

Modelling the accumulation and transport of microplastics by sea ice

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Abstract

Plastic pollution is ubiquitous within the marine environment. Despite increasing public and scientific attention to the issue, there still remain gaps in the knowledge of the full global extent of the distribution of this microplastic pollution. The presence and transportation of microplastics in sea ice is an emerging area of research, particularly with regards to sea ice in the Southern Ocean. This study uses numerical modelling to explore the accumulation and transport of positively and neutrally buoyant microplastics in both Arctic and Southern Ocean sea ice. In general, sea ice may be an important seasonal sink for microplastics pollution in both the Arctic and the Antarctic. Positively buoyant microplastics dominate in Arctic sea ice, whereas in the Southern Ocean, neutrally buoyant plastics, which arrive in the region through deep water transport, appear to be dominant. The overall distribution of microplastics in the Arctic is in keeping with the current literature, although direct comparisons between the results of this model and observational data should be made with caution. There is a clear need for further observational data in the Southern Ocean to elucidate both the transport mechanisms and accumulation of microplastics in Southern Ocean sea ice.

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Key points:

- Both Arctic and Southern Ocean sea ice have the potential to be important seasonal sinks for microplastics
- Arctic sea ice is dominated by positively buoyant microplastics, transported to the area through surface transport
- The Southern Ocean is dominated by neutrally buoyant plastics, transported to the area through deep water

Keywords: microplastics, marine plastics, sea ice, Arctic Ocean, Southern Ocean, ocean modelling

Abstract

Plastic pollution is ubiquitous within the marine environment. Despite increasing public and scientific attention to the issue, there still remain gaps in the knowledge of the full global extent of the distribution of this microplastic pollution. The presence and transportation of microplastics in sea ice is an emerging area of research, particularly with regards to sea ice in the Southern Ocean. This study uses numerical modelling to explore the accumulation and transport of positively and neutrally buoyant microplastics in both Arctic and Southern Ocean sea ice. In general, sea ice may be an important seasonal sink for microplastics pollution in both the Arctic and the Antarctic. Positively buoyant microplastics dominate in Arctic sea ice, whereas in the Southern Ocean, neutrally buoyant plastics, which arrive in the region through deep water transport, appear to be dominant. The overall distribution of microplastics in the Arctic is in keeping with the current literature, although direct comparisons between the results of this model and observational data should be made with caution. There is a clear need for further observational data in the Southern Ocean to elucidate both the transport mechanisms and accumulation of microplastics in Southern Ocean sea ice.

Plain Language Summary

Plastic pollution is present everywhere within the marine environment. Despite increasing public and scientific attention to the issue, we still do not know the full global extent of precisely where this microplastic pollution is. Microplastics have recently been discovered in sea ice, although there is still much research to be done, particularly when it comes to sea ice in the Southern Ocean. This study uses a numerical model to explore the accumulation and transport of positively buoyant (floating) and neutrally buoyant (passive) microplastics in both Arctic and Southern Ocean sea ice. In general, sea ice may seasonally trap microplastic pollution in both the Arctic and Antarctic. Positively buoyant plastics are most prevalent in Arctic sea ice, whereas in the Southern Ocean neutrally buoyant plastics are more prevalent. The results we see in Arctic sea ice are similar to current observations, although we must be careful when comparing the results. There is a clear need for more research and observations in the Southern Ocean to explore the transport and presence of microplastics in Southern Ocean sea ice.

1. Introduction

Marine plastic pollution was first documented in the 1970s but has gained attention and popularity both within the scientific community and with the general public over the past decade. Despite public awareness of the issues associated with plastic pollution and a societal shift towards a reduction in single-use plastics, global plastic production reached 359 million tonnes in 2018 (PlasticsEurope, 2019), of which between 4.8 and 12.7 million tonnes are thought to enter the marine environment (Jambeck et al., 2015). Floating marine plastic pollution is estimated at around 250,000 tonnes, although this is thought to only reflect around 1% of the total amount of plastic that has entered the marine environment over the past 60-70 years and much of the “missing” plastic may be within the water column and within marine sediments (Mountford and Morales Maqueda, 2019; van Sebille et al., 2020). Both empirical data and the use of numerical modelling have shown that plastics have pervaded remote regions of the world’s oceans, from deep sea sediments (Courtene-Jones et al., 2020; Peng et al., 2020) to remote islands (Lavers and Bond, 2017) and both poles (Lusher et al., 2015; Waller et al., 2017). Recently, microplastics (plastic particles smaller than 5 mm in diameter) have also been discovered in sea ice at concentrations comparable to those at the sea surface within “garbage patches” (Peeken et al., 2018). The Arctic has been suggested as a final resting place for marine plastics, with the Thermohaline Circulation transporting plastics from the North

Atlantic into the Barents and Greenland seas (Cózar et al., 2017). However, Arctic sea ice may act as a temporary and seasonal sink for microplastics. Climate change and the associated increase in sea temperature are leading to both a decrease in sea ice extent and a shift from thicker multiyear ice to thinner seasonal ice, which may influence the concentrations of microplastics in Arctic sea ice and the surrounding waters (Obbard et al., 2014). The seasonal trapping and release of microplastics could transport them into areas which may have otherwise not have received an inflow of plastics to the area, and a decrease in sea ice extent may open up potential new shipping routes through the Arctic, which could lead to an increase in direct deposition of plastic pollution (Cózar et al., 2017). Despite evidence suggesting that microplastics may be present around the whole of the Antarctic continent (Hoffmann et al., 2020; Lacerda et al., 2019), far less is known about the potential for microplastic accumulation in sea ice in the Southern Ocean, with only one study reporting empirical data from Antarctic sea ice at the time of writing (Kelly et al., 2020). Kelly et al. (2020) report an average of 11.71 particles L⁻¹ in east Antarctic sea ice and suggest that sea ice in the Southern Ocean may act as a sink for microplastic pollution, with the potential to impact the biogeochemistry and food webs of this once thought to be pristine environment.

The process of incorporation of microplastics into sea ice is not yet fully understood, although mesocosm experiments conducted by Geilfus et al. (2019) have shed light on these mechanisms. During sea ice formation in each of the mesocosm experiments, the highest concentrations of suspected microplastics were within the top centimetre of the newly formed sea ice. Hoffmann et al. (2020) suggest that entrainment of microplastics into sea ice may occur through freezing but theorise that marine organisms that have ingested microplastics or have microplastics adhered to them may actively transport these microplastics into the ice through ice brine channels.

Despite the recent advances in our knowledge of the distribution, environmental impacts and behaviour of marine plastic pollution (see Tirelli, Suaria and Lusher (2020) for a comprehensive review of microplastics in polar samples), there still remain many gaps in our understanding. The global nature of the plastic problem is a challenge in the sense of the scale and difficulty of producing a global inventory of marine plastics. Numerical modelling allows us to explore likely pathways and to gain understanding of behaviours of marine microplastics and can help to reinforce existing empirical data and inform about potentially overlooked areas of accumulation and controlling processes. The model presented in this study explores the role of sea ice in the uptake and transport of microplastics in the both the Arctic and Southern oceans. Through this model, we aim to quantify the accumulation of plastics in sea ice relative to the surface water and water column. This paper will first give a description of the model itself (section 2), followed by a discussion of the results (section 3) in the context of the current literature. A general overview of the global distribution of positively, neutrally and negatively buoyant will be given first, followed by detailed discussion of the accumulation of positively buoyant plastics in Arctic sea ice, and both positively and neutrally buoyant plastics in Southern Ocean sea ice. Finally, we will conclude this paper with a summary of our results and their significance (section 4).

2. Materials and Methods

2.1 Model description

This study uses the Nucleus for European Modelling of the Ocean (NEMO) version 3.6 (Madec et al., 2008) configuration ORCA1-LIM2, which is based on a global, isotropic 1° Mercator horizontal grid with a refinement of the meridional resolution of up to 1/3 of a degree at the Equator and a bipolar cap in the northern hemisphere poleward of 20° N. The vertical grid is made of 42 levels with a resolution of about 1 m near the surface and 200 m at 6000

m. The sea ice model is the dynamics-thermodynamics, 2 ½-layer model LIM2 (Fichefet and Morales Maqueda, 1997, Bouillon et al., 2009). The domain is global. The marine plastic model is described in Mountford and Morales Maqueda (2019). In keeping with the formulation of the rest of the ORCA1-LIM2 model, we use an Eulerian formulation of the plastic transport problem. Microplastics were added each year, using coastal plastic waste input data from van Sebille (2015), based upon estimated global plastic waste for the year 2010, as described in Jambeck et al. (2015) (Figure 1). Inputs began at zero in the first year of the simulation, and increased on a yearly basis to a global release of 5.72 million tonnes by year 60 of the simulation (although we only ran the simulation to year 50 for this study), to reflect the increase in production and (inferred) increase in the flow of plastics into the oceans since global mass production of plastics began. Inputs from specific riverine sources and at-sea sources are not included in this simulation. The simulation includes three distinct plastic types: buoyant, neutrally buoyant and non-buoyant (detailed in Table 1). For a given plastic type in water, the model's change in concentration (mass per unit volume) of plastic (C_w) over time (t) is governed by

$$\frac{\partial C_w}{\partial t} = -\vec{\nabla}_H(\vec{u}C_w) - \frac{\partial(wC_w)}{\partial z} + \vec{\nabla}_H(K_H \vec{\nabla}_H C_w) + \frac{\partial}{\partial z}\left(\kappa \frac{\partial C_w}{\partial z}\right) - w_r \frac{\partial C_w}{\partial z}, \quad (1)$$

where $\vec{\nabla}_H$ is the horizontal divergence operator, \vec{u} is the horizontal advection flux, w is, similarly, the vertical current, z is the vertical coordinate, $K_H = 1000 \text{ m}^2 \text{ s}^{-1}$ is the horizontal (geopotential) eddy diffusivity, κ is the vertical, diapycnal diffusivity (Blanke and Delecluse, 1993) and w_r is the rise velocity of plastic, which is calculated as in Mountford and Morales Maqueda (2019).

Plastic release into the ocean by year 60 (10^6 t a^{-1})

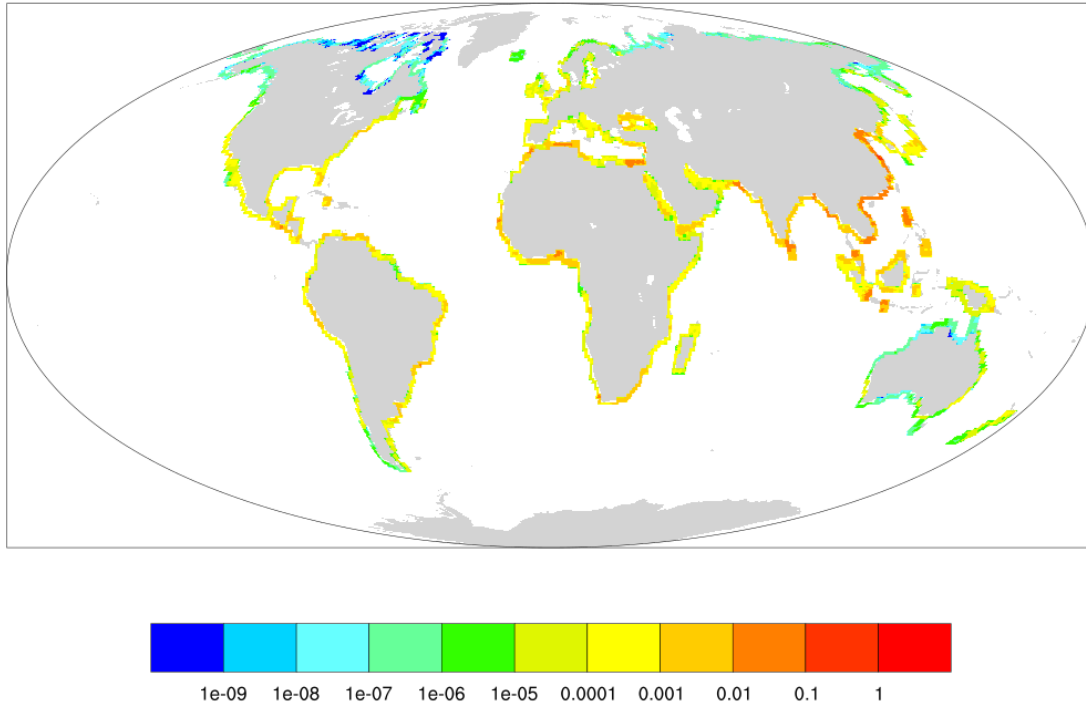


Figure 1. Global distribution of plastic release into the ocean by year 60 (10^6 t a^{-1}).

Table 1. Details of the three distinct plastic types (buoyant, neutrally buoyant and non-buoyant) included in the simulation: the fraction of the total plastic released, density and indicative rise velocity (assuming seawater density of 1.025 kg m^{-3}).

	Fraction of total plastic released	Density (kg m^{-3})	Indicative rise velocity (m s^{-1})
Buoyant	0.491	926	0.0010
Neutrally buoyant	0.190	1023	0.0001
Non-buoyant	0.319	1217	-0.0013

The most salient model novelty compared to the work of Mountford and Morales Maqueda (2019) is the inclusion of plastic fluxes into and out of the sea ice cover. The capture and release of the microplastics by the sea ice occurs through three processes, described as follows, and visually represented in Figure 2. Microplastics present in underlying waters become trapped in newly formed sea ice, via basal accretion; subsequent basal melting releases trapped microplastics back into underlying waters and similarly microplastics trapped within the surface layers of the sea ice are released through surface melt. Finally, thick snow cover on top of the sea ice may cause the sea ice to sink below the sea surface and a certain portion of snow becomes submerged. Sea water (and any associated microplastics) is able to permeate the submerged snow, forming snow ice, and hence the microplastics become entrapped within the snow ice matrix. The snow that falls in this simulation is pristine, so any microplastics present in snow ice have come from surrounding sea water. Trapped plastics are passively transported by the ice. These processes can also be expressed as follows:

$$\frac{\partial(hC_i)}{\partial t} = -\vec{\nabla}_H(\vec{u}_i h C_i) + (B_{acc} + T_{si})C_w + (B_{abl} + T_{abl})C_i, \quad (2)$$

where h is the volume of ice per oceanic unit area, C_i is the concentration of plastic in sea ice (mass per unit area), $\vec{\nabla}_H$ is the horizontal divergence operator, \vec{u}_i is the sea ice velocity, B_{acc} and T_{si} are the basal accretion rate and the rate of formation of non-meteoritic snow ice (both positive or zero), and B_{abl} and T_{abl} are the basal and top melt, or ablation, rates (both negative or zero). In the model, lateral accretion and melt in leads are the result of basal processes and so, no explicit term relating to these processes is necessary in the above equation. Note also that, although the sea ice model of Fichefet and Morales Maqueda (1997) has two ice layers, we assume, for simplicity, a uniform distribution of plastic in the vertical within the ice. However, this assumption could be easily relaxed. We also assume that the concentration of plastic in freezing water is the same as in the surroundings.

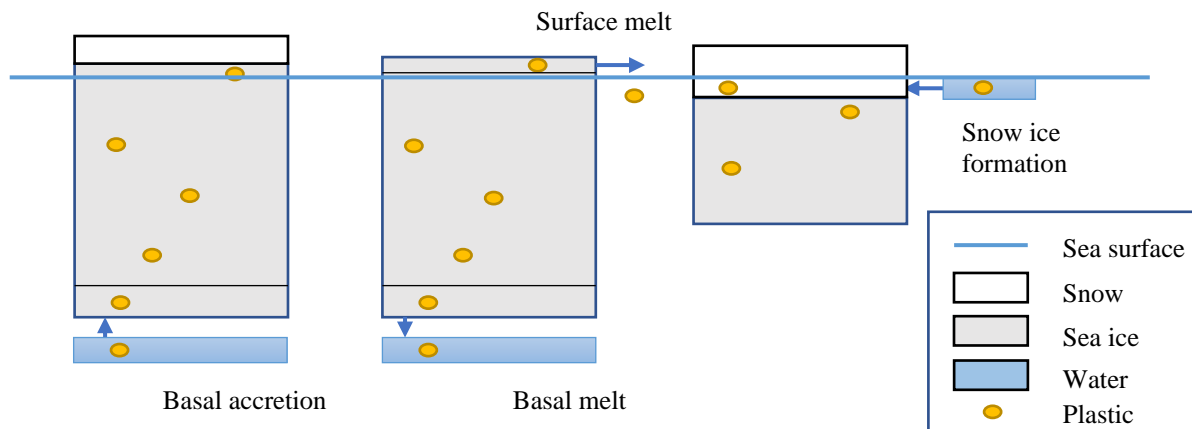


Figure 2. Capture and release processes of microplastics in sea ice included in this model.

2.2 Model limitations

As previously mentioned, the snow that falls in this model is pristine (containing no microplastics). However, it has been suggested that atmospheric deposition may play a role in the flux of microplastics to the Arctic. Bergmann et al. (2019) sampled snow from ice floes in Fram Strait, and found $0 - 14.4 \times 10^3$ microplastics per litre of snow, although at present it would be too speculative with regards to spatial and temporal variability, and the potential origins of the atmospheric particles to include a parameterisation of atmospheric deposition in this model. Efforts have also been made in the quantification of atmospheric microplastics in more well populated areas such as Dongguan City (Cai et al., 2017), Shanghai (Liu et al., 2019) and London (Wright et al., 2020), but the applicability of these data for our purposes is limited.

As stated above, there is no representation of the vertical distribution of the microplastics within the sea ice itself. Most recently, Peeken et al. (2018) and Kanhai et al. (2020) investigated the concentrations of microplastics throughout the ice cores that were collected during sampling. There appeared to be no consistent pattern in the vertical distribution of the microplastics, but the use of modelling may allow for the exploration of the vertical distribution to elucidate if there are any trends or patterns in the trapping of microplastics over time.

Finally, this model does not include yearly interannual atmospheric forcing. As such, the variability of sea ice formation and melt due to climatic variability and climatic change (for example through anthropogenic forcing) is not represented. This will, no doubt, be a beneficial addition to further iterations of this model, in order to evaluate the importance of including interannual variability and climatic trends in the context of the trapping and release of microplastics into sea ice and the implications for their global distribution.

3. Results and Discussion

3.1 Global distributions of microplastics

We begin by briefly presenting the global distributions of each of the plastic types, further details of which can be found in Mountford and Morales Maqueda (2019) albeit at lower resolution. By year 50 of the simulation, the buoyant plastics can be found at high concentrations within the five well-documented “garbage patches” within subtropical gyres in the North and South Pacific, North and South Atlantic and Indian oceans (Figure 3a). There is also evidence of a possible smaller patch in the Gulf of Guinea, off the west coast of Africa, although observational data in the region are lacking, leaving this accumulation unconfirmed. Microplastics also accumulate within southeast Asia, an area of relatively high

coastal plastic inputs, and in the Mediterranean Sea, a semi-enclosed region which makes it difficult for microplastics to escape once they have entered the sea. The inflow into the Arctic, particularly following the Norwegian coastline, leads us to focus on the accumulation of buoyant plastics in Arctic sea ice for the present study. As expected, buoyant microplastics are concentrated within approximately the top 100 m of the ocean. However, in areas of strong surface winter mixing, they can be drawn down to depths of many hundreds of meters. The central panel of Figure 4 shows the distribution of maximum mixed layer depths in the model north of 40°N during year 50 of the integration. The mixed layer depth was determined by calculating the depth at which the water potential density had increased by one percent with respect to the potential density at 10 m below the surface (de Boyer Montégut et al., 2004). The remaining panels of the figure display the seasonal cycle of the vertical distribution of buoyant plastics at select points where winter mixed layers are deep, showing that buoyant plastics can be drawn down well below surface as a result of convective mixing.

The neutrally buoyant microplastics do not have such well-defined areas of accumulation, and instead are distributed far more widely than the buoyant microplastics (Figure 3b). For example, unlike the buoyant microplastics, these neutrally buoyant microplastics are pervading the tropical-equatorial regions and the Southern Ocean. The areas of highest accumulation are, once again, southeast Asia and the Mediterranean. Due to their neutral buoyancy, these microplastics are transported through the water column, and are present from the sea surface down to depths of over 5000 m.

Finally, the non-buoyant microplastics, which sink rapidly to the seafloor once they enter the marine environment, can be seen to invade the abyssal plains, and abyssal and hadal trenches. Peng et al. (2020) reported average microplastic abundances of 71.1 items per kg dry weight sediment across six abyssal plain and hadal trench sites, including the Challenger Deep trench, suggesting that hadal trenches are the ocean's "ultimate trashcan". Non-buoyant microplastics are also abundant in shallower coastal regions, such as in southeast Asia, where they settle on continental shelves before being transported by bottom currents into deeper regions.

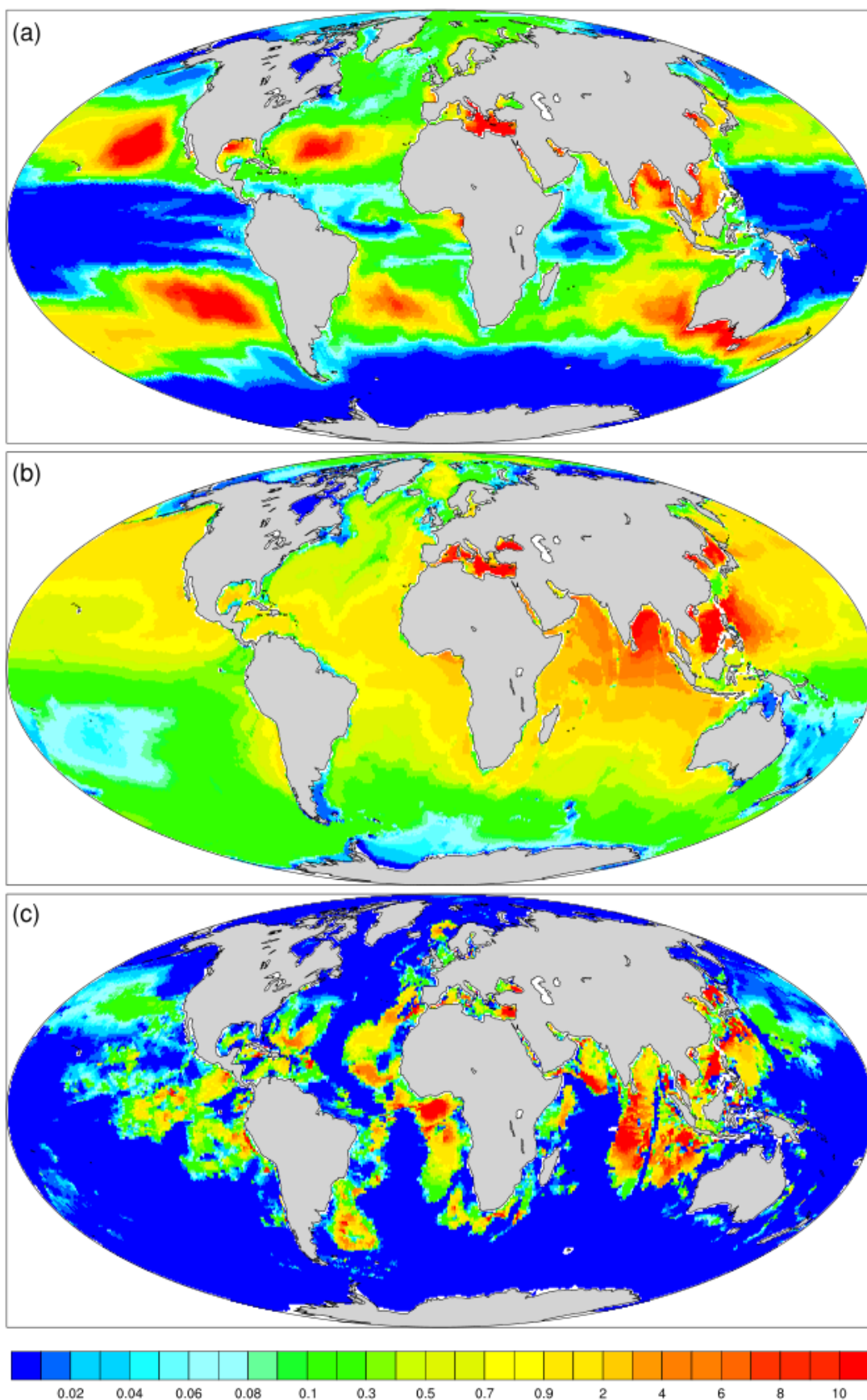


Figure 3. Relative abundance of (a) positively buoyant, (b) neutrally buoyant and (c) negatively buoyant microplastics in the global ocean to global average microplastic concentration (shown is the vertical integral from the 50th year of integration).

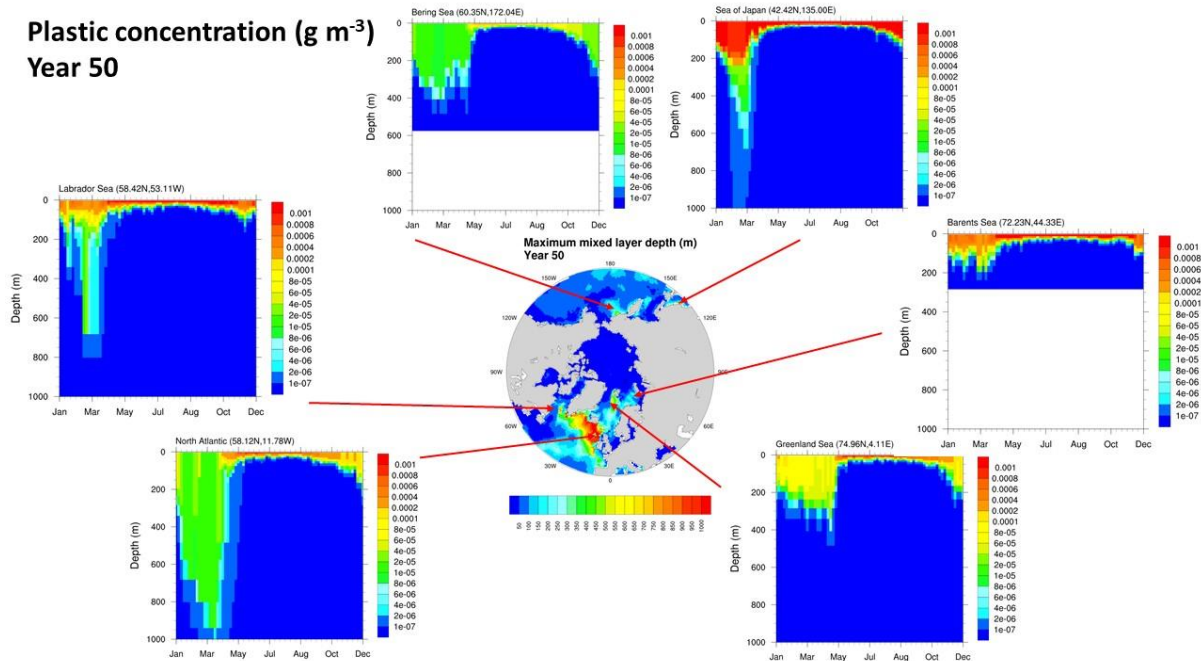


Figure 4. The central panel shows maximum mixed layer depths north of 40°N during year 50 of the simulation. The surrounding panels display the volumetric concentrations of buoyant plastics (g m^{-3}) at selected points where mixed layers deeper than 200 m develop in winter.

3.2 Microplastics in Arctic sea ice

The main influx of microplastics into the Arctic region within sea water is from the North Atlantic, with plastics transported along the Norwegian coastline and entering through the Norwegian and Barents seas, which can be seen in the concentrations of microplastics in underlying waters (Figure 5a). This is consistent with the hypothesis of Cózar et al. (2017) that Thermohaline Circulation may transport buoyant plastics from the more highly populated latitudes south of the Arctic into the region. The concentrations of neutrally buoyant plastics in underlying waters are shown in Figure 5b for comparison. Figures 5a and 5b show the vertical integral (and hence abundance) of the whole water column, whereas Figures 5c and 5d show the vertical integral of plastics in the top 55 m for positively and neutrally buoyant plastics respectively. When comparing the distribution of buoyant plastics in the surface water (Figure 5c) and the entire water column (Figure 5a), there are minimal differences, except for in areas of deep-water formation such as the Labrador Sea and south of Iceland in the North Atlantic. This can also be seen in Figure 4. Comparatively, the differences between the abundance of neutrally buoyant plastics in the surface waters (Figure 5d) and the rest of the water column (Figure 5b) is quite considerable. Neutrally buoyant plastics are present in the top 55 m, the largest amount of these plastics is to be encountered well below the sea surface and at depth.

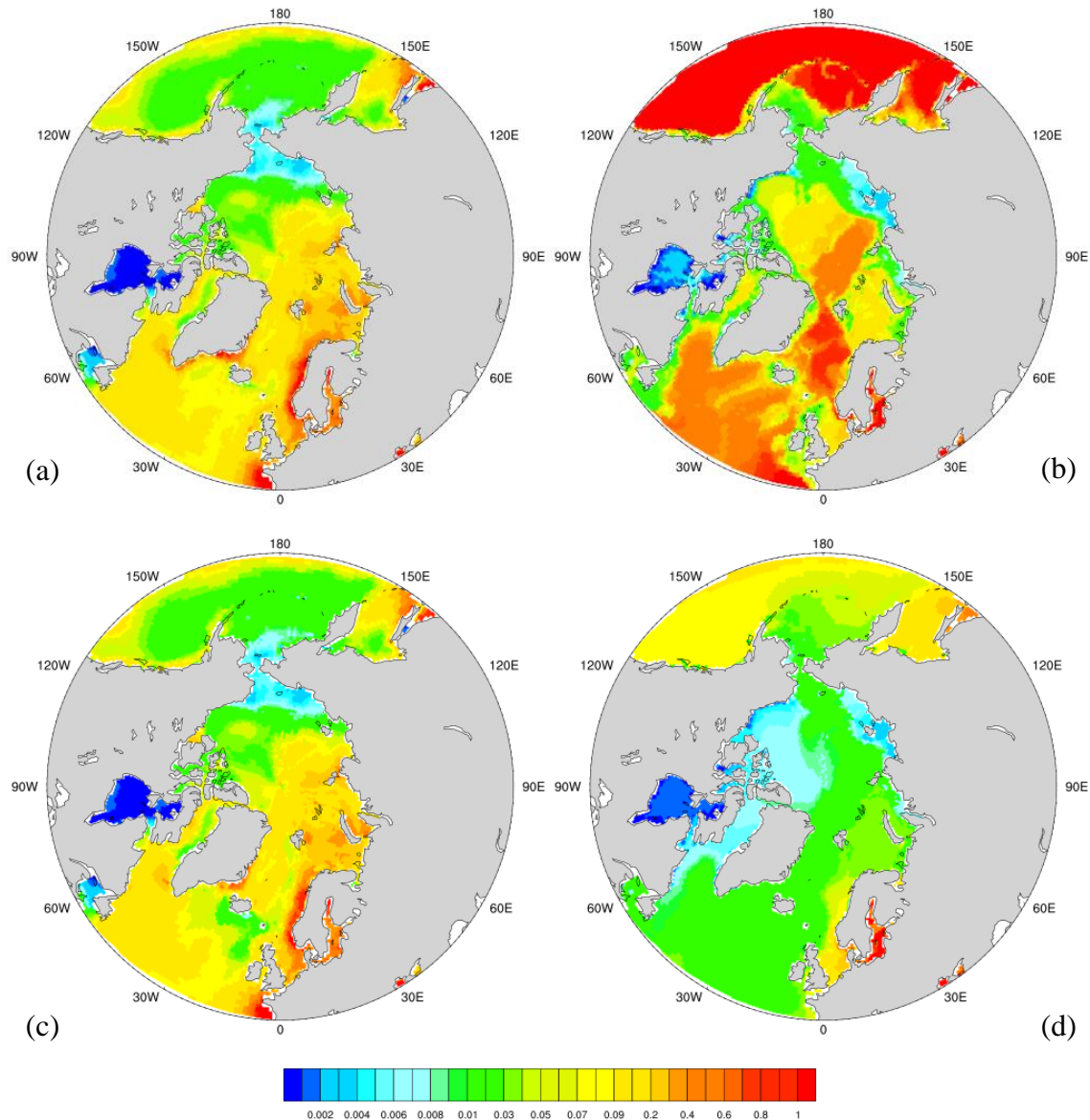


Figure 5. Abundance of (a) positively buoyant microplastics and (b) neutrally buoyant microplastics in the full water column, and of (c) positively buoyant microplastics and (d) neutrally buoyant microplastics in the top 55 m of underlying Arctic sea water, relative to global average microplastic concentration (shown is the vertical integral from the 50th year of integration).

In the model, we first begin to see evidence of microplastics invading the Arctic sea ice south of Novaya Zemlya in February-March of the fifth year of the simulation, and it is the Eurasian basin of the Arctic which shows the first signs of increasing levels of microplastics. Over time, the buoyant microplastics trapped within sea ice (Figure 6) can be seen to be transported across the Barents Sea and the north of Svalbard, as well as by the Transpolar Drift towards Fram Strait, as suggested by the observations of Peeken et al. (2018). The Transpolar Drift can be clearly seen in the annual mean Arctic sea ice current, which is shown in Figure 7. The continued influx of microplastics via the Transpolar Drift results in the highest concentrations at the end of the 50 year simulation being around the north of Greenland, and towards Ellesmere Island and the Canadian Arctic Archipelago (Figure 6). C  zar et al. (2017) found through observational and modelling work that 95% of the plastic

load for the Arctic was confined to the Greenland and Barents Sea, which is spatially consistent with the findings of this simulation. There is very little inflow of microplastics to the region through Bering Strait, either within the sea ice (Figure 6) or in underlying waters (Figure 5a), which suggests that the Pacific may not be a great contributor to microplastic concentrations in the Arctic. Despite this, by the end of the simulation microplastics are seasonally incorporated in sea ice in the Bering Strait and Bering Sea regions. As suggested within the literature (Kanhai et al., 2020; Obbard et al., 2014; Peeken et al., 2018), sea ice can also act as a seasonal repository of microplastics. Figure 8a shows the mass of positively buoyant microplastics in sea ice compared to the mass of positively buoyant microplastics in the water column north of 57°N, while Figure 8b shows the ratio of the mass of plastic in sea ice to the total mass of plastic in the water column underneath the ice cover. The seasonal cycle of capture and release of the plastics is apparent in these figures, with a consistent rise and fall in the quantities of microplastics trapped within the sea ice. Following a rapid increase over approximately the first 15 years of the simulation, the ratio of the mass of plastic in sea ice appears to reach a steady state, with fluctuations between approximately 6 and 12% for the remainder of the simulation, despite the mass of plastics in sea ice (and water column) continuing to increase. This suggests that perhaps there may be a “capacity” for the proportion of microplastics that can be sequestered from the underlying water at any given time, which must depend on the rates of sea ice formation and melt. Our model tends to underestimate the thickness of multi-year sea ice North of the Canadian Arctic Archipelago and so, it may also underestimate the relative size of the sea ice plastic repository. While the mass of neutrally buoyant microplastics in the water column north of 57°N may be comparable to that of positively buoyant microplastics, the mass of neutrally buoyant plastics in Arctic sea ice is negligible in comparison (Figure 8c). The ratio of neutrally buoyant plastics in sea ice to underneath sea ice barely reaches 1% (Figure 8d), suggesting that even when these neutrally buoyant plastics reach the Arctic, the sea ice is not a significant sink. This is consistent with the relative abundance of neutrally buoyant plastics at the sea surface (in the top 55 m) compared to within the full water column, which can be seen in Figure 5c and 5d. As such, we do not present the distribution of neutrally buoyant plastics within Arctic sea ice. While quantitative comparisons between the present study and empirical data should be made with caution, the patterns of accumulation and transport mechanisms observed in this study agree well with those observed in the field. The importance of size detection as a limiting factor in sampling should not be overlooked, particularly below 100 microns (Kanhai et al., 2020). Peeken et al. (2018) were able to detect particles down to a size of 11 microns and reported concentrations of microplastics 2-3 orders of magnitude higher than previous studies. In this sense, modelling is particularly useful, as there are no detection limits. However, continued comparison between modelling and observational data is essential to assess the validity of both modelling and sampling techniques.

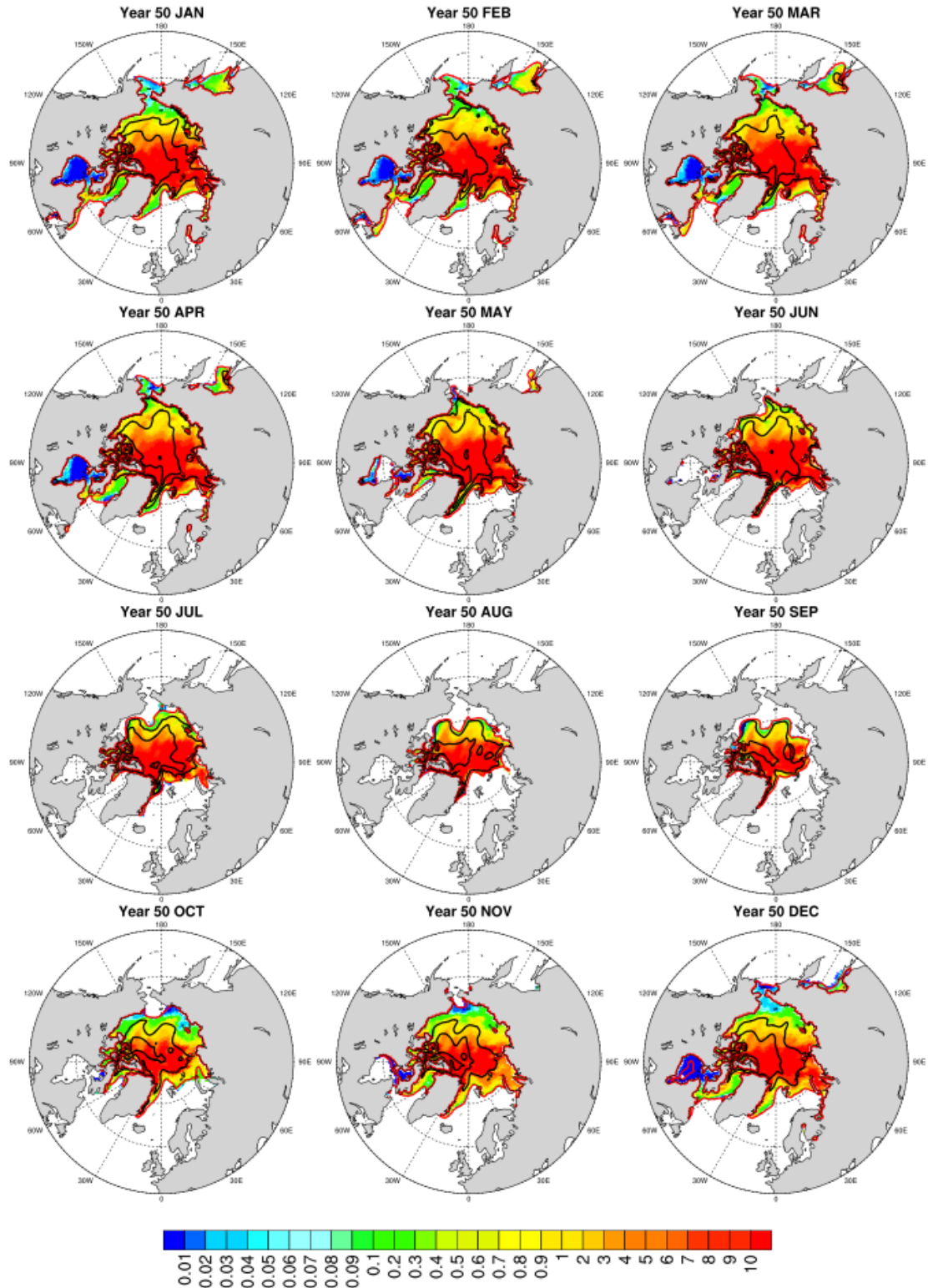


Figure 6. Relative abundance of positively buoyant microplastics in Arctic sea ice to global average microplastic concentration (50th year of integration). Contours of sea ice thickness, in black, are also shown at 1 m interval.

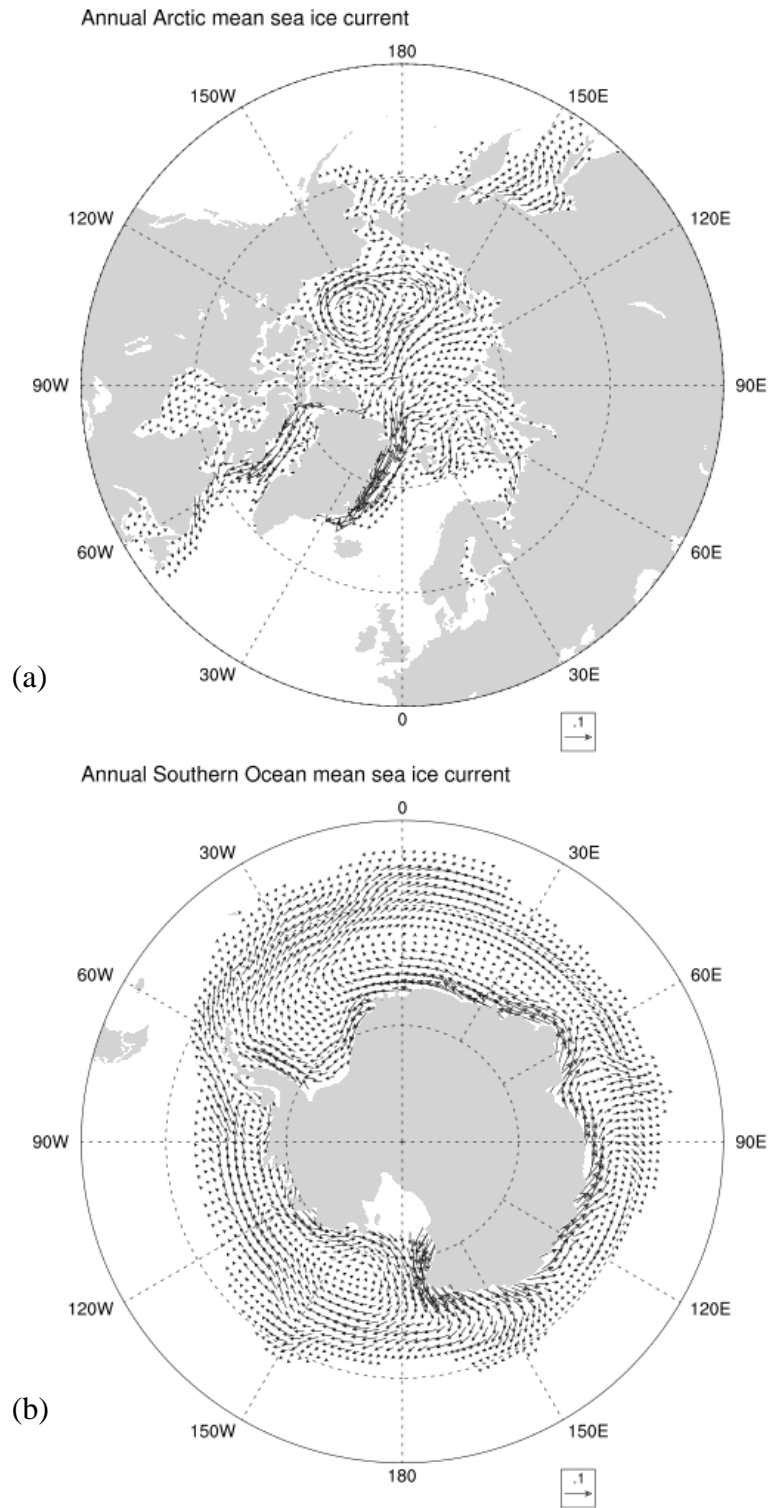


Figure 7. Annual mean sea ice current (m s^{-1}) in (a) Arctic and (b) Southern Ocean sea ice.

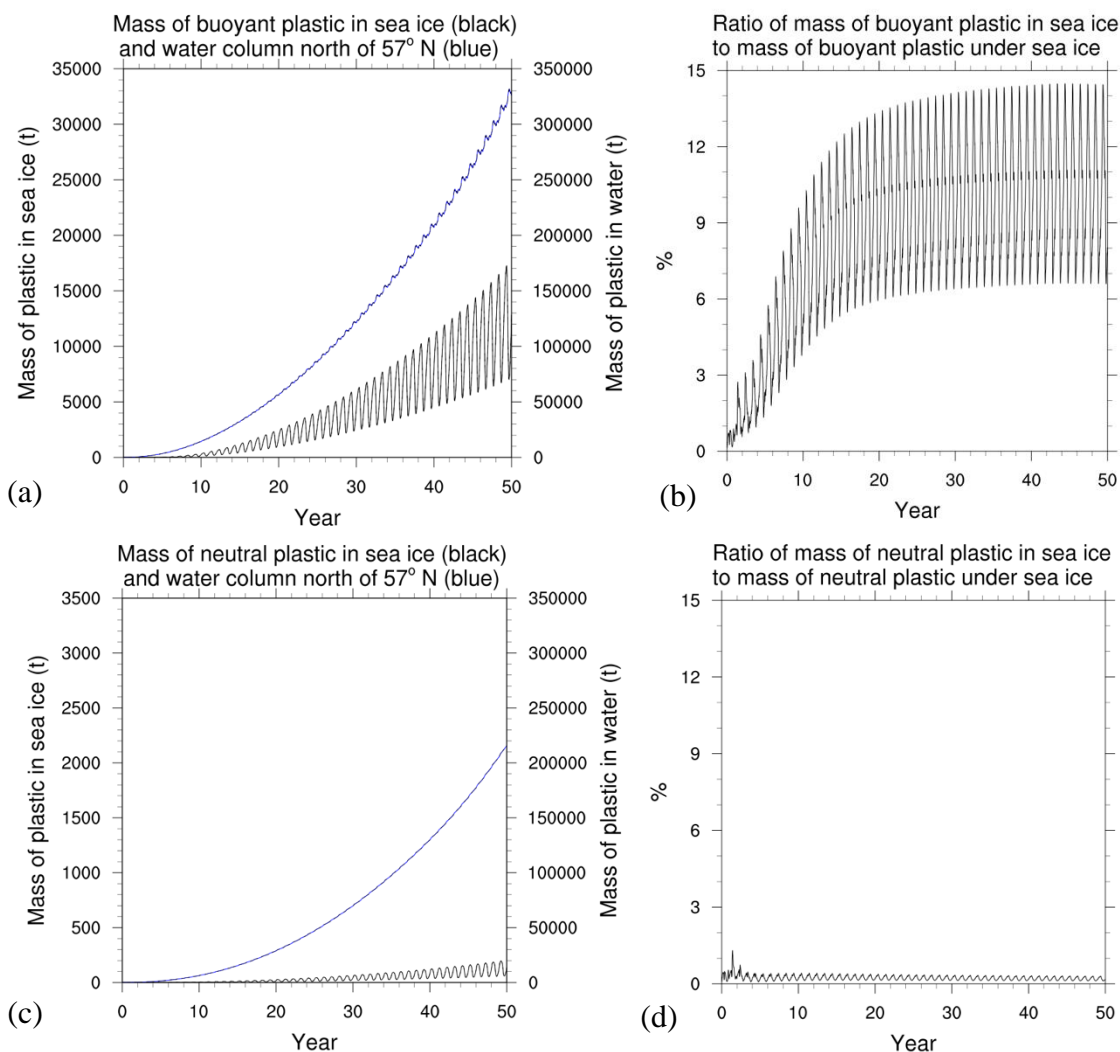


Figure 8. (a) Mass of positively buoyant plastic (tonnes) in Arctic sea ice (black line) and in the water column north of 57°N (blue line) and (b) the ratio of the mass of positively buoyant plastic in sea ice to the total mass of plastic under sea ice over the 50-year simulation period. (c) Mass of neutrally buoyant plastic (tonnes) in Arctic sea ice (black line) and in the water column north of 57°N (blue line) and (d) the ratio of the mass of neutrally buoyant plastic in sea ice to the total mass of plastic under sea ice over the 50-year simulation period.

3.3 Microplastics in Southern Ocean sea ice

3.3.1 Positively buoyant plastics

As in the Arctic, the abundance of buoyant microplastics in the surrounding waters, both throughout the water column (Figure 9a) and at the sea surface down to 55 m (Figure 9c) is shown. Here we see that the Antarctic continent is reasonably well protected from external sources of buoyant microplastics due to ocean surface dynamics, namely the dominant northward Ekman divergence towards the Antarctic Convergence. The Pacific Ocean sector appears to be the most likely and prevalent source region of buoyant microplastics to the Southern Ocean. Indeed, microplastics first begin appearing within Southern Ocean sea ice in approximately the austral winter of the seventh year of integration, around Thurston Island and Pine Island Glacier. By the ninth year of integration, there is evidence of small concentrations of microplastics all around the coastlines of the continent, except to the east of the Antarctic Peninsula, which appears to be shielded by the Peninsula to an extent. Due to the general cyclonic circulation in the Weddell Sea, plastics are most likely to enter this

393 region of the Southern Ocean predominantly from the east. By the end of the 50 year
394 simulation, microplastics have eventually penetrated the sea ice around the entirety of the
395 coastline of the Antarctic continent (Figure 10). During the winter months, the regions of
396 greatest accumulation are in the West Antarctic, in particular the Bellingshausen Sea, but as
397 ice cover increases, the microplastics can be observed extending east around the Antarctic
398 Peninsula and into the Weddell Sea. Given the strong seasonality of the Southern Ocean sea
399 ice cover, plastic concentration in sea ice are largely a reflection of the concentrations in the
400 underlying waters.

401 At the time of writing, there is only one study which has investigated instances of
402 microplastics within Antarctic sea ice: Kelly et al. (2020) measured microplastic enrichment
403 in one ice core from 12 km north of Casey station, on the East Antarctic coastal fast ice. A
404 total of 96 microplastic particles were identified, which equates to 11.71 particles per litre.
405 According to the results of the present study, the East Antarctic, where the core was
406 collected, is likely to be a region of lower microplastic abundance, in comparison to areas
407 such as the Bellingshausen Sea and the West Antarctic, as seen in Figure 10.

408 The results of this simulation show that the mass of positively buoyant microplastics in the
409 water column south of 57°S rapidly increases over the 50 year period (Figure 11a), although
410 the mass itself is very low when comparing the masses of plastic in the Southern Ocean and
411 the Arctic. As such, the mass of positively buoyant plastics in Southern Ocean is
412 understandably small. However, the ratio of microplastics within sea ice to underneath the
413 sea ice reaches between over 5% (Figure 11b), suggesting that as in the Arctic, the small
414 quantities of positively buoyant microplastics that are reaching the Antarctic continent may
415 be sequestered within sea ice, albeit on a far smaller and more seasonal basis.
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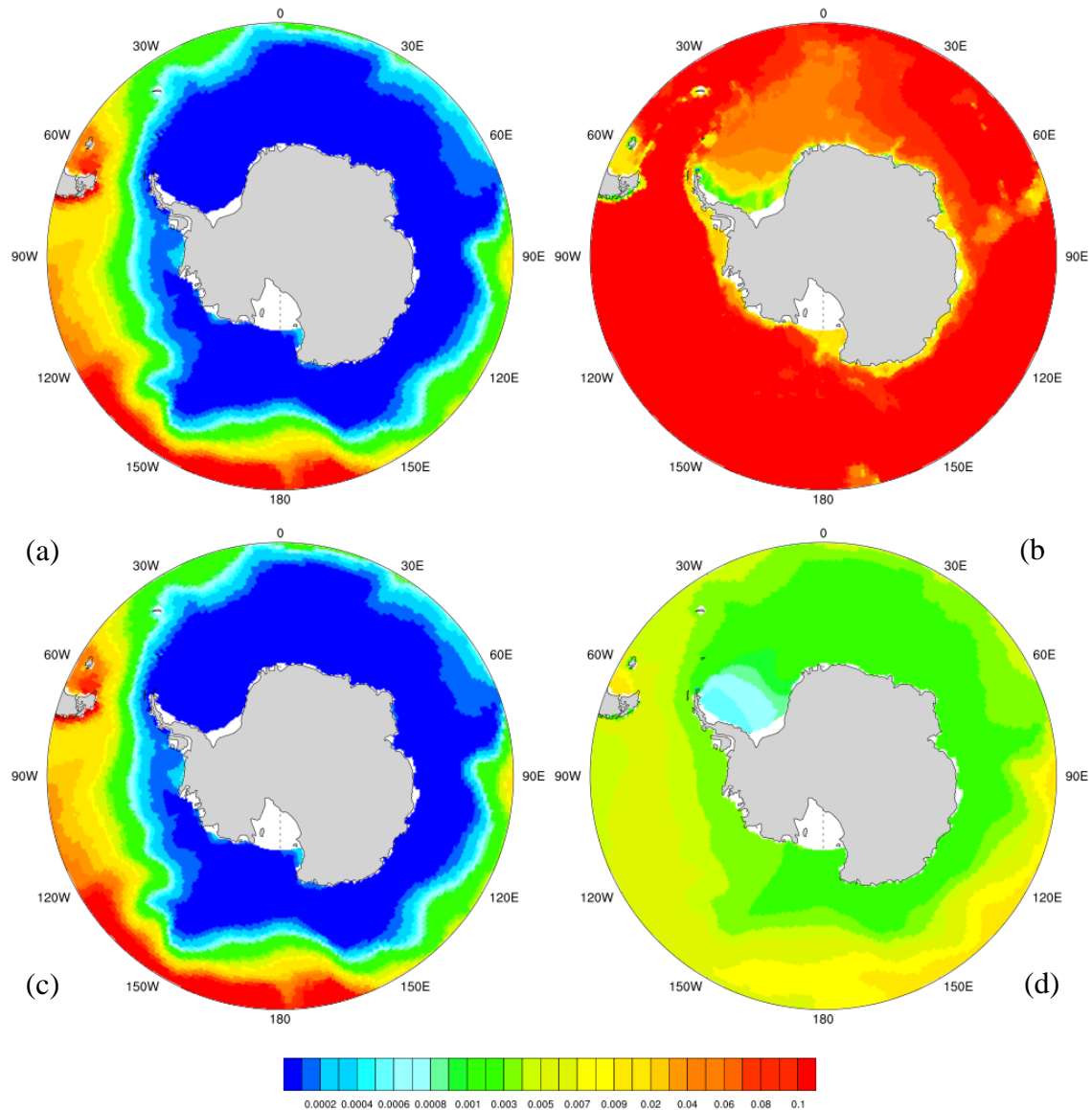


Figure 9. Abundance of (a) positively buoyant microplastics and (b) neutrally buoyant microplastics in the full water column, and of (c) positively buoyant microplastics and (d) neutrally buoyant microplastics in the top 55 m of underlying sea water in the Southern Ocean, relative to global average microplastic concentration (shown is the vertical integral from the 50th year of integration).

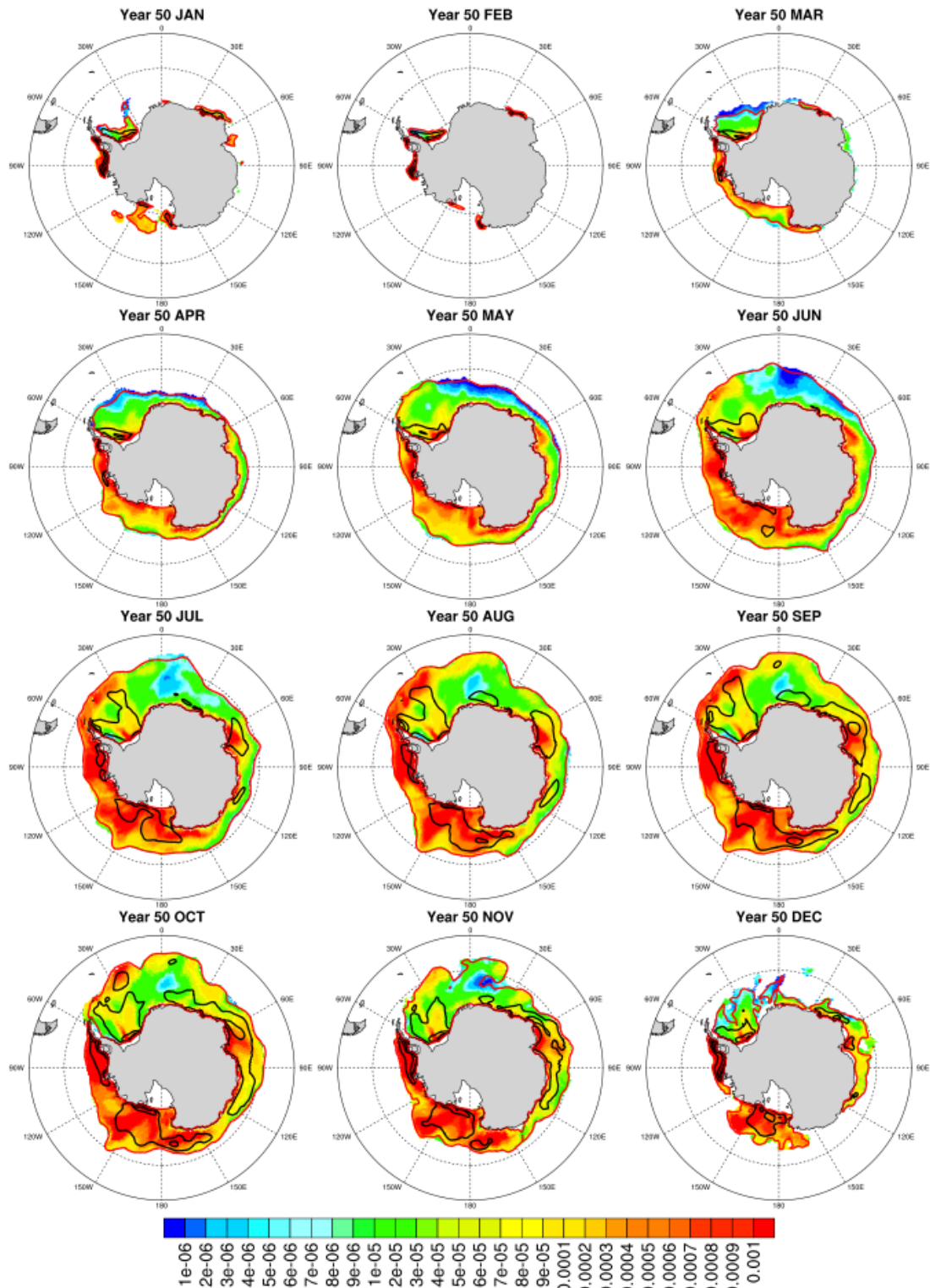


Figure 10. Relative abundance of positively buoyant microplastics in Southern Ocean sea ice to global average plastic concentration (50th year of integration). Contours of sea ice thickness, in black, are also shown at 1 m intervals.

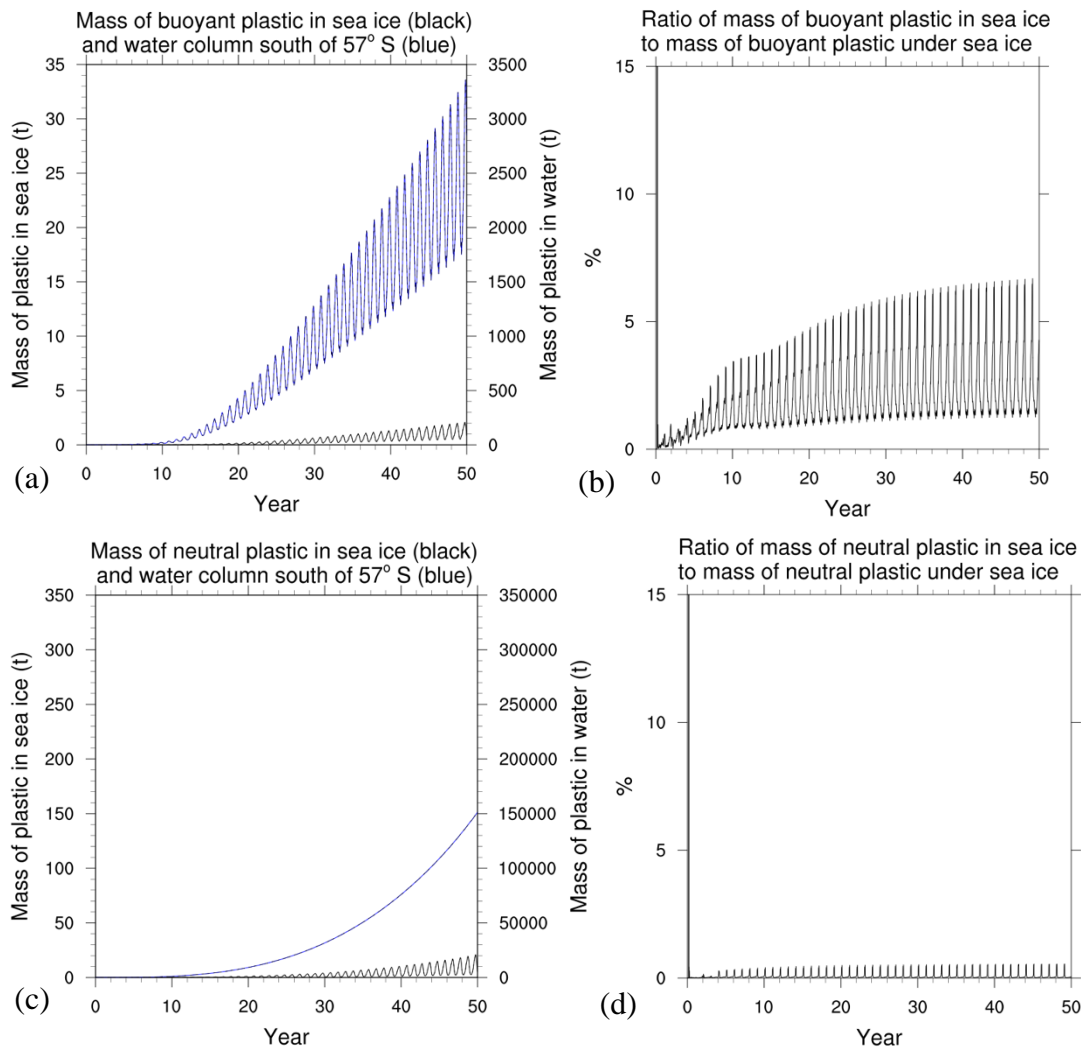


Figure 11. (a) Mass of positively buoyant plastic (tonnes) in Southern Ocean sea ice (black line) and in the water column south of 57°S (blue line) and (b) the ratio of the mass of positively buoyant plastic in sea ice to the total mass of plastic under sea ice over the 50-year simulation period. (c) Mass of neutrally buoyant plastic (tonnes) in Southern Ocean sea ice (black line) and in the water column south of 57°S (blue line) and (d) the ratio of the mass of neutrally buoyant plastic in sea ice to the total mass of plastic under sea ice over the 50-year simulation period.

3.3.2 Neutrally buoyant plastics

In comparison to the positively buoyant plastics present within the water column in the Southern Ocean, the neutrally buoyant plastics are present nearly ubiquitously, with the lowest concentrations directly around the coastlines and also within the Weddell Sea (Figure 9b). However, as in the Arctic, it is worth noting that the distribution of neutrally buoyant plastics partly reflects the bathymetry of the region, so these lower concentrations are likely reflective of the shallower coastal waters. This is demonstrated in Figure 9d, which shows the concentrations of neutrally buoyant plastics in the upper 55 m of the Southern Ocean. As mentioned previously, near the ocean surface, both buoyant and neutrally buoyant plastics are subject to very similar dynamics, which in this region is dominated by northward Ekman divergence that makes very difficult the surface inflow of plastics into the Southern Ocean across the Antarctic Convergence. Therefore, the difference in the simulated concentrations must come about as a result of the supply of neutrally buoyant plastic from deeper in the

water column (Figure 9b), this plastic having been transported meridionally to these latitudes with the northern water masses that feed into the Circumpolar Deep Water (e.g., Downes et al., 2011).

This pervasiveness of neutrally buoyant plastic is also apparent in the concentrations of microplastics within the sea ice, as seen in Figure 12. There are some regions of higher accumulation, namely in the West Antarctic (similar to the positively buoyant plastics), but there are also consistently high abundances within the Weddell Sea, as these plastics presumably become trapped in the circulation by the Weddell Gyre. Key here is to realise that, contrary to plastics in Arctic sea ice, which are predominantly buoyant, plastics trapped in Southern Ocean sea ice are for the most part neutrally buoyant. In the model, neutrally buoyant plastics effectively represent not only microplastics that are truly neutrally buoyant but also any microplastics that are sufficiently small so that their rise velocity becomes negligible for their dynamics (e.g., Kooi et al., 2017).

The mass of neutrally buoyant microplastic that reaches the Southern Ocean (Figure 11c) over the 50 years of simulation is comparable to the mass in the Arctic Ocean (Figure 8c). While the mass that is sequestered within the sea ice is low, reaching around only 20 tonnes, it is not insignificant considering the Antarctic and surrounding sea ice were thought to be the last remaining pristine region of the global ocean. As such, when considering the global distribution and inventories of microplastics, particularly in the Southern Hemisphere, it is imperative to include neutrally buoyant microplastics in both modelling and sampling research.

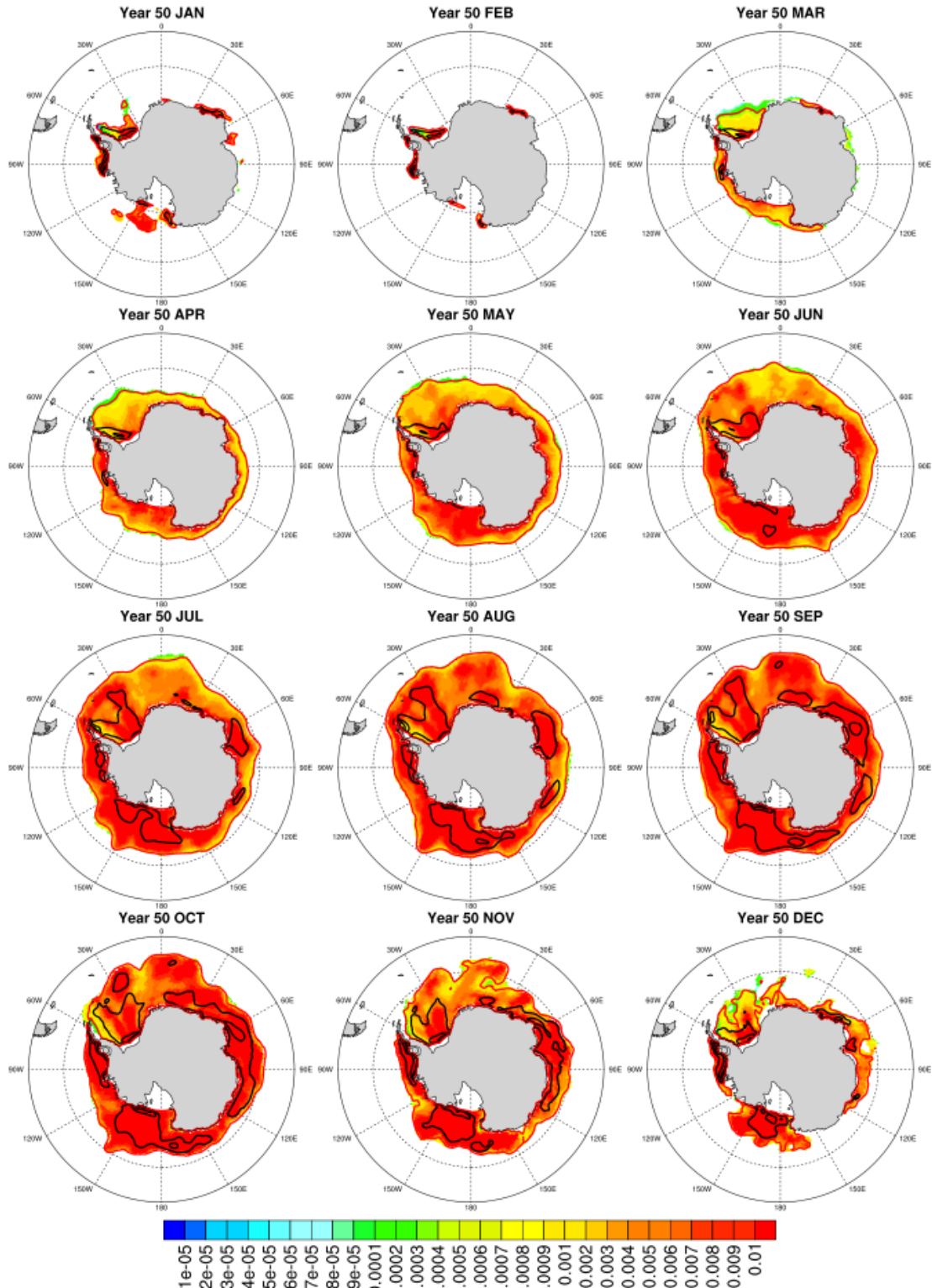


Figure 12. Relative abundance of neutrally buoyant microplastics in Southern Ocean sea ice to global average microplastic concentration (50th year of integration). Contours of sea ice thickness, in black, are also shown at 1 m intervals.

4. Conclusions

Empirical and modelling evidence suggest that both Arctic and Southern Ocean sea ice are seasonal sinks for microplastic pollution. Previous observational and modelling work in the

Arctic has already highlighted the Arctic as a potential “dead end” for microplastic pollution, but further research is needed to establish the possible long-term distributions and patterns of plastic pollution in the region. Aside from one recent study, the potential and extent of microplastic accumulation in Southern Ocean sea ice has previously not been explored. Using the ORCA1-LIM2 configuration of NEMO, we modelled the three-dimensional distribution of microplastics with removal mechanisms to incorporate positively and neutrally buoyant microplastics into Arctic and Southern Ocean sea ice. While the mechanisms and possible implications for the trapping of microplastics within sea ice are not yet fully understood, modelling is a valuable tool for identifying possible affected areas. Within Arctic sea ice, positively buoyant microplastics dominate, with the ratio of buoyant plastics in sea ice to buoyant plastics in the waters underneath the sea ice reaching over 10%. The majority of the plastics enter the Arctic region from the North Atlantic, and as such higher concentrations of these plastics are accumulating in the Eurasian, as opposed to the Canadian, basin. The circulation of Arctic sea ice, in particular the Transpolar Drift, acts as a transport mechanism for microplastics trapped within the sea ice. In the Southern Ocean, the sea ice is less of a repository for positively and neutrally buoyant microplastics. Quantities of positively buoyant plastics south of 57°S are minimal compared to in the Arctic, but the quantities of neutrally buoyant reaching south of 57°S are comparable with those within the Arctic, a remarkable and worrying fact that suggest that levels of microplastic pollution in the Southern Ocean might be comparable to those in less pristine areas of the global ocean. Concentrations are higher within the Pacific sector than the Atlantic sector, which is where we first sea microplastics becoming incorporated within Southern Ocean sea ice. As such, the inclusion of neutrally buoyant microplastics in future research into microplastics in the Southern Ocean, and within Southern Ocean sea ice, is imperative.

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