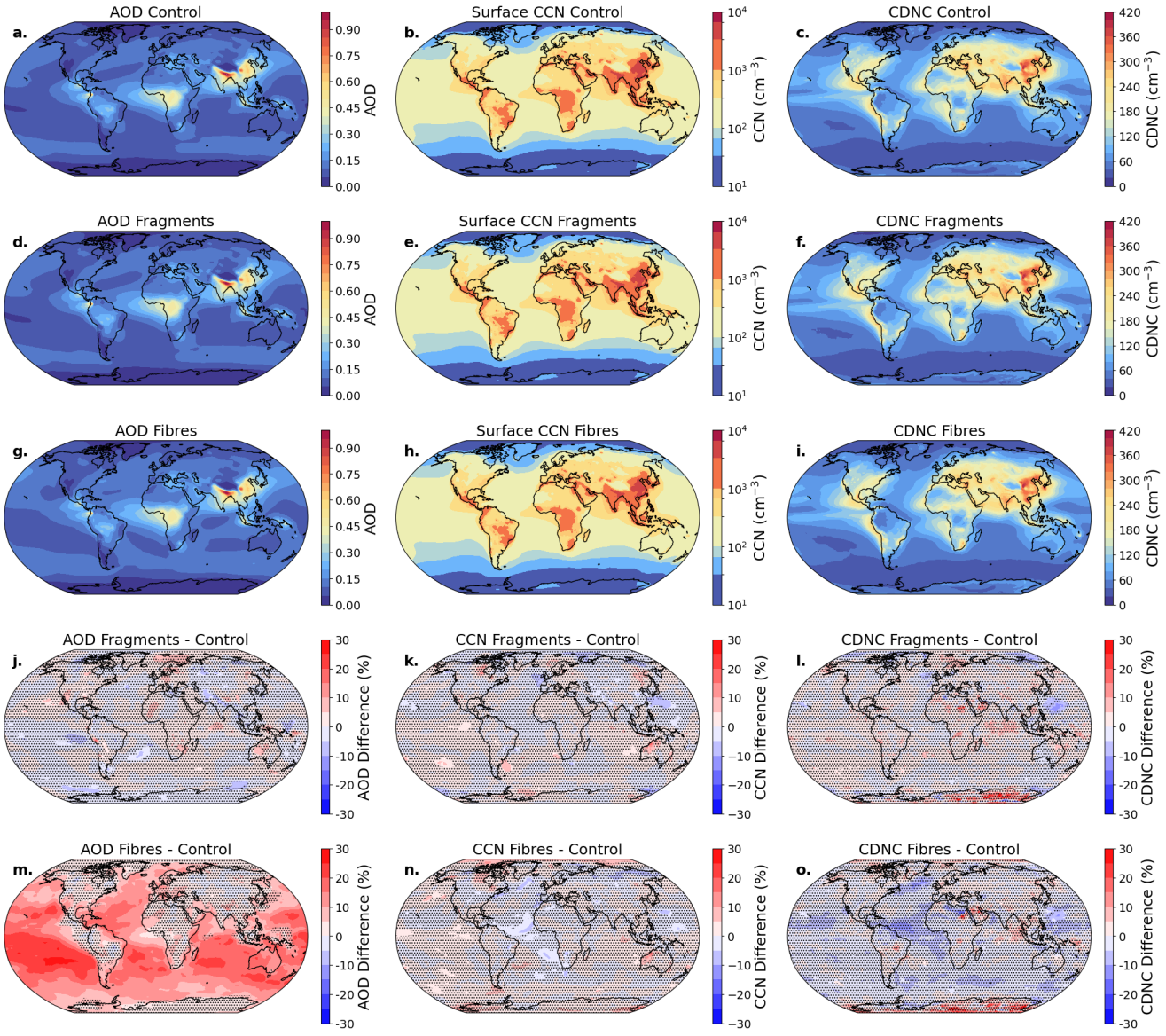

Figure A6. Annual mean aerosol optical depth (AOD), surface cloud condensation nuclei (CCN), and cloud droplet number concentration (CDNC) from UKESM1.1-AMIP (2005–2014) for microplastic fragments, fibres, and the control simulation. (a-c) AOD, CCN, and CDNC for the control simulation without microplastics respectively (d-f) same as (a-c) but for microplastic fragments (g-i) same as (a-c) but for microplastic fibres (j-i) show the percentage difference between the microplastic fragments and control simulations for each variable. (m-o) same as (j-i) but for microplastic fibres and control simulations. Stippling in the difference plots indicates areas where changes are not statistically significant at the 95% confidence level.

Author contributions. CM developed the microplastics scheme, with assistance from FG and AJH. CM performed the simulations and analysis, with assistance from LER and CH. AA provided the observational data. NE provided the microplastics emissions inventory. AJH made further technical developments to the microplastics scheme in order for it to be included in the UM at version 13.9 , with assistance from CM and CH. CM wrote the manuscript with assistance from all co-authors.

Competing interests. The authors declare they have no competing interests.

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