

Role of Microplastics in Global Ocean Circulation and Climate Change

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Distinguished delegates, the challenge of microplastics may be daunting, but it is precisely such challenges that define the responsibility of the academic community—to uncover environmental threats, raise alarms, and drive solutions. Today, we gather not just to discuss microplastics but to inspire action, foster collaboration, and chart a course toward a cleaner, safer future.

We all use plastics daily, often without thinking of their impact. However, when the prefix “micro” is added, concern intensifies—and rightly so. In nature, the smaller the invader, the greater its potential danger. While large predators can harm us, microscopic threats—like the coronavirus, invisible yet devastating—are far more insidious. Viruses measure just 20–300 nanometres, a fraction of a human cell’s size. Likewise, microplastics, defined as particles under 5 millimetres (often down to 1 micrometre or less), and nanoplastics (below 1 micrometre), are far smaller than our cells. Their minute size makes them highly invasive, enabling them to spread widely in the environment and potentially infiltrate living systems. Laboratory research and animal experiments increasingly suggest that nanoplastics can penetrate human lung and intestinal cells, and may even pass through the blood–brain barrier. While studies in humans remain scarce, microplastics and nanoplastics have already been found in human blood, placental tissue, and lungs. The microplastics with smaller sizes are more toxic in general, as they are more susceptible to uptake by aquatic organisms and plants (Huang et al, 2021; Mateos-Cárdenas et al, 2021).

Two key questions arise: How might current climate change worsen the microplastic problem, and how might microplastics, in turn, influence climate change? Together, they form a positive feedback loop that amplifies the overall risk. Rising temperatures speed up plastic breakdown, causing it to fragment into smaller microplastics (Zhang et al., 2021). Heat also helps plastics break down through thermal processes, making them more likely to degrade further (Kamweru et al., 2011). Changes in ocean currents caused by climate change carry microplastics over long distances, spreading pollution to new areas (Obbard et al., 2014). This means that warming and shifting oceans help plastic pollution travel farther and degrade faster.

Oceans play a crucial role in regulating the Earth’s climate. Warm ocean currents flowing from equatorial regions toward the poles transport vast amounts of heat, helping to moderate temperatures in higher latitudes. The Gulf Stream, for example, keeps much of North America and Europe relatively mild by delivering significant heat from the tropics. The Leeuwin Current, originating in the Indonesian Throughflow region, flows southwards towards the poles and delivers heat to the region adjoining Antarctica. Recent research has found that, conversely, cold currents moving from polar regions toward lower latitudes cool the adjacent landmasses. Notable examples include the Humboldt Current, the West Australian Current, and the Benguela Current.

Recent studies have shown that large ocean currents transport significant volumes of microplastics across latitudes. Advanced analytical techniques, such as Raman microspectroscopy, have revealed that microplastics are widespread within the Gulf Stream Current. The majority of particles detected were extremely small, ranging from 1 to 14 micrometers, with none larger than 53 micrometers. Alarming, about 86% of the microplastics were smaller than 5 micrometers (Faull, S.B. et al., 2024). This is of particular concern because the Gulf Stream carries microplastics into the North Atlantic, where deep water forms and sinks, sustaining thermohaline circulation.

Similarly, Yuan et al. (2023) measured microplastic fragments (>0.30–0.35 mm) in the tropical Northwestern Pacific Ocean and the Indonesian seas. Spectroscopic analyses revealed that microplastics in the western Pacific were dominated by nylon, polyester, and polyethylene, whereas polyethylene was most prevalent in the Indonesian seas. Microplastic abundance was very low (<0.018 particles m^{-3}) in the North Equatorial Current and Kuroshio, suggesting no westward spread of the Great Pacific Garbage Patch or accumulation in boundary currents. In contrast, higher concentrations occurred in the Makassar Strait—likely due to riverine inputs—with the highest levels observed in the northeastern Maluku Sea, where strong current convergence and the Indonesian Throughflow transport microplastics. These findings highlight the critical role of ocean circulation in redistributing microplastics and emphasize the need for high-resolution spatial mapping in global assessments.

The Leeuwin Current, which derives much of its water from the Indonesian Throughflow, also exhibits high microplastic concentrations when its flow is strongest. Reported concentrations ranged from 950 to 60,000 particles per km^2 , with offshore levels peaking during periods of strong current activity. Plastics identified included hard fragments, fishing lines, and cosmetic microbeads. Importantly, Raman spectroscopy confirmed the presence, types, and sizes of plastics, providing robust data on their abundance. The study further suggested that climate-driven and seasonal variability in the Leeuwin Current could intensify microplastic loads in the region (Hajbane & Pattiaratchi, 2017).

Widespread contamination has also been reported in both warm currents flowing poleward and cold currents originating from the Antarctic Circumpolar Current (ACC). Cunningham et al. (2022) directly investigated Antarctic air, seawater (including subsurface waters), and sediments, confirming that microplastics are not only present locally but can also cross the ACC—challenging earlier assumptions that the current acted as a barrier. Microplastic fibers were detected on both sides of the ACC, including within Antarctic waters, indicating transport via both air and ocean pathways.

The Benguela Current, derived from the ACC, also shows evidence of microplastic pollution. Bakir et al. (2020) documented the widespread presence of microplastics in commercially important small pelagic fish species inhabiting South African waters influenced by the southern Benguela upwelling ecosystem. Significant spatial variation was observed along the South African coast, with microplastic loads generally increasing from the west to the south coast within the Benguela region.

Taken together, these studies demonstrate that major surface currents—whether flowing from the equatorial regions to the poles or from polar regions back toward the equator—are contaminated with microplastics. These currents play a key role in dispersing plastics globally,

not only along latitudes but also through equatorial systems such as the North and South Equatorial Currents driven by trade winds. Understanding ocean circulation, its influence on climate, and the role of microplastics in disrupting both is therefore of critical importance.

In addition to surface ocean currents, the global thermohaline circulation—the *Great Ocean Conveyor Belt*—connects the upper and deep oceans, transporting dissolved atmospheric gases to the deep sea and sustaining marine life. In the geological past, disruptions to this circulation have triggered abrupt climate events, such as the Younger Dryas about 12,000 years ago, which plunged North America and Europe into near-glacial conditions. This global circulation is driven by processes in the ocean's upper layer, known as the *mixed layer*. When warm surface waters reach polar regions, sea ice forms, and the resulting brine rejection increases the water's salinity and density. This dense, cold, gas-rich water sinks in vast quantities—about 20 Sverdrup (Sv), equivalent to twenty times the combined discharge of all the world's rivers (1 Sv). Once initiated, the conveyor belt takes roughly 1,000 to 1,600 years to complete a full cycle.

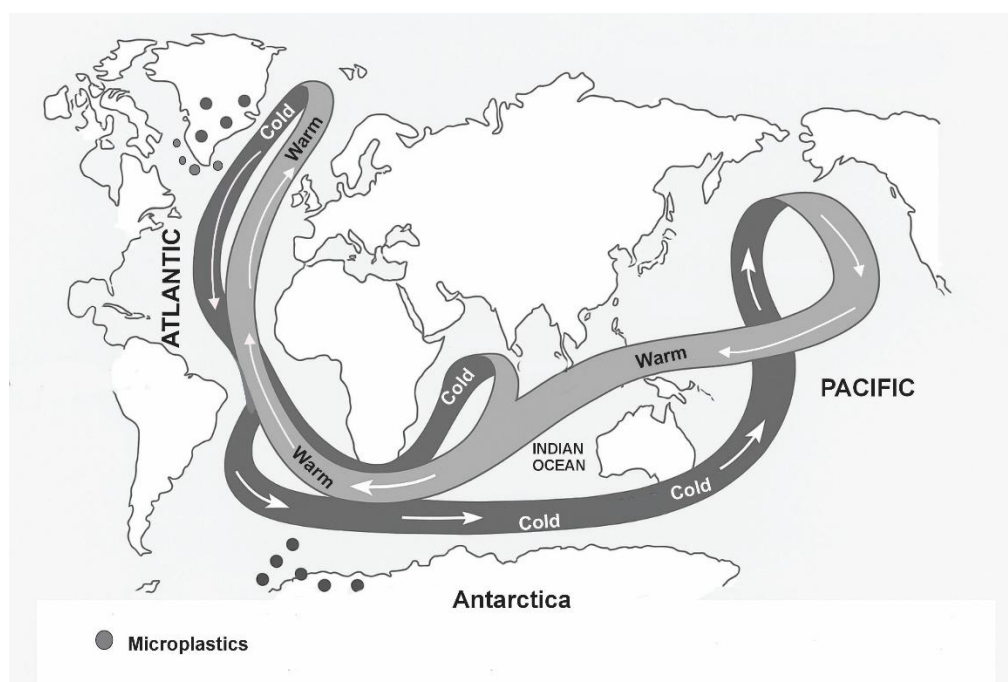


Fig. 1. The great Ocean Conveyor Belt conceptualised by Broecker (1987, 1991). The cold and salty waters sink in the North Atlantic – Greenland-Iceland-Norwegian Seas (GIN Seas) and the Weddell Sea near Antarctica. These deep and bottom waters travel worldwide and upwells in the Pacific to return as the upper arm of the conveyor belt through the Indonesian Throughflow, Agulhas, and Benguela Current System back to the Atlantic. The microplastic accumulation in the high latitudes may cause the polar ice to warm quickly due to a change in albedo by darker microplastics.

In recent years, scientists have expressed concern that, under the influence of global warming, the Great Ocean Conveyor Belt could slow down or even shut down, potentially repeating past climate disruptions. In his landmark 1987 paper—later discussed in detail in 2012—Wallace S. Broecker cautioned that a complete shutdown was unlikely in the immediate

future and that the threat was often overstated. Nonetheless, in his *Natural History* magazine article “*The Biggest Chill*” (1987), he raised the possibility of such an event. From a theoretical standpoint, this scenario remains plausible—and it represents one of the most severe potential consequences of global warming. Adding microplastics to such areas where sea ice forms may lead to a change in albedo and enhance ice melting, resulting in meltwater pulses. Such pulses can interrupt the thermohaline circulation and thus affect the global ocean conveyor belt (Fig.1) . Surface circulation models and observational data indicate that the poleward branch of the Thermohaline Circulation moves floating debris from the North Atlantic towards the Greenland and Barents seas, effectively acting as a terminus for this plastic transport pathway Fig.1) . Considering the restricted surface movement of plastic accumulated in this region and the processes promoting its downward movement, it is proposed that the seafloor below this part of the Arctic is a significant repository for plastic debris (Faull L.E.M., 2024, Cózar et al, 2017).

Understanding the potential influence of microplastics on ocean circulation requires consideration of the ocean’s vertical density structure. The upper ocean is typically stratified into the mixed layer, the thermocline (which approximately coincides with the pycnocline), and the deep ocean. This stratification is maintained by density gradients arising from variations in temperature and salinity. The vertical distribution of microplastics is governed by particle size, density, and buoyancy characteristics. Fine microplastics (1–100 μm), with low settling velocities, are readily entrained and remain relatively homogeneously distributed throughout the water column, including the mixed layer. In contrast, larger particles (100 μm –5 mm) often exhibit enhanced residence times at density interfaces, leading to preferential accumulation within stratified layers such as pycnoclines, both within and immediately beneath the mixed layer (Fig.2). Such size-dependent retention at density gradients could, in principle, interact with physical processes controlling vertical mixing and water-mass transformation (Zhao et al, 2025).

Sunlight exposure causes microplastics to degrade, releasing hydrocarbon gases such as methane (CH_4), ethylene (C_2H_4), ethane (C_2H_6), and propylene (C_3H_6). Methane is a potent greenhouse gas, while the other hydrocarbons contribute to ozone formation, which is also a significant greenhouse gas. Because microplastics have a high surface-area-to-volume ratio, so they generate these gases more rapidly than larger plastic debris. However, biofouling—the growth of microbial film on plastic surfaces—can limit sunlight penetration and reduce gas emissions. Although methane emissions from plastics are globally negligible, releasing other hydrocarbons may hold localized importance for greenhouse gas contributions (Goddijn-Murphy et al., 2023).

Henderson and Green (2020) estimated that millions of metric tonnes of microplastics enter the oceans yearly. The cumulative impact of this influx has contaminated marine habitats, posing a serious threat to numerous species within these ecosystems. Microplastics affect primary producers such as phytoplankton and small zooplankton, including foraminifera. Montoya et al. (2024) reported that microplastics can indirectly reduce marine productivity by altering bacterial and phytoplankton assemblages. These phytoplankton primarily inhabit the ocean’s mixed layer. Ziervogel et al. (2024) found that microplastics may diminish the ocean’s capacity to mitigate the climate crisis by slowing carbon transfer from the surface to deeper waters. Such findings are deeply concerning because oceans absorb the majority of

anthropogenic CO₂ emissions. Moreover, the impacts of microplastics on the marine food chain and mixed-layer hydrography could further exacerbate climate deterioration.

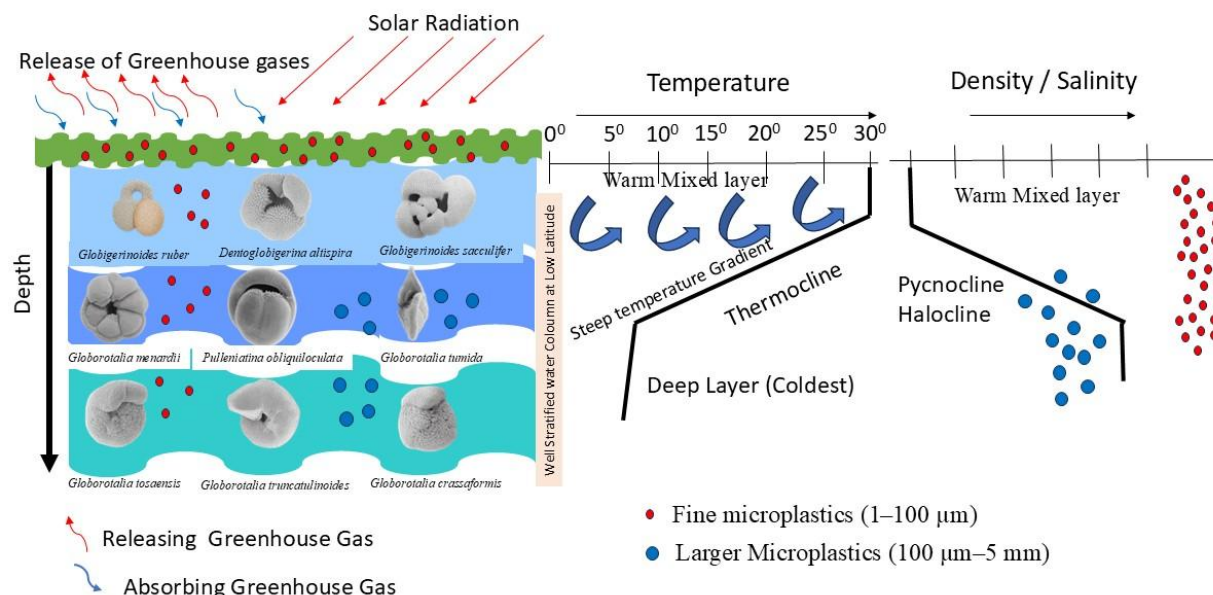


Fig.2 . The water mass stratification of the ocean is shown here. The density of the ocean water is a function of temperature and salinity. This makes the thermocline (zone of rapidly decreasing temperature) almost coincide with the Halocline (Zone of rapidly increasing salinity) and the Pycnocline (Zone of rapidly increasing density). The large Microplastics typically concentrate in or below the pycnocline, while the small particles are uniformly distributed. In a typical case, the surface oceans, due to phytoplankton, absorb CO₂, but if microplastics disrupt this process, it can even lead to the release of greenhouse gases.

Thus, can we conclude that the Great Ocean Conveyor Belt is ultimately at risk? Perhaps not immediately, but if millions of tonnes of microplastics continue to enter the oceans each year, their cumulative impact could eventually trigger unpredictable outcomes. Given the highly nonlinear nature of the climate system, an unknown threshold could be crossed—disrupting ocean circulation, intensifying climate change, and, most critically, destabilizing the marine food web of which phytoplankton and planktic foraminifera are very important so far as the biological pump concept is concerned.

The cryosphere is no longer untouched by microplastics. Scientists have recently discovered microplastics in Antarctic ice, including sea ice and snow. Kirstie Jones-Williams et al. (2025) detected microplastic particles in snow and ice across several remote regions of Antarctica. They found microplastics as small as 11 micrometres in snow near deep field camps and at the South Pole, with concentrations ranging from 73 to 3,099 particles per litre of snow. These microplastics included common polymers such as polyamide, polyethylene terephthalate, and polyethylene. Moreover, scientific surveys of Antarctic Sea ice have identified a variety of microplastic polymers, with polyethylene and polypropylene being the

most prevalent. Pack ice often contains higher concentrations than landfast ice, and these microplastics likely originate from both local sources and long-distance atmospheric and oceanic transport mechanisms. Microplastics are now acknowledged as widespread contaminants even in these remote polar environments (Kelly et al., 2024).

In addition to Antarctica, recent research has also identified the presence of microplastics and nanoplastics in the Greenland ice sheet, highlighting atmospheric long-range transport as a significant source. These findings indicate that the cryosphere—including glaciers and ice caps such as Greenland—serves as a temporary storage and transport medium for these plastic contaminants. Multiple studies and reviews confirm the presence of microplastics in Arctic glaciers and the Greenland ice sheet. However, this field of research is still developing, and data on concentration levels remain limited (Hamilton et al., 2022).

Microplastics (MPs) and their associated chemical leachates can induce the production of reactive oxygen species, lipid peroxidation, and direct physical damage to phytoplankton cells. These stress responses reduce photosynthetic efficiency and primary productivity (Amaneesh et al., 2023). MPs also alter zooplankton (e.g., Foraminifera) feeding behavior by decreasing their grazing on phytoplankton, which may result in elevated phytoplankton abundance near the ocean surface. However, excess phytoplankton's subsequent death and decomposition increase oxygen demand, potentially aggravating hypoxic conditions (Yadav & Kumar, 2023).

Planktic foraminifera play a crucial role in carbon sequestration through calcification and the deposition of their calcium carbonate (CaCO_3) shells on the seafloor. While inhabiting the upper ocean, these microscopic zooplankton incorporate dissolved inorganic carbon—including atmospheric carbon dioxide (CO_2)—into their shells. Following their death, the shells sink rapidly to the deep ocean, where the stored carbon can remain trapped in sediments for thousands to millions of years (Schiebel, 2002). This mechanism represents a significant pathway of the biological carbon pump. Estimates suggest that planktic foraminiferal CaCO_3 flux ranges between 1.3 and 3.2 Gt annually (average 2.9 Gt), accounting for 23–56% of the total global marine “steady” calcite flux at 100 m depth (Milliman et al., 1999) and approximately 6% of the total carbon flux (Berger, 1989; Schiebel, 2002).

Therefore, microplastics disrupt phytoplankton dynamics through direct physiological stress and indirect food-web effects, threatening both primary producers and marine ecosystems and global biogeochemical cycles (Shen et al., 2020).

Often, pollutants do not seem to pose an immediate threat, leading humanity to remain indifferent to problems that do not appear to affect us directly. However, when it comes to pollution and climate change, it is essential to think not only of our lifetimes but also of the many generations to come. Several neglected issues—such as the excessive production of CO_2 driven by industrialization, which was once considered a marker of progress—have now become serious challenges. Carbon dioxide has an average atmospheric residence time of centuries, meaning that the present concentrations will persist for hundreds of years even if emissions were halted today. The climate system and pollutant levels degrade gradually, but mitigation becomes nearly impossible once a critical threshold is crossed.

Microplastics represent another growing menace, slowly accumulating across biological systems, oceans, soils, land surfaces, atmosphere, and even the cryosphere. The time is not far when the impacts of microplastics may draw as much concern as greenhouse gases—especially since they also contribute to climate change.

The only viable path forward lies in advancing research on plastic degradation, particularly biodegradation. Although some breakthroughs have been achieved, they have not reached commercial scale. At the same time, alternatives to plastics must be actively pursued. While many regulations are already in force, greater public awareness and collective responsibility are urgently required.

I therefore commend the organizers of Nivetha Institute of Earth and Environmental Science for taking this timely initiative to organize a conference on microplastics. This issue indeed represents the need of the hour.

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