

## Microplastics and nanoplastics in the marine-atmosphere environment

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## 1 **Micro- and nano-plastics in the marine-atmosphere environment**

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78

79 **Abstract**

80 Effective management of marine micro(nano)plastic (MnP) depends on a good  
81 understanding of their sources and cycling. The discovery of atmospheric MnP transport  
82 and ocean-atmosphere exchange points to a highly complex marine plastic cycle. Yet,  
83 observations are currently limited. In this Perspective, we quantify marine-atmospheric  
84 MnP cycle processes and fluxes, with the aim of highlighting the remaining unknowns in  
85 atmospheric MnP transport. Up to 25 (a range of 0.013-25) million metric tons per year  
86 (Mt) of MnP are potentially being transported within the marine atmosphere and deposited  
87 in the oceans. However, the high uncertainty in these marine-atmosphere fluxes is related  
88 to data limitations and a lack of study inter-comparability. To address the uncertainties  
89 and remaining knowledge gaps in the marine-atmospheric MnP cycle, we propose a  
90 future global marine-atmospheric MnP observation strategy, incorporating novel sampling  
91 methods and the creation of a comparable, harmonised and global data set. Together  
92 with long-term observations and intensive investigations, this strategy will help define the  
93 trends in marine-atmospheric pollution and any responses to future policy and  
94 management actions.

95  
96  
97  
98 **Website summary:**

99 Atmospheric transport of microplastic could be a major source of plastic pollution to the  
100 ocean, yet observations currently remain limited. This Perspective quantifies the known  
101 budgets of the marine-atmospheric micro(nano)plastic cycle, and proposes a future  
102 global observation strategy.

103 **[H1] Introduction**

104 Over 368 million metric tons of single-use plastic were created in 2019 (refs. <sup>1,2</sup>) and is  
105 projected to increase further owing to rapid and inexpensive plastic production, non-  
106 circular economic models and a single-use plastic culture. Plastic pollution has been  
107 evidenced across all environmental compartments, including aquatic, soil and air<sup>3-6</sup>.  
108 Projections indicate plastic pollution will treble by 2040 under a business as usual  
109 scenario, up to ~80 million metric tons (Mt) of waste per year (based on 2016  
110 environmental plastic pollution estimates)<sup>7</sup>. Of the total managed and mismanaged plastic  
111 waste created, ~12% is projected to enter the aquatic environment and ~22% to enter the  
112 terrestrial environment, with an estimated ~60 Mt per year lost to just aquatic and  
113 terrestrial environmental compartments by 2030<sup>7,8</sup>. However, there is currently limited  
114 assessment of the atmospheric compartment.

115  
116 The global oceanic microplastic cycle<sup>9,10</sup> is currently quantified based on observational  
117 and modelled data of microplastics in marine and fresh water, biota and sediments, as  
118 these environments are frequently studied<sup>11-13</sup>. Terrestrial runoff, river discharge and  
119 marine currents carry micro(nano)plastic (MnP; see Box 1 for definitions) from terrestrial  
120 sources to distal areas such as the Arctic, Antarctic and deep-sea locations over months  
121 to years<sup>14</sup>. Whilst relatively slow, this mechanism is important in transporting MnP to  
122 remote areas where they can negatively impact marine life<sup>15,16</sup>. Although studied less,

123 atmospheric transport research similarly illustrates that wind can transport MnP at trans-  
124 continental and trans-oceanic scales<sup>17-20</sup>. Atmospheric transport is comparably much  
125 faster than oceanic transport, as it can convey particles from sources to remote locations  
126 over a matter of days to weeks<sup>18,20,21</sup>. Long-distance transport to remote and Polar  
127 Regions could occur through a combination of atmospheric and marine conveyance  
128 (Supplementary Note 1), enabling plastic pollutants to infiltrate and influence even the  
129 most remote and uninhabited ecosystems of Earth.

130  
131 Atmospheric MnP can also affect surface climate, and therefore ecosystem health, via  
132 theorised influences on surface albedo<sup>19</sup>, cloud formation<sup>22</sup> and radiative forcing<sup>23</sup>  
133 (Supplementary Note 2). Although MnPs have diverse colours, they are hypothesised to  
134 influence surface albedo and accelerate cryosphere melting when deposited on snow and  
135 ice<sup>19,24</sup>. In addition, laboratory-based experiments demonstrate that atmospheric MnP  
136 particles are effective ice nucleation particles, potentially influencing cloud lifetime and  
137 albedo<sup>22,25,26</sup>. Similarly, MnP have been modelled to cause positive and negative radiative  
138 forcing via direct effects, depending on their size and vertical distribution<sup>23</sup>. For example,  
139 greater radiation absorption and resultant atmospheric warming occurs when MnP are  
140 present throughout the troposphere<sup>23</sup>. While these theories have been hypothesised or  
141 modelled (with notable constraints and assumptions), physical monitoring and  
142 observation studies are urgently needed to validate and quantify MnP atmospheric  
143 influences. Critically, the only radiative forcing calculations performed to date were for  
144 non-pigmented polymers<sup>23</sup>.

145  
146 Beyond ecosystem health, MnPs are also an emergent pollutant of human health concern  
147 through ingestion and inhalation<sup>27,28</sup>. Potentially comparable to soot or black carbon,  
148 atmospheric MnP transported from proximal or distal sources can result in human  
149 exposure through direct inhalation and via the human food web through deposition on  
150 agricultural land and water reservoirs, inclusion or contamination during agricultural, food  
151 manufacturing and preparation activities. This atmospheric MnP is in addition to other  
152 sources of plastic widely used in agriculture, directly added to soils, used in food  
153 packaging, or uptake by seafood<sup>9,29-31</sup>. As a result, atmospheric MnP forms part of the  
154 threat to global sustainability and the ability of the global community to implement all or  
155 most of the United Nations Sustainable Development Goals<sup>32</sup>.

156  
157 In this Perspective, we synthesize current atmospheric MnP data and propose that the  
158 atmosphere provides an important but unconstrained flux of marine MnP. While  
159 atmospheric data is still limited, several studies have identified key processes that could  
160 substantially promote global transport to the oceans. Modelling suggests that there is  
161 considerable atmospheric transport of terrestrial MnP to marine environments<sup>18,19</sup>.  
162 Furthermore, the incorporation of atmospheric MnP transport processes into the marine  
163 MnP cycle highlights the importance of marine MnP export to the atmosphere and  
164 potential transportation to terrestrial environments. Therefore, it is important to quantify  
165 the atmospheric compartment (emission, transport and deposition) to obtain an accurate  
166 estimate of marine MnP fluxes. A collective effort is needed to better quantify and  
167 characterise the marine atmospheric MnP cycle, so that the roles of MnP in the  
168 atmosphere, ocean and land can be more fully understood.

170

## 171 [H1] Marine plastic cycle processes

172

173 Micro and nano plastic that is atmospherically transported to and deposited on the ocean  
174 surfaces can originate from a multitude of sources (both marine and terrestrial)<sup>33</sup> and can  
175 be conveyed long distances. However, quantitative assessment of atmospheric emission  
176 of MnP specific to land use type or activity is limited. This lack of quantification has  
177 resulted in numerous assumptions and uncertainties in global modelling and estimation  
178 of atmospheric MnP budgets and flux estimates. This section discusses what is known  
179 and unknown regarding the sources, transport and deposition of marine-atmospheric  
180 MnP.

181

182

183

## 184 [H2] Sources

185 Activities that result in atmospheric MnP creation and emission can generally be  
186 characterised as terrestrial or marine. Marine emission of MnP to the atmosphere is an  
187 emerging field of research and formative investigation in the field and laboratory point  
188 towards MnP ocean-air interface exchange. As such, the coastal zone is thought to serve  
189 as a source of MnP through beach sand erosion and entrainment, sea spray and bubble  
190 burst ejection along the surf zone due to wind and waves<sup>34-36</sup>. In the coastal and open-  
191 ocean environments, MnP particles could be scavenged from the water column by  
192 bubbles and ejected into the atmosphere when the bubbles burst<sup>37,38</sup>. As with coastal  
193 zone processes, wind and wave action could increase the rate of ocean emission of MnP,  
194 for example along the ever-changing boundary between Arctic and Antarctic sea water  
195 and glacial ice or sea ice edge<sup>39</sup>. Aquaculture, coastal and offshore fishing have also  
196 been identified as a source of marine MnP<sup>40</sup>.

197

198 The emission and (subsequent) atmospheric entrainment (the transition from surface to  
199 air followed by atmospheric transport) of agricultural soil MnPs have been quantified in  
200 the field and estimated in specific soils conditions (well sorted quartz sand, poorly-sorted  
201 organic soil, semi-arid soils)<sup>41,42</sup>. These studies, which focused on specific processes  
202 rather than the complex surface-atmosphere flux, suggest MnP emission of 0.08-1.48 mg  
203 m<sup>-2</sup> minute<sup>-1</sup> for relatively large microplastic particles (generally 100-200µm in size)<sup>41,42</sup>. It  
204 is acknowledged that there might be local or immediate (re-)deposition, but this is  
205 currently unquantified and requires further, focused research. However, if the values are  
206 used without localised (re-)deposition considerations. Acknowledging that 11% of  
207 habitable surface is agricultural (crop) land use (11 million km<sup>2</sup>)<sup>43</sup>, a global emission of  
208 0.0009 to 0.016 million metric tons (Mt) suspended per minute can be estimated when  
209 agricultural land is exposed to erosive wind (0.5–22m s<sup>-1</sup>)<sup>41</sup>. During strong wind events,  
210 there is potential for atmospheric emission of agricultural MnP to extend to the region of  
211 million metric tons per year. The wind erosion and emission rate of smaller MnP still needs  
212 to be determined.

213

214 Tyre and brake wear become atmospherically emitted and entrained through road use  
215 and vehicle movement<sup>44,45</sup>. Early estimates suggested potential tyre emissions of ~6 tons



216 km<sup>-1</sup> year<sup>-1</sup> <sup>46</sup>. However, published studies acknowledge the highly variable  
217 concentrations of MnP in road dust due to spatial, temporal and meteorological  
218 characteristics, road and vehicle per year conditions (for example country, season,  
219 vehicle type and road maintenance). Current tyre and brake wear atmospheric emissions  
220 are suggested to be up to ≤40% of total tyre and brake wear emissions, amounting to 0.2-  
221 5.5kg per capita for particles ≤10µm<sup>19,45</sup>. Alternative emission estimations are based on  
222 a constant tyre wear to CO<sub>2</sub> ratio (0.49 mg TWP g<sup>-1</sup> CO<sub>2</sub>) or using the Greenhouse gas–  
223 Air pollution Interactions and Synergies (GAINS)<sup>47</sup> model estimations (<0.25-~32 tonnes  
224 per year, based on region-specific, distance-driven and vehicle-type emission  
225 information). These different estimation techniques result in a global atmospheric flux of  
226 tyre and brake wear ranging from <0.15 to 4.3 million metric tons per year. It is important  
227 to note that many atmospheric MnP findings (MnP per m<sup>3</sup> or MnP per m<sup>2</sup>) do not include  
228 tyre or brake wear particles due to analytical difficulties.

229  
230 Cities and dense urban living are considered an atmospheric MnP source due to human  
231 activities (for example commerce, industry, transport, household)<sup>44,48,49</sup>, plastic use and  
232 waste management (landfills, recycling centres, incineration)<sup>49-53</sup>. While there is a  
233 growing dataset of urban atmospheric MnP quantitative characterisation, the atmospheric  
234 emission rates from specific materials, actions and environments are currently unknown.  
235 Within urban environments, atmospheric MnP has been quantified from 0.9MPm<sup>-3</sup> (Paris  
236 outdoor air<sup>54</sup>) to 5700 MP m<sup>-3</sup> (Beijing outdoor air<sup>55</sup>) (Supplementary Data, Figure 2).  
237 However, these estimates were reported without any differentiation to indicate the  
238 proportion of MnP transported to each location from a local or distal source, or the  
239 proportion occurring as local emission, or the quantity lost due to atmospheric transport  
240 away from the local urban source. One study has used field data extrapolation and simple  
241 transport modelling to estimate the indoor microplastic fibre contribution to marine MnP  
242 deposition, suggesting a contribution of 7-33 metric tons per year<sup>56</sup>. Due to the early stage  
243 in field observation and MnP source emission research, urban atmospheric MnP emission  
244 rates are very uncertain and currently based primarily on theoretical estimates.

245  
246

## 247 [H2] Transport and deposition

248 There have been numerous quantitative observations of MnPs in remote locations where  
249 plastic pollution is attributed to atmospheric transport. These include the Ecuadorian  
250 Andes<sup>57</sup>, French Pyrenees<sup>17</sup>, Italian Alps<sup>58</sup>, US conservation areas<sup>59</sup>, snow in the  
251 Arctic<sup>39,60</sup>, Nunavut (Canadian Arctic)<sup>61</sup>, Isle of Helgoland (Germany)<sup>39</sup>, Austrian and  
252 Swiss Alps<sup>20,39,62</sup>, the Iranian Plateau<sup>63</sup>, and the Tibetan Plateau<sup>64</sup>. Atmospheric transport  
253 of MnP particles is extensive, reaching hundreds to potentially thousands of kilometres  
254 from major emission sources (for example, cities, intensive agriculture, industry).  
255 Therefore, while there is limited quantitative field observation of atmospheric MnP, the  
256 observed atmospheric transport and modelling suggest the atmosphere to contain,  
257 transport and deposit MnPs throughout the marine environment.

258 There is a substantial body of literature on microplastics in the environment. However,  
259 most research is focused on the aquatic or terrestrial environments (855 and 366  
260 publications respectively in 2020)<sup>65,66</sup>. In total, over 70 published scientific studies (field  
261 or laboratory research) are on atmospheric MnP, of which only 6 focus on the marine

262 environment (Supplementary Data, Google Scholar, Web of Science and Scopus search).  
263 The concentration of suspended microplastic particles in urban air range up to 5700 MPm<sup>-3</sup>  
264 <sup>3</sup> (in Beijing<sup>55</sup>) and studies generally suggest that particle concentrations decrease with  
265 distance from city centres<sup>67</sup>.

266 Marine air samples generally present lower atmospheric microplastic concentrations  
267 compared to terrestrial levels. Marine atmospheric MnP concentrations of up to 0.06-1.37  
268 MP m<sup>-3</sup> have been reported over the North Atlantic Ocean, South China Sea, Indian  
269 Ocean and Western Pacific Ocean (Figure 2). However, this marine sampling comprises  
270 particles collected predominantly in the range of 20µm-5mm<sup>68-70</sup> (limited focus or analysis  
271 on the smaller particle size range, Supplementary Data) and is thus an underestimation.  
272 Comparatively, the Beijing and other terrestrial studies extend down to 5µm (limit of  
273 quantification), potentially resulting in relatively elevated particle counts given the  
274 increasing particle count with decreasing particle size. However, it has been shown that  
275 coastal air samples of wind in an onshore direction (blowing from the sea to the land) can  
276 carry elevated microplastic concentrations of ~2.9 MP m<sup>-3</sup>, rising to 19 MP m<sup>-3</sup> during  
277 turbulent sea conditions<sup>37</sup>. Bubble and sea spray studies of ocean chemical species  
278 suggest that this increase in atmospheric microplastic could be due to the bubble burst  
279 ejection process and spume entrainment<sup>71,72</sup>, where the bubble source (horizontally within  
280 the water column and spatially such as within a gyre or coastal environment) might be  
281 particularly important<sup>18,73</sup>.

282  
283 The deposition of airborne MnP has been measured across a range of terrestrial  
284 environments, but publication of marine MnP offshore measurements of air<sup>69</sup> and MnP  
285 deposited snow on ice floes<sup>39</sup> only commenced in 2019 (Supplementary Data). MnP  
286 particles collected using passive deposition sampling can present different particle counts  
287 and morphology compared to active (pumped) air samples<sup>54,70,74-76</sup>. This difference might  
288 be due to the different transport processes in action (for example scavenging, settling,  
289 convective or advective transport) or the sampling methodology (active versus passive  
290 sampling, deposition versus suspended particle sampling), and is an important area of  
291 future investigation.

292  
293 To quantify the marine atmospheric MnP flux, both air and depositional field studies must  
294 consider the full atmospheric transport process and quantify marine MnP flux. The  
295 morphology and quantitative characterisation of marine atmospheric MnP deposition  
296 beyond these polar regions are unknown, and thus marine deposition assessments are  
297 primarily theoretically modelled estimates due to lack of field data. The quantitative  
298 assessment of marine aquatic MnP particle ejection to the atmosphere and transport of  
299 these particles is also in its infancy, resulting in estimations based on limited field data.

300  
301 Thus, while current understanding of atmospheric MnP in the marine environment  
302 identifies the cyclic nature of MnP movement (ocean-atmosphere flux) the quantification  
303 of this flux (deposition, emission and atmospheric concentrations) require substantial  
304 further study.



## 306 [H1] Marine-atmosphere plastic flux

307 Atmosphere-ocean MnP interactions are important to understand so that the particle sizes  
308 and quantities can be identified. The atmosphere transports predominantly small micro-  
309 and nano-plastics compared to fluvial processes, and is a notably faster transport  
310 pathway, potentially resulting in substantial marine particle deposition and exchange  
311 between the ocean and atmosphere. Smaller micro and nanoplastics are also of concern  
312 to species and ecosystem health, therefore quantifying the marine atmospheric exchange  
313 and transport process is necessary to monitor marine ecosystem health. Conversely,  
314 quantifying the marine emission and atmospheric transport of MnPs to terrestrial  
315 environments is necessary as many remote areas, distal from terrestrial micro and  
316 nanoplastic sources, could be notably influenced by marine atmospheric MnP. In this  
317 section, the estimates, uncertainties and future improvements in marine-atmosphere  
318 fluxes are discussed (Figure 3).

## 319 [H2] Estimates

320 Early estimates of the atmospheric MnP within the marine environment have been  
321 undertaken using simple extrapolation of continental data through to more dynamic  
322 atmospheric process modelling. The 2017 IUCN report suggests 15% of marine plastic  
323 pollution is wind transported (estimated primary microplastic marine pollution input of 0.8-  
324 2.5 million metric tons, therefore 0.12-0.38 million metric tons of atmospheric  
325 deposition)<sup>77</sup>. Acknowledging that both primary and secondary MnP particles are  
326 atmospherically transported to the marine environment, simplistic extrapolation of  
327 atmospheric MnP deposition onto the ocean surface has been carried out. Using the  
328 reported remote area atmospheric MnP deposition quantities and the global ocean  
329 surface area ( $3.6 \times 10^8$  km<sup>2</sup>), microplastic deposition (particles between 1µm and 5mm in  
330 size) on the marine environment has been estimated as 10 million metric tons per year<sup>78</sup>.  
331 New nanoplastic deposition analysis, considering only the <200nm particle fraction,  
332 suggests that this smaller sized plastic pollution might result in up to 15 million metric tons  
333 of nanoplastic deposition on the ocean surface per year<sup>20</sup>. For context, 10 million metric  
334 tons is equivalent to 3% of current annual global total plastic production (2018, 359 million  
335 metric tons)<sup>78,79</sup>, represents 11% of mismanaged plastic waste (2016, 91 million metric  
336 tons year<sup>-1</sup>)<sup>7</sup>, is comparable to the plastic (macro and micro) entering aquatic ecosystems  
337 (11-23 million metric tons per year)<sup>7,8</sup> and potentially transported to the marine  
338 environment (4-13 million metric tons) (2010)<sup>80</sup> (Figure 1).

341 Global model estimations have been undertaken using estimated emission rates from  
342 terrestrial (and marine) sources and current atmospheric MnP transport dynamics.  
343 Lagrangian transport and dispersion modelling (FLEXPART) of tyre and brake wear MnPs  
344 (high density polymers that form a fraction of the total atmospheric and marine plastic  
345 pollution) illustrate that >30-34% of these continental MnP particles are atmospherically  
346 transported and deposited on ocean surfaces (analysis of only MnPs  $\leq 10\mu\text{m}$ , Figure 4)<sup>19</sup>.  
347 FLEXPART modelling suggests that net tyre and brake wear MnP input into the oceans  
348 via atmospheric transport and deposition could be ~0.14 million metric tons per year<sup>19</sup>.  
349 This is comparable to the annual quantity of tyre wear reported to enter the oceans via  
350 fluvial transport (0.064 million metric tons per year, tyres wear only)<sup>19</sup>. Gross atmospheric  
351

352 deposition and marine microplastic flux has also been globally modelled (using the  
353 Community Atmospheric Model, CAM)<sup>18</sup>. The CAM estimate incorporates land based  
354 atmospheric microplastic emissions and as such has a high uncertainty due to data  
355 availability and associated assumptions. The CAM model includes ocean ejection and  
356 recirculation (resuspension) of microplastic particles, incorporating marine bubble burst  
357 ejection and wave action into the marine microplastic cycle. Gross atmospheric deposition  
358 to the ocean is estimated as 0.013 million metric tons<sup>18</sup>. It is important to note that the  
359 CAM model microplastic particle size distribution is notably more coarse than the  
360 FLEXPART tyre and brake wear modelling, adopting a particle size distribution generally  
361 above 5µm and focused on particles 10-50µm in size. The model suggests that potentially  
362 >11% of urban atmospheric deposition comes from sea spray or bubble burst ejection in  
363 the marine environment and that up to 99% of the total marine microplastic ejection to the  
364 atmosphere (re)deposits within the marine environment (Figure 1, Supplementary Note  
365 3).

## 366 [H2] Uncertainties

367 These early marine flux and deposition estimates range from 0.013 to 25 million metric  
368 tons per year, illustrating the uncertainty resulting from data and research limitations.  
369 There is limited global representation of atmospheric MnP concentrations due to the  
370 limited number of studies, limited parallel air concentration and deposition studies and the  
371 limited global observation extent (Figure 2). Field data is especially scarce in the marine  
372 atmospheric environment, a lack that constrains the capacity to accurately calculate and  
373 validate estimated and modelled marine environment results of emission, deposition,  
374 marine atmospheric burden and flux. As a result, current marine atmospheric MnP  
375 understanding and flux estimations are based on available data and assumptions,  
376 resulting in large uncertainties around calculated flux and transport results.  
377

378  
379 A primary knowledge gap is the quantitative assessment of source emissions to the  
380 atmosphere, both marine and terrestrial. The quantitative characterisation of atmospheric  
381 MnP primary and secondary source emission is needed across the full temporal (all  
382 seasons and weather patterns) and spatial range (Arctic to Antarctic, remote to urban  
383 areas). Currently, atmospheric emission rates (for example particles or mass released  
384 per hour or m<sup>2</sup>) are assumed or estimated, both in models and flux calculations due to  
385 the complexity of in field study assessment (specifically the disaggregation of background  
386 atmospheric MnP presence from the source specific emission). To advance the  
387 atmospheric flux accuracy and to understand key sources of atmospheric MnP, these  
388 emission rates require field observation and validation using advanced field sampling  
389 methods (for example horizontal and vertical array sampling across a prospective source  
390 area to define upwind and local atmospheric MnP concentrations relative to emission  
391 specific concentrations).

392  
393 The understanding and experimental validation of wet removal (scavenging) of  
394 atmospheric MnP is relatively unknown. While MnPs are often considered hydrophobic,  
395 once within the environment it is unknown whether this hydrophobicity changes, for  
396 example, due to corona effects, photodegradation and weathering, or leaching of  
397 phthalates. Field and laboratory controlled studies are needed to describe changes to the  
398 microphysical behaviour of environmental MnPs as a result of environmental exposure

399 and therefore corresponding changes to the emission, transport and deposition behaviour  
400 of these particles. Furthermore, entrainment and turbulent mixing dynamics of MnP are  
401 also poorly understood; they are generally modelled using proxies (for example Saharan  
402 dust, or Cesium-137) or theoretical particle motions (based on particle mass, shape and  
403 density). To improve flux estimates and model outputs, laboratory and field  
404 experimentation and data are needed to adequately describe the emission, (re-  
405 )entrainment, turbulent mixing and deposition dynamics (Figure 3) of these generally  
406 negatively charged<sup>81,82</sup>, low density, non-uniform MnP particles.

407  
408 Comparability between studies is difficult at best. The wide range of sampling methods,  
409 analytical techniques and reporting standards has resulted in publication of MnP  
410 observations with differing limits of detection (LOD) or quantification (LOQ), incomparable  
411 size fractionation, differing particle characterisation (shape, polymer type) and sampling  
412 of different processes (for example snow deposition versus pumped volume of air)<sup>3,83,84</sup>.  
413 Atmospheric (terrestrial and marine) MnP studies need to provide comparable results to  
414 ensure data advances the understanding of source, transport, deposition and flux  
415 quantification. To achieve this, inter-method comparison studies are needed to define the  
416 method specific limitations and the relative uncertainties of each method, allowing  
417 published findings to be directly compared. For example, a sample analysed by  $\mu$ Raman  
418 and Nile Red fluorescence microscopy could provide similar MnP counts, but the relative  
419 uncertainties for each analytical method have not been quantified to support effective  
420 direct comparison. Early comparative studies have started to identify under or over  
421 estimations relative to specific analytical methods but without direct comparison and  
422 quantification of these uncertainties specific to particle shape, size and polymer type<sup>85,86</sup>.  
423 Similarly, there is an assumption that sample collection methods are accurate and  
424 effective representations of the environment or medium they sample. However, the  
425 respective comparable sampling efficiencies of deposition and air concentration  
426 collectors, and the associated uncertainties, are unquantified. For example, deposition  
427 sample collectors such as funnels connected to a collection bottle<sup>75</sup>, petri dishes with  
428 double sided tape<sup>87</sup>, NILU deposition collectors<sup>88</sup>, or Brahney Buckets<sup>89</sup> (to name a few)  
429 have different blow-by (particle not collected due to turbulence at sampler opening  
430 resulting from sampler design or wind conditions), entrapment and retention efficiencies,  
431 resuspension and sample losses. These comparative analysis and method unknowns  
432 result in unquantifiable uncertainties in flux estimates.

433  
434 Tyre and brake wear can comprise an important fraction of urban MnP pollution and might  
435 be an important component of marine atmospheric MnP<sup>19,45</sup>. However, in practice, these  
436 black particles can be difficult to characterise by spectroscopic methods because of  
437 limited signal due to absorption of input wavelengths and strength of vibrational response.  
438 Therefore, tyre and brake wear particle chemical characterisation is often achieved with  
439 destructive thermal degradation methods, without particle morphology  
440 characterisation<sup>45,90</sup>. As a result, many atmospheric MnP studies either focus on tyre and  
441 brake wear or exclude these particle types and quantify classic plastics (for example  
442 polyethylene, polypropylene, polyvinyl chloride, polyester, polyethylene terephthalate and  
443 others). This has created a disjointed dataset of MnP that does not represent the total  
444 (tyre and brake wear plus all other polymer types) MnP concentration, burden, emission

445 or deposition. This disjoin creates uncertainty in total MnP calculations and representation  
446 (both atmospheric and marine).

## 447 [H2] Methods to advance the flux estimate

449  
450 To advance the accuracy in the marine atmospheric MnP flux, greater understanding of  
451 atmospheric concentrations, deposition, emission and entrainment mechanisms and  
452 rates are needed across the global spatial and temporal range. There are numerous  
453 atmospheric processes that have not yet been quantitatively characterised or  
454 parameterised (orange processes highlighted in Figure 3) which need to be assessed to  
455 close the marine air mass balance, advance the particle flux estimation, and limit the  
456 uncertainty in flux and transport estimations. These include the vertical distribution of  
457 MnPs both on the inshore and offshore, ocean ejection of MnPs offshore, and coastal  
458 and offshore deposition.

459  
460  
461 It is a challenging task to properly sample atmospheric fluxes of MnP in any environment,  
462 but it is particularly difficult in remote marine environments. Marine atmospheric sampling  
463 (for dust and particulates, not plastic) has been undertaken using Modified Wilson and  
464 Cook samplers (MWAC), which typically collect particles  $>50\mu\text{m}$  (losing the smaller  
465 particle fraction)<sup>21,91</sup>. In addition, pump sampling devices have been mounted on buoys  
466 and ships<sup>38,68,69</sup>. Modified versions of these methods can be included in the array of  
467 sampling methods effective for MnP marine atmospheric research on ocean or coastal  
468 platforms<sup>92</sup>, but field testing is needed to ensure these methods provide appropriate MnP  
469 data across the full particle size range and function in the complex marine climate  
470 (inclement weather). Method advances and innovation are needed to sample the  $<50\mu\text{m}$   
471 MnP particles, especially in open-ocean and remote locations, and to provide sample  
472 methods close to the water surface.

473  
474 While the study of marine MnP emission to the atmosphere via bubble-burst ejection and  
475 sea spray processes is in its infancy<sup>35–37,73</sup>, since the 2000's there has been extensive  
476 research on the mechanism of sea-salt aerosol production and other materials involved  
477 with ocean-atmosphere exchange<sup>72,93,94</sup>. These provide a foundation on which to base  
478 future research of ocean ejection of MnP to the atmosphere. To quantify ocean MnP  
479 emissions via bubble-burst ejection, it might be possible to use sampling methods such  
480 as the Bubble Interface Microlayer Sampler (BIMS)<sup>95</sup>. The BIMS was originally designed  
481 for sea salt aerosol studies, however its use is limited to calm seas. When used in  
482 conjunction with deposition measurements and pumped air sampling campaigns, a BIMS-  
483 type device could effectively advance the quantification of ocean-atmosphere MnP  
484 exchange in the field. In the laboratory, wave flumes and marine aerosol reference tanks,  
485 extensively used in sea-spray aerosol research, could provide a tool to observe and  
486 quantify the MnP wave and bubble ejection processes<sup>96,97</sup>.

487  
488 Atmospheric MnPs generally fall within the lower range of microplastics ( $<500\mu\text{m}$ ) down  
489 to nanoplastics, a complex particle size to analyse<sup>98,99</sup> and within the range of concern  
490 for environmental and human health. The majority of atmospheric MnP studies are  
491 constrained by their particle counts, polymer type and shape, and limit of quantification

492 (published down to 11 $\mu$ m using an FTIR or 2 $\mu$ m using a  $\mu$ Raman, but with pixel size  
493 limitations and in LOD of 10 $\mu$ m for FTIR, 1 $\mu$ m for Raman under standard analytical  
494 setup)<sup>100,101</sup>. Polymer identification analysis, across the full particle size range, is a vital  
495 requirement for MnP analysis and reporting<sup>3,102,103</sup>. Analysis of individual particles below  
496 1 $\mu$ m can be achieved (for example using equipment such as Raman tweezers, AFM-  
497 IR)<sup>98,104,105</sup> but is resource heavy and difficult to analyse a representative proportion of a  
498 field sample. To advance the understanding and flux assessment of atmospheric marine  
499 MnPs, new techniques and advancements in technology are needed to enable submicron  
500 particle polymer analysis that provides comparable results to the micron particle studies  
501 published to date.

502  
503 There is limited testing or parallel analysis of mass and particle counts to date<sup>84,85</sup>,  
504 resulting in mass based results being mathematically converted to particle counts and  
505 vice versa, and the uncertainty associated with this mathematical estimation. Mass  
506 analysis of MnP using destructive methods (thermal degradation) is now possible for very  
507 low concentrations of nanoplastics in environmental samples<sup>20,106</sup>. While thermal  
508 degradation methods do not have a theoretical size limit, these methods are constrained  
509 by the minimum concentration (total mass) required to achieve detection. However, the  
510 uncertainty associated with comparative mass to particle count and particle  
511 characterisation analysis is unquantified for nano and micro plastic studies. To ensure  
512 accurate conversion of mass-particle count<sup>37,59</sup> and the comparability of analytical results  
513 using these different methods, comparative experimental analysis of spectroscopic and  
514 thermal degrading methods is necessary for atmospheric MnP samples.

515  
516 Within the research community, it is acknowledged that reporting must be prescriptive  
517 and standardised. While it might not be possible to standardise the collection or analytical  
518 methods across individual studies and institutions, future studies need to present the  
519 following to ensure a comparable and consistent knowledge base and database of MnPs:  
520 the limits of detection and quantification of studies (LOD and LOQ); a clear description of  
521 analytical methods to support inter-study comparison; quality assurance and control (use  
522 of field blanks and spiked sample recovery, positive and negative controls);  
523 documentation of contamination controls (clean room use, field and laboratory  
524 contamination prevention actions); method and calculations for blank correction of sample  
525 results; sample replication and individual replicate results<sup>102,103,107,108</sup>. While visual or  
526 graphical representation of MnP findings can be done in coarse particle increments, it is  
527 necessary for inter-study comparability that findings are presented in the smallest,  
528 consistent particle size increments possible (for example, a table of 5  $\mu$ m size increments  
529 provided in a data repository or supplementary dataset). Similarly, MnP particle sizes  
530 need to be presented as physical particle sizes for ecotoxicology assessment and also  
531 as aerodynamic diameters for transport modelling and inhalation studies<sup>109,110</sup>. Analytical  
532 methods have advanced beyond visual identification (effective to  $\sim$ 500 $\mu$ m)<sup>111–113</sup> and  
533 while polymer identification by thermal degradation or spectroscopy (chemical  
534 fingerprinting) methods for all particles is not always possible due to resource constraints,  
535 a minimum of 10% (ideally 30%+) of reported particles must be validated using (at least  
536 one) of these methods.



538 Ocean-atmosphere flux estimations using current information hold large uncertainties due  
539 to data availability, sampling methods and study inter-comparability. To advance ocean-  
540 atmosphere flux understanding a global quantitative characterisation of MnP that provides  
541 more standardised and comparable data is needed.  
542

## 543 **[H1] A global strategy**

544 The oceans comprise over 70% of the Earth's surface, highlighting the global importance  
545 of understanding the marine atmospheric MnP cycle, transport and exchange processes.  
546 Knowledge of these processes is a prerequisite to assessing the risk posed by the  
547 atmospheric transport of MnP on species, ecosystems, and human health<sup>114</sup>. Individual  
548 MnP studies undertaken suggest that MnP are omnipresent over the oceans and that  
549 long-distance transport of atmospheric MnP could be a critical factor in supplying these  
550 particles to the oceans. In order to quantify these processes, a comprehensive, formalised  
551 global program is needed that follows a harmonised protocol of sampling and analysis. A  
552 key objective is to provide comparable datasets that enable detailed characterisation of  
553 MnP concentrations and properties over the ocean, their temporal and spatial variability,  
554 as well as the importance of the atmospheric compartment to marine plastic pollution.

555  
556  
557

## 558 [H2] Global long-term observation network

559 Multi-year measurements at selected long-term observation sites will identify current state  
560 and trends in atmospheric MnP concentrations. Such long-term observation activities are  
561 usually a part of a globally coordinated research or monitoring network(s) due to cost and  
562 to ensure data uniformity. We propose an organizational approach to address these  
563 research needs (Box 2). These activities are broadly compartmentalized under  
564 Measurement Studies and Modelling Studies. The objective of this research organization  
565 is to ensure the identified data limitations, inter-study comparability issues and process  
566 knowledge gaps are fully addressed with specific objectives in mind. However, there must  
567 be cooperation and integration across all activities.  
568

569 Early modelling of atmospheric MnP gross deposition shows considerable atmospheric  
570 deposition to the oceans, especially the Mediterranean Sea, and the North Pacific and  
571 North Atlantic Oceans (Supplementary Figure 4)<sup>18</sup>. However, these estimates must be  
572 used with caution because much of the deposition theoretically represents both MnP  
573 ejected from the ocean surface and transported from the terrestrial environment<sup>18,37</sup>.  
574 Studies looking only at tyre and brake wear show substantial net atmospheric MnP  
575 deposition in the mid-and high-latitude North Atlantic, North Pacific and the northern  
576 Indian Ocean (Figure 4)<sup>19</sup>. These early findings, although limited to a subset of  
577 microplastic types, provide guidance in establishing location priorities in studies of the  
578 global MnP cycle.  
579

579  
580



581 To expedite these studies, it is recommend that the existing stations (Figure 4) in the  
582 World Meteorological Organization (WMO) Global Atmosphere Watch (GAW)  
583 program<sup>115,116</sup> be used as the initial long-term monitoring platform network<sup>115,116</sup>. The  
584 proposed sites are non-prescriptive but form an effective basis for a long-term observation  
585 network for atmospheric MnPs. GAW coordinates activities in a global array of fixed  
586 platforms and follows a fully developed protocol of high-quality measurements of a wide  
587 range of atmospheric composition variables, including aerosol properties<sup>117</sup> and of  
588 atmospheric deposition<sup>118</sup>. It is recommended that as part of the international effort all  
589 observational sites adopt common measurement and quality assurance protocols and  
590 centralized data reporting. At least two GAW stations have tentatively undertaken  
591 microplastics measurements. As such, the WMO/GAW program presents an ideal and  
592 cost-effective global monitoring network to commence long-term observation of  
593 atmospheric MnP.

594  
595 The sites (Figure 4) are suggested based on their capacity to create multi-year time series  
596 for extended sets of variables, ranging from atmospheric constituents to atmospheric  
597 dynamics, key to MnP variability analysis. Sites located on isolated coasts or islands are  
598 ideal in that they minimize the impact from local and regional sources of MnP. The  
599 network configuration includes the most intense deposition areas as identified through  
600 early modelling effort and published field data (Supplementary Note 4). A selection of  
601 coastal and marine locations would ensure good coverage on a global scale (Figure 4),  
602 including regions where transport is potentially weak. Atmospheric MnP modelling  
603 suggests transport and deposition plumes downwind of North and South America, Africa,  
604 Australia and Asia<sup>19</sup>. Long-term observation stations are scarce in these regions and  
605 additional stations need to be added to the network (future network expansion) to  
606 represent these areas.

#### 607 [H2] Observation and sampling campaigns

608 Long-term observations and monitoring activities are designed to provide multi-year to  
609 decadal datasets that can illustrate long-term and event specific trends and fluxes<sup>119–123</sup>.  
610 Past and currently active global monitoring networks studying non-plastic atmospheric  
611 substances have used a variety of sampling platforms, sampling methods, observation  
612 and monitoring campaigns. Building on this wealth of marine and atmospheric research  
613 experience, the proposed coordinated research strategy incorporates a unified and  
614 standardized long-term monitoring campaign. It is recommended weekly sampling (to  
615 yield monthly mean MnP particle quantitative particle characterisation and mass  
616 analyses), which could initially suffice for the gross characterisation of transport quantities  
617 (although it is acknowledged this for such a novel global study, adjustments will be made  
618 after initial datasets are created).

619 In addition to the long-term observations, complementary exploration and process studies  
620 would occur within the network. These studies would create high resolution datasets  
621 (minute, hour, daily sampling dependent on the research focus) undertaken through  
622 shorter-term intensive research campaigns using specialized equipment and platforms  
623 (for example, UAVs, BIMS). It is important that these exploration and process campaigns  
624 create data comparable with the global long-term observation dataset, therefore following  
625 (at an overview level) the basic observation outputs of the long-term dataset. The

626 intensive research campaigns will link detailed process and event specific data and  
627 findings to specific source regions, synoptic conditions or transport processes.

628 The global observation network may take several years to develop a full description of  
629 the atmospheric MnP burden, flux and trends due to annual and inter-annual variability of  
630 conditions that affect entrainment, transport and deposition of atmospheric particles<sup>124</sup>. A  
631 fundamental aspect of such a monitoring network is that MnP measurements must be co-  
632 located with other observations, in particular aerosol chemical and physical properties  
633 and meteorological conditions. In the long run, fixed-point observatories in the ocean  
634 should become part of the observation network. As a part of the international efforts<sup>116</sup>,  
635 the proposed observational sites will adopt centralized data reporting (similar to the World  
636 Meteorology Organisation dataset management).

637

## 638 [H2] Proposed sampling platforms

639 Sampling strategies to achieve long-term observations are initially proposed for fixed  
640 stations (Figure 4) using both passive deposition and active (pumped air, such as Tisch  
641 HiVol) sampling methods. These sites could include sampling towers similar to those  
642 used in the SEAREX and AEROCE networks (17-20m walk-up scaffold sampling towers  
643 equipped with elevated atmospheric samplers supported by temporary or permanent field  
644 laboratories located on both continental coast and islands at the terrestrial-marine  
645 interface)<sup>119-122</sup>.

646

647 It is proposed that the fixed (coastal and island) long-term observations will be augmented  
648 by offshore long-term observations attained from repetitive research vessel campaigns.  
649 Research vessels often carry out repeat transits and cruises to the Arctic, Atlantic, Pacific  
650 and Antarctic waters (any sea or ocean)<sup>123,125,126</sup>. Such campaigns are typically 20-40  
651 days' duration and entail frequent location changes, which enable offshore sampling over  
652 a wide spatial and temporal range (Supplementary Note 4). Offshore atmospheric  
653 microplastic sampling has been limited to air filter sample collection<sup>38,68,69</sup>. Future  
654 campaign protocols must be extended to include deposition and nanoplastic sampling.  
655 Intensive studies to quantitatively characterise the under-studied processes and  
656 environmental conditions (Figure 3) will need to use novel and innovative sampling  
657 methods, redesigned and validated specifically for MnP observation. It is expected these  
658 will include platforms and methods based on research vessels, aircraft, UAVs, buoys, or  
659 temporary sampling towers. Intensive offshore and coastal water interface sampling is  
660 novel, and initially it is recommended that methodology such as the Bubble Interface  
661 Microlayer Sampler (BIMS) (with advancements specific to MnP analysis) is used.

662 Low latitude air sampling, vertical and horizontal array sampling over coastal and offshore  
663 environments, can be achieved through use of unmanned aerial vehicles. Unmanned  
664 aerial vehicles (UAVs) have limitations on flight duration but can sample over extensive  
665 vertical and spatial distances provided sampling payloads are kept minimal<sup>127,128</sup>. UAVs  
666 are cost-effective, they sample at low airspeed and can maintain a selected altitude and  
667 location (for minutes to hours) to allow sampling of specific air masses. Furthermore,  
668 UAVs can fly close to high-risk surfaces and locations (for example, sea surface and  
669 urban areas, potentially high-emission activities) with fewer constraints. This level of  
670 control in flight path and, therefore, sample precision could be very useful for intensive air

671 and emission source sampling in the marine environment (Supplementary Note 4). UAVs  
672 will enable sampling in locations where access is limited. Use of UAV could improve  
673 measurements of the overall marine atmospheric MnP burden and help to quantify ocean-  
674 atmosphere exchange.

675  
676 The proposed global observation network and sampling strategy would provide a  
677 comprehensive assessment of marine atmospheric MnP and the ocean-atmosphere MnP  
678 flux. Combined with intensive process, environment or meteorologically specific focused  
679 studies, the global strategy will enable more accurate marine atmospheric MnP flux  
680 estimations, highlight hot spots and key exchange or transport processes that will support  
681 improved policy, management and mitigation measures tackling MnP.

## 682 **[H1] Summary and future directions**

683 There is consensus that microplastic and nanoplastic pollution can harm the environment  
684 and, potentially, human health. However, despite the growing body of evidence of the  
685 importance of atmospheric MnP, there is limited marine atmospheric MnP information.  
686 MnP particles are emitted from primary and secondary sources and transported to the  
687 marine atmosphere, but the atmospheric MnP burden is also comprised of resuspended  
688 particles. Limited source emission and resuspension studies, alongside transport and  
689 deposition studies, have resulted in high uncertainty in global-scale and marine MnP  
690 burden and flux estimations.

691  
692 Reviewing the current state-of-the-art sampling and analysis methods makes it evident  
693 that both sampling and analytical methodologies need to be advanced to incorporate the  
694 marine atmosphere in the plastic pollution cycle. Terrestrial atmospheric MnP sample  
695 collection methods could be implemented to effectively collect coastal and high-altitude  
696 samples but have limitations for deployment in the marine environment. Adaption and  
697 advancement of marine and terrestrial sampling methods used in aerosol and  
698 atmospheric chemistry research could provide an inroad to marine atmospheric MnP  
699 collection but require field experimentation and transport process focused studies to test  
700 their capabilities and effectiveness. Furthermore, research vessel studies currently  
701 provide low altitude air MnP concentrations but have the potential to observe a greater  
702 air column sample and ocean-atmosphere exchange if a wider range of sampling  
703 methodologies are employed (for example, UAV, BIMS, deposition collectors). Future  
704 sampling campaigns should incorporate a range of open-ocean sampling platforms and  
705 sampling methods to help address the marine atmospheric MnP research gap.

706  
707 In conjunction with the complexity of marine atmospheric MnP sampling, there is a need  
708 to advance analytical methods to help quantify the marine MnP flux. Current analytical  
709 methods have advanced to the point where these measurements can be reliably made,  
710 however, a harmonised approach is fundamental. Despite an increasing particle count  
711 with decreasing particle size, to date the majority of analysis has focused on larger  
712 microplastic particles ( $>10\mu\text{m}$ ), and there is limited nanoplastic analysis and unquantified  
713 uncertainties surrounding the comparison of different analytical methods. Analytical  
714 advances to enable both mass and particle characterisation of marine atmospheric MnP  
715 are necessary, complemented by detailed studies to create an easy comparison between  
716 different analytical results. These studies will enable future studies using particle

717 characterisation to be directly comparable to mass concentration studies and include the  
718 nano-sized particle range.

719  
720 Early estimates suggest that the atmospheric MnP influx to the oceans are comparable  
721 to that from rivers<sup>78</sup>. However, early model estimates show a huge range of  
722 uncertainty<sup>18,19,78</sup>. An expanded and coordinated global-scale research effort must be  
723 undertaken to constrain the uncertainties and provide a clear representation of the marine  
724 MnP flux. We propose a global observation network built upon existing long-term  
725 monitoring platforms to create a baseline and trend analysis dataset, augmented with  
726 intensive, short-term monitoring and experimentation research focused on specific  
727 processes, events or locations. Looking forward, we recommend the global monitoring  
728 effort expands to include research vessels and open-ocean observations, which will  
729 complement existing monitoring in inland water bodies and estuary sites.

730  
731 After several years of network operations, we expect that researchers will be able to  
732 identify the key locations, processes, and sources of MnP that impact the marine  
733 environment. Conversely, this research will also demonstrate the influence and relative  
734 importance of emissions from the marine environment influencing the terrestrial  
735 atmospheric MnP burden. This improved understanding of MnP flux and the global plastic  
736 cycle will be vital for evaluating the success of urgently needed mitigation strategies  
737 against plastic pollution. The information is also vital to inform risk assessments for  
738 humans and the biosphere, which need to be based on realistic environmental micro- and  
739 nanoplastic concentrations.

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414 JMP substantially contributed to the discussion of the content and writing of this article. TJ and  
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### 433 **Figure Captions**

434

#### 435 **Figure 1. Atmospheric transport, potential annual flux, burdens and current knowledge gaps.**

436 The atmospheric compartment of the total dynamic microplastic (MP) cycle (in million metric tons, Mt,  
437 per year) can be separated into the marine and terrestrial burdens, which in turn are partitioned into  
438 inland, coastal and offshore zones. Deposition, emission and total burden values are compiled from  
439 model analyses<sup>18,19</sup>, early flux estimations<sup>78</sup> and reported field studies<sup>37,80,129</sup>. \*The coastal zone  
440 onshore emission estimate is for localised coastal marine transport at low altitude (<200m above mean  
441 sea level)<sup>37</sup>, and does not include long-distance transport microplastic or high altitude marine  
442 (secondary) sourced atmospheric microplastic. Atmospheric micro and nano plastic is a key part  
443 (potential up to 25Mt) of the marine (micro and nano) plastic cycle and the calculation of the marine  
444 micro(nano)plastic (MnP) flux.

445

#### 446 **Figure 2. Summary of published micro and nano plastic atmospheric and marine research.**

447 The marine surface MnP results are reproduced from the Van Sebille model<sup>130</sup>. The atmospheric MP values  
448 are derived from 73 research studies (full details of which are provided in the Supplementary Data) . It  
449 is noted that these atmospheric studies are not directly comparable due to the range of methodologies  
450 and individual studies' limits of detection but are provided here for spatial information. The map shows  
451 the spatial limitations of atmospheric MnP research, which highlights the need for global, comparative  
452 and standardised sampling.

453

#### 454 **Figure 3. Critical known and unknown atmospheric processes .**

455 Specifically, micro(nano)plastic (MnP) processes that have been (†) or have yet to be (\*) observed (not modelled), quantified,  
456 characterised or parameterised for MnP either in the laboratory or in the field. The processes listed are  
457 indicative, considered to be 'unknowns' in atmospheric transport but given they are untested this list is  
458 not exhaustive or prescriptive. Understanding, quantitative characterisation and parameterisation of  
459 these atmospheric MnP processes is vital for accurate modelling of atmospheric MnP transport and  
460 accounting for field MnP findings.

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462

#### 463 **Figure 4. The proposed global observation network.**

464 Suggested potential sampling sites (primarily taken from the established WMO and/or GAW networks or European Monitoring and Evaluation  
465 Programme stations) illustrated on the map of FLEXPART modelled net deposition of tyre wear and  
466 brake wear particles<sup>19</sup> (gross global MP deposition CAM model output is provided in Supplementary  
467 Figure 4). Locations identified with \* are high altitude (tropospheric) sites, all other locations are coastal  
468 monitoring sites. Potential sites are: ALT Alert (Canada); AMS Amsterdam Island (France); BHD Baring  
469 Head (NZ); BMW Tudor Hill (Bermuda); BRW (Barrow, USA); CGO Cape Grim (Australia); CPT Cape  
470 Point (South Africa); FKL Finokalia (Greece); GSN Gosan (Korea); IZO Izana (Spain, 2373 m); LLN  
471 Lulin (Taiwan, China 2862 m); MHD Mace Head (Ireland); MLO Mauna Loa (USA, 3397 m); NEU  
472 Neumayer (Antarctica); RPB Ragged Point (Barbados); RUN La Reunion (France, 2160m); SMO  
473 American Samoa (USA); SPO South Pole (Antarctica, 2841 m); ZEP Zeppelin (Norway). Figure adapted  
474 from ref.<sup>19</sup> X, CC BY 4.0.

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## Boxes

Box 1| Key micro(nano)plastic terminology definition and descriptions

### **Microplastic (MP)**

Plastic particles greater than 1µm and less than 5 mm (aerodynamic) diameter<sup>9,10,131,132</sup>.

### **Nanoplastic (NP)**

Plastic particles less than 1µm (aerodynamic) diameter<sup>9,10,131,132</sup>.

### **Micro(nano)plastic (MnP)**

All plastic particles ≤5mm (both micro and nano plastic)<sup>131–133</sup>. MP and NP are measured in the atmosphere as particles or mass per volume of sampled air, for example, MP m<sup>-3</sup>; and deposition as particles or mass per surface area sampled over a specified duration, for example, MP m<sup>-2</sup> day<sup>-1</sup>.

### **Primary micro(nano)plastic**

MP manufactured to be 1µm-5mm (for example, nurdles<sup>134</sup>, personal care products<sup>135</sup>, textiles<sup>136</sup>).

NP manufactured to be <1µm (for example, medical applications<sup>137</sup>, printing ink<sup>138</sup>, electronics<sup>107,139,140</sup>).

### **Secondary micro(nano)plastic**

MP or NP produced through mechanical, chemical or photodegradation (for example, plastic bottle breakdown to MP and NP on a beach due to UV, salt and wave action)<sup>107,141–143</sup>.

### **Source**

An activity that results in MP or NP emission, described both in location and time and with reference to the plastic particle emission characteristics (primary or secondary).

### **Point source**

MP or NP emission from a defined location at specific times (for example, waste water treatment plant release to receiving waterway, recycling plant emission due to mechanical plastic deconstruction, plastic factory emission due to production activities)<sup>144–146</sup>.

### **Diffuse source**

MP or NP emission (and re-emission) from activities that have no single emission time and location (for example, road dust or agricultural emissions)<sup>144,145,147–149</sup>.

Box 2| Proposed global network structure and coordinated international research

## **Measurement Studies**

### *Monitoring Studies*

Long-term (multi-year) atmospheric concentration and deposition measurements of MnP at Global Atmosphere Watch (GAW) and other sites (weekly or monthly composite samples continuously collected using standardised sample collection and analysis methodology, standardised Limit of Detection (LOD) / Limit of Quantification (LOQ)

### *Exploration Studies*

Site specific studies from coast to offshore across a wide range of platforms and analytical methods, including:

- Ship based atmospheric sampling offshore (north and southern oceans, Arctic and Antarctic)
- Ice cores in Greenland, Antarctica, the Arctic (and other locations)
- High altitude aircraft measurements, coastal and offshore
- Marine air concentration buoy-type platform measurements

### *Process Studies*

Emission, deposition and transport process studies (potentially including degradation, leaching, Trojan horse and other studies) and to quantitatively characterise MnP marine atmosphere dynamics, including:

- Assessment of the ocean as a source (emission and resuspension of MnP)
- Differentiated wet and dry deposition on ocean and/or marine surfaces
- Marine atmospheric MnP source identification
- MnP particle count to mass comparative measurement technique development

## **Modelling Studies**

### *Transport*

Modelling, built from the field study findings, to define the local, national, regional, and global transport of atmospheric MnP in the marine (and terrestrial) environment.

### *Sources*

Modelling to identify the potential (key) MnP sources of atmospherically transported particles found in the marine environment, remote and coastal areas. Process specific models are also needed to quantify and detail ocean-atmosphere exchange (ocean emission or ejection).

537 *Flux*

538 Using global, comparable and uniform datasets that are temporally and spatially representative, global  
539 flux modelling will quantify the marine atmospheric MnP burden and flux through quantitative  
540 assessment of the full plastic cycle (emission, transport, deposition). Flux trends and responses to  
541 policy or practice changes can be derived using these models (long-term data mining and modelled  
542 forecasting).

543