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The Influence of Atmospheric Microplastics on Global Climate Dynamics: An Interdisciplinary Review

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ABSTRACT

This article examines the growing concern over microplastics in the atmosphere and their potential effects on climate systems and atmospheric circulation. It explores the role of natural aerosols in atmospheric processes, highlighting how these particles influence cloud formation, radiative forcing, and global circulation patterns. It contrasts these natural aerosols with microplastics, which, because of their unique physical and chemical properties, behave differently in the atmosphere. Microplastics, unlike natural aerosols, are resistant to degradation, leading to their cumulative accumulation in the atmosphere. Their persistence and transport in the atmospheric column are influenced by diffusion dynamics, allowing them to travel over long distances, potentially impacting weather patterns and climate systems far from their original sources. Microparticles may also alter cloud properties, influencing precipitation, radiation balance, and atmospheric chemistry. The diffusion behavior of microplastics, their interaction with other airborne pollutants, and their potential to influence advanced climate models are discussed. The cumulative effect of these persistent pollutants, coupled with their resistance to biological degradation, may have serious long-term implications for atmospheric composition and global climate patterns. There is a growing need for further interdisciplinary research into the interaction between microplastics and natural aerosols in order to fully understand their diverse impacts on climate systems and atmospheric dynamics.

Keywords: Microplastics; Atmospheric Circulation; Aerosols; Climate Impact; Environmental Persistence

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1. Introduction

Over the past few decades, the presence of microplastics in various environmental compartments has become a central issue in the global pollution discourse. Traditionally associated with aquatic and terrestrial ecosystems, these contaminants—defined as plastic particles smaller than 5 millimeters—have been increasingly detected in the atmosphere, revealing their potential for regional and intercontinental airborne transport [1,2]. This widespread dispersion raises concerns not only on ecological and human exposure but also about the potential impacts on global climate dynamics, which has been little explored.

Since the mid-20th century, global plastic production has expanded exponentially, driven by its low cost, durability, and versatility across countless industries. Plastic production surged from approximately 2 million tonnes in 1950 to over 460 million tonnes, with single-use plastics and packaging accounting for a significant share [3]. Plastics fragment over time due to mechanical, thermal, and photochemical degradation producing microplastics that accumulate in the environment, including the atmosphere [4–6]. Airborne microplastics can act as cloud condensation nuclei (**Figure 1**), influence the absorption and reflection of solar radiation, and alter the physicochemical properties of the atmosphere. However, their role in climate modulation is poorly understood [7].

By compiling recent findings and integrating them with the underlying physical mechanisms, we aim to contribute to an interdisciplinary understanding of this emerging pollutant as a potential climate-active agent. This approach integrates insights from climatology, atmospheric chemistry, oceanography and environmental sciences to suggest and support future research and policy frameworks.

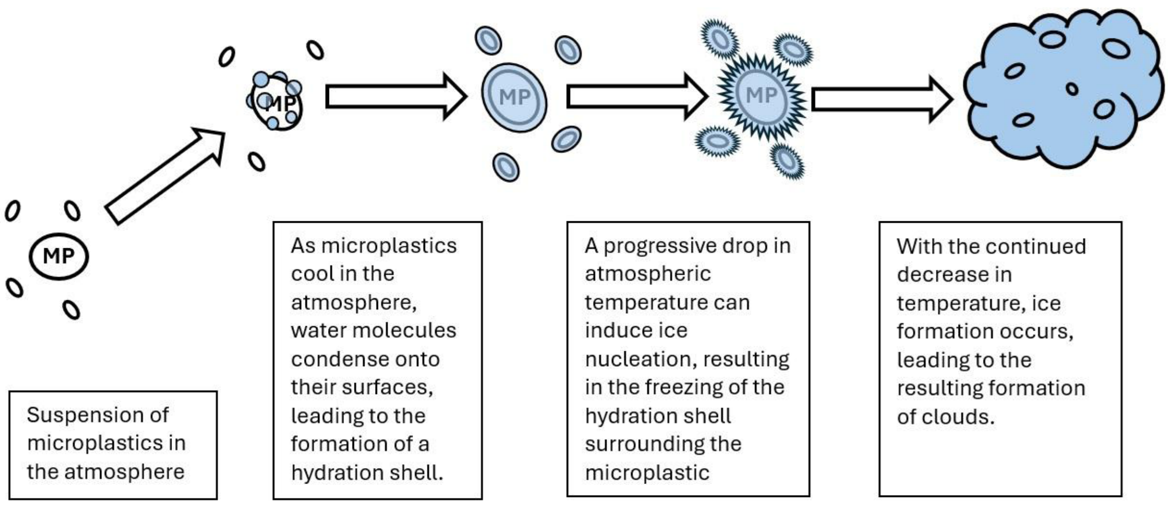

Figure 1. Microplastics Stimulate Cloud Formation.

2. Do Microplastics Influence the Atmosphere?

Human activities, as well as natural aerosols such as dust, sea salt, and biogenic particles (including pollen and spores), influence the dynamics of Earth's atmospheric circulation, particularly the latitudinal climate cells—Hadley, Ferrel, and Polar—that govern global heat and moisture distribution [8,9]. These large-scale atmospheric structures are sensitive to changes in temperature gradients, radiation balance, and aerosol loading, all of which can be altered by anthropogenic inputs [10]. Intensified radiative forcing from the rising CO_2 and CH_4 concentrations of global warming has been linked to the poleward expansion of the Hadley cell, disrupting subtropical rain and wind patterns [11]. Anthropogenic aerosols such as sulfates and black carbon impact cloud microphysics, solar radiation absorption and scattering, and vertical atmospheric motion, all of which modulate the intensity and structure of these climate cells [10].

Land use changes, such as deforestation and urban expansion, alter surface albedo and evapotranspiration. These changes weaken convective systems—particularly near the Intertropical Convergence Zone (ITCZ), affecting tropical rainfall regimes [12]. Similarly, biomass burning releases large amounts of aerosols that influence cloud condensation nuclei concentrations and thermal gradients, further disturbing atmospheric circulation patterns [13].

Atmospheric microplastics now emerge as an under-explored anthropogenic component that can also influence climate cell dynamics. Unlike many natural aerosols, microplastics, such as polyethylene and polypropylene, are lightweight, mainly hydrophobic, and chemically stable, allowing them to remain suspended for extended periods and be transported within atmospheric layers [6]. They have irregular shapes and varied colors and surface textures that affect their absorption or reflection of solar radiation, causing localized radiative imbalances [14], and thus affecting vertical temperature gradients, cloud formation, and atmospheric stability. These are all key drivers of convective circulation within Hadley and Ferrel cells. Their resistance to degradation and tendency to accumulate may introduce long-term shifts in aerosol dynamics, distinct from short-lived natural particles [15–17].

Recent research from Penn State University has confirmed that microplastics can act as ice-nucleating particles (INPs) in the atmosphere [18]. The study demonstrated that pristine and aged microplastics—such as low-density polyethylene (LDPE), polypropylene (PP), polyvinyl chloride (PVC), and polyethylene terephthalate (PET), can facilitate ice formation through immersion freezing. These particles allow water droplets to freeze at significantly higher temperatures (−22 °C to −28 °C) than would occur through homogeneous nucleation (typically around −38 °C). Thus atmospheric microplastics may influence cloud microphysics by altering the balance between liquid water and ice in mixed-phase and cirrus clouds. By affecting cloud and ice formation, they also affect precipitation, cloud albedo, and even the location and intensity of atmospheric fronts. Such processes influence the formation and migration of weather systems, including cold fronts and intercellular boundaries, especially in urban and industrial regions with higher microplastic levels. Thus microplastics are not merely passive pollutants but may interact with the same processes by which other anthropogenic emissions disrupt atmospheric circulation. As a result of their global distribution, persistence, and unique aerosol behavior, microplastics should be considered as emerging climatic agents with the capacity to influence atmospheric cell structures and the hydrological cycle [19].

3. Sources and Transport of Microplastics in the Atmosphere

Fragmented, airborne microplastics can reach even the most remote regions on Earth [20–22]. The abrasion of synthetic textiles during washing and drying, tire wear on roads, industrial dust, and emissions from construction sites release substantial quantities of microplastics into the lower atmosphere [23,24]. Agricultural practices, such as the use of plastic mulch films and biosolids, also contribute to atmospheric microplastic load through wind erosion and movement, while coastal and marine environments can act as indirect sources, with sea spray processes lifting microplastics from ocean surfaces into the air (**Figure 2**) [19,25,26].

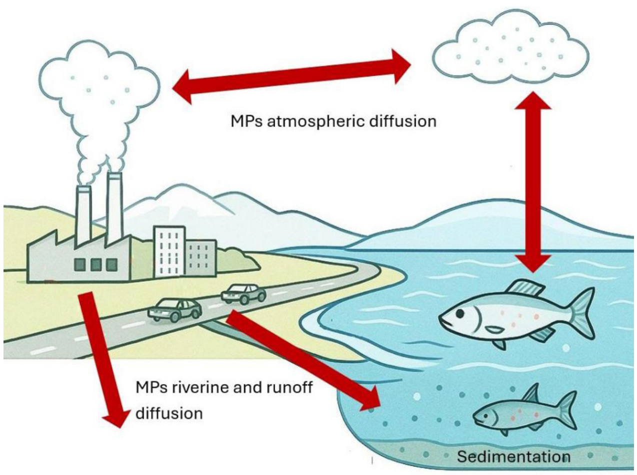

Figure 2. Diffusion Cycle of Microplastics.

Once airborne, the particles are readily transported vertically by thermal convection and turbulent mixing, and horizontally by prevailing winds, enabling long-range and even transcontinental dispersion [2].

Recent studies have documented the presence of microplastics in remote and high-altitude regions such as the Arctic, the Alps, and the Himalayas, locations far from most direct human activity, providing compelling evidence of their long-distance transport capabilities [27,28]. This highlights the global nature of the problem, with microplastics being able to interact with atmospheric processes on multiple spatial and temporal scales.

Understanding the sources and pathways of microplastic transport is essential for assessing their role in atmospheric systems and for developing targeted mitigation strategies. However, significant knowledge gaps remain, particularly regarding the residence time of microplastics in the atmosphere, their interactions with aerosols, and their deposition dynamics.

4. The Influence of Natural Materials in Suspension and the Role of Microplastics in Atmospheric Processes

4.1. Natural and Anthropogenic Aerosols and Atmospheric Circulation

Natural aerosols play key roles in cloud formation, radiative forcing, and global circulation [14]. For example, dust particles can act as cloud condensation nuclei (CCN) and ice nucleating particles (INPs), influencing precipitation patterns and radiation balance in both tropical and arid regions [29]. They impact the thermal structure of the atmosphere and atmospheric circulation cells and can influence the Earth's large-scale circulation systems [30]. In arid and semi-arid regions, dust storms can significantly modify the wind patterns and temperature distribution in the boundary layer, affecting global atmospheric circulation [30]. The presence of these aerosols can alter pressure gradients, potentially shifting the position and intensity of the intertropical convergence zone (ITCZ) and influencing monsoon systems and regional precipitation regimes [31].

Anthropogenic activities have dramatically increased the concentration of atmospheric suspended particulate matter, particularly since the onset of the Industrial Revolution, through combustion of fossil fuels, industrial emissions, agricultural activities, and biomass burning [32,33]. These particles, such as black carbon, sulfates, nitrates, and secondary organic aerosols, not only exacerbate air quality issues but also impact climate by altering the Earth's radiative balance. While sulfate aerosols typically exert a cooling effect by reflecting incoming solar radiation, black carbon absorbs radiation and contributes to regional warming [34].

Anthropogenic aerosols also influence cloud microphysics by increasing CCN concentrations, leading to clouds with more numerous but smaller droplets, which can suppress precipitation and increase cloud albedo—a phenomenon known as the "aerosol indirect effect" [35]. This has profound consequences for the hydrological cycle and regional climate, including delayed rainfall and altered monsoon dynamics [36]. Urban centers, in particular, experience localized climate anomalies such as urban heat islands and modified convective activity due to high levels of particulate pollution [37].

While natural aerosols are often composed of organic matter or minerals that can degrade over time, microplastics are resistant to biological degradation, leading to their long-term persistence in the atmosphere [5,38]. They may remain airborne for extended periods, leading to cumulative effects [21].

The properties of microplastics differentiate them from natural aerosols. Microplastics, especially polyethylene (PE) and polypropylene (PP), are lightweight and hydrophobic, enhancing their suspension time in the atmosphere. Thus microplastics can travel further than many natural aerosols, potentially affecting regions far from their source [39]. Together with their differences in color and surface texture, and thus radiative properties, microplastics can produce localized heating or cooling effects [15]. Hence they alter cloud formation processes differently than natural aerosols, especially in urban and industrial regions where they are more concentrated [40].

4.2. Cumulative Impact of Microplastics and Their Resistance to Degradation

One of the most concerning aspects of microplastics in the atmosphere is their resilience to degradation. Unlike natural aerosols, which can be broken down by biological processes, sunlight, or wet deposition, microplastics accumulate over time. Their persistence in the atmosphere means that once they are introduced, they may continue to circulate globally for decades or longer [35]. This cumulative effect can lead to their gradual build-up in the atmosphere, leading to long-term shifts in atmospheric composition and amplifying their impact on climate systems.

Their accumulation can also exacerbate the effects of other pollutants in the atmosphere, as microplastics adsorb and transport chemicals, such as heavy metals, persistent organic pollutants (POPs), and pharmaceuticals, further impacting the atmospheric system. The cumulative burden of microplastics will pose challenges for future climate modeling, as they may interact with other climate drivers, including greenhouse gases, aerosols, and cloud dynamics, in complex ways that are not yet fully understood [15].

4.3. Diffusion and Transport of Microplastics in the Atmospheric Column

The behavior of microplastics in the atmosphere is governed by complex interactions involving diffusion dynamics, atmospheric turbulence, and large-scale wind systems. Diffusion refers to the passive movement of microplastic particles driven by Brownian motion and thermally induced random movement, particularly significant for ultrafine particles (<10 μm). In the lower troposphere, microplastics are primarily introduced via resuspension from terrestrial and aquatic surfaces, urban emissions, and atmospheric fallout [41]. Once in the boundary layer, vertical transport mechanisms such as turbulent mixing, orographic uplift, and convective currents may elevate these particles to higher altitudes. Once entrained into the free troposphere or even the stratosphere, microplastics become susceptible to long-range atmospheric transport (LRAT) via global circulation systems such as the Jet Stream, Hadley Cell, and Trade Winds. This enables their deposition in remote regions including polar ice caps, alpine environments, and isolated oceanic gyres [42]. Empirical evidence supports this mechanism: microplastics have been found in Arctic snowpacks [43], remote mountain ranges such as the French Pyrenees [1], and abyssal zones including the Mariana Trench [44]. These findings underscore the globalized nature of microplastic contamination and the pivotal role of atmospheric processes in disseminating synthetic polymers far from their anthropogenic sources. The diffusion coefficient and gravitational settling velocity of microplastic particles are influenced primarily by their size, shape, and density. Smaller particles, such as fibers and nanoplastics, exhibit low settling velocities and high residence times in the atmosphere, potentially remaining aloft for days to weeks. Their aerodynamic properties allow them to be scavenged by cloud droplets, facilitating deposition via wet precipitation. Conversely, larger or denser microplastics, such as fragments of polyethylene or polypropylene, are more prone to dry deposition and gravitational settling, particularly under stable atmospheric conditions.

Recent studies have also explored the interaction between airborne microplastics and atmospheric water vapor. Owing to their hydrophobic and often irregular surfaces, microplastics may act as CCN and INPs, especially when coated with organic compounds, biofilms, or atmospheric pollutants [2]. This raises critical questions about their potential to influence cloud microphysics, precipitation regimes, and even radiative forcing. Moreover, microplastics in the upper troposphere may alter the optical properties of clouds or contribute to aerosol-cloud-climate feedback loops, though these mechanisms remain under-investigated.

In summary, the atmospheric transport of microplastics is a multifactorial process influenced by particle characteristics and dynamic meteorological systems. The capacity of these particles to remain suspended, interact with cloud processes, and be transported globally renders them a novel component of the Earth's atmospheric aerosol system, with implications not only for environmental health but also for climate dynamics and hydrological cycles.

5. Interactions with Atmospheric Processes

As microplastics become integrated into the atmosphere, they are not merely passive particles but can actively interact with physical and chemical processes that regulate climate and weather, serving as CNN and INPs [45]. Laboratory simulations and atmospheric sampling suggest that both natural and synthetic particles, including degraded polymers, can alter cloud microphysics, potentially affecting cloud albedo, longevity, and spatial distribution [8].

Airborne microplastics can modify radiative balance. Certain microplastics, especially those containing carbon black or other dark pigments, absorb solar radiation, contributing to localized heating of the atmosphere [15,46]. Others may scatter sunlight, similar to aerosols like dust or sulfate particles, influencing Earth's energy budget in more complex ways [47]. These radiative effects will play a subtle but cumulative role in atmospheric thermodynamics.

The surfaces of microplastics can adsorb pollutants such as ozone, nitrogen oxides, and volatile organic compounds, potentially altering atmospheric chemistry in ways not yet fully understood [19,27], and they can act as carriers of biological agents, including airborne pathogens, with implications for both climate and public health.

These interactions suggest that microplastics are an emerging class of aerosols with climate-relevant properties. Incorporating them into atmospheric and climate models, however, remains a challenge due to the lack of standardized data on emission rates, particle characterization, and atmospheric residence times, areas in need of future research.

5.1. The Impact of Microplastics on High and Low-Pressure Zones and Cold Front Formation

5.1.1. Microplastics and Atmospheric Pressure Systems

Atmospheric pressure systems, such as high-pressure (anticyclonic) and low-pressure (cyclonic) systems, are fundamental in controlling wind patterns, precipitation distribution, and the overall circulation of the atmosphere. High-pressure systems are typically associated with clear skies and stable air, while low-pressure systems bring cloud formation, precipitation, and more dynamic weather patterns. These systems also govern the movement of cold and warm fronts.

Introducing microplastics into these systems may have far-reaching effects on both pressure systems and weather patterns [16]. Their lightweight and hydrophobic nature means that microplastic particles can remain suspended in the atmosphere for extended periods, potentially affecting the distribution and intensity of high and low-pressure systems [48].

Recent studies have highlighted that the accumulation of microplastics in oceanic gyres, particularly in the North Pacific Subtropical Gyre (commonly known as the Great Pacific Garbage Patch), can alter the physicochemical properties of surface seawater, with clear implications for local climate regulation [49]. Floating microplastics can influence the ocean's albedo, either enhancing or reducing the absorption of solar radiation at the sea surface [50]. These changes in surface energy balance can affect ocean-atmosphere heat exchange, thus modulating local sea surface temperatures. According to Hossain et al. [51], the presence of microplastics can also disrupt gas exchange processes and modify thermal dynamics at the air-sea interface, potentially influencing regional wind patterns and microclimatic conditions. Such alterations in surface temperature and heat flux can contribute to changes in cloud formation and precipitation patterns, especially in coastal or insular areas. While further research is required to fully quantify these interactions, the emerging evidence underscores the significance of microplastic pollution as not only a marine ecological threat but also a potential atmospheric and climatic modifier.

5.1.2. Influence of Microplastics on Low-Pressure Systems

Low-pressure systems, characterized by rising warm air and associated precipitation, may be impacted by the presence of microplastics. The particles can alter cloud formation processes [52]. Having a higher surface area than natural aerosols, they could affect the microphysics of clouds, changing the size distribution of water droplets or ice crystals within them. This would result in altered precipitation patterns, such as intense storms or reduced rainfall.

The movement of low-pressure systems could be influenced by microplastics, since they affect the radiative properties of the atmosphere, modifying temperature gradients that are crucial for the formation and movement of low-pressure systems [48]. This interaction could shift storm tracks, causing low-pressure systems to intensify or weaken, depending on microplastic concentration.

5.1.3. Microplastics and High-Pressure Systems

High-pressure systems are generally associated with stable atmospheric conditions. While these systems are typically characterized by subsiding air and clear skies, the presence of microplastics, in altering the radiative balance of the atmosphere, would influence the strength of the high-pressure system. For instance, they can lead to localized heating, weakening high-pressure systems or changing their position on the Earth's surface. This would result in unusual weather patterns such as longer droughts or unseasonably high temperatures [53], augmenting climate change.

Polar regions, characterized by persistent high-pressure systems due to the descending motion of cold, dense air, play a unique role in atmospheric circulation. They contribute to the stability of the atmosphere and to the formation of the polar cell, which drives surface winds outward from the poles [54]. Despite their remoteness and limited vertical convection, both Arctic and Antarctic environments contain microplastics. This suggests that upper-atmospheric winds, such as the polar jet stream, have brought airborne particles to these areas traditionally considered isolated from direct anthropogenic influence [1,43]. The presence of microplastics in polar regions can influence the local climate through changes in the albedo of snow and ice surfaces. Microplastics, especially those with darker colors, have a lower reflectivity compared to pristine snow and ice, leading to increased absorption of solar radiation. Apart from increasing ice melt, the localized warming could disrupt the stability of the high-pressure systems typically observed in these regions, altering the dynamics of the polar cell, influencing local weather patterns and contributing to the broader effects of climate change [1,37].

5.1.4. Influence on Cold Front Formation and Movement

Cold fronts, which form at the boundary between cold and warm air masses, are an essential component of weather systems. They typically bring dramatic changes in temperature, pressure, and precipitation. The presence of atmospheric microplastics could influence the speed and intensity of cold front formation. As microplastics modify cloud properties and alter radiative forcing, they could affect the temperature difference between air masses, which is crucial for the formation and movement of cold fronts [48]. They can also influence atmospheric instability, which plays a significant role in frontogenesis—the formation and intensification of fronts. By altering the temperature gradient between the air masses, microplastics could affect the development of cold fronts, leading to more frequent or intense frontal systems. This would have profound implications for regional climate patterns, particularly in areas prone to storm systems and severe weather [16].

Microplastics can affect the physical properties of the ocean surface, thereby influencing local climate aspects. Microplastics can alter the absorption of solar radiation at the ocean surface, affecting the temperature of water masses. This occurs because microplastics, when accumulated on the ocean surface, can modify the albedo, the surface's ability to reflect or absorb sunlight. This can influence the heat exchange between the ocean and the atmosphere, affecting water temperature and, consequently, the local climate, especially in coastal regions [55]. Cózar et al. highlight how the distribution of plastics in the oceans can interfere with heat and gas exchange processes between the ocean and the atmosphere [56]. The accumulation of microplastics on the ocean surface alters its behavior, influencing thermal dynamics and heat exchange, which impacts wind patterns, temperature, and other local climatic aspects. The alteration in sea surface temperature can modify atmospheric moisture and instability, influencing cloud formation and the intensity of rainfall. Elevated water temperatures caused by microplastic accumulation could intensify cloud formation and precipitation in some regions, while in others, reduced heat exchange may lead to decreased rainfall. This dynamic could significantly impact the formation of weather systems and regional climate patterns, particularly in coastal areas or tropical regions, where the interaction between the ocean and the atmosphere plays a crucial role in climate dynamics.

5.1.5. Potential Impacts of Microplastics on Ocean Density and Thermohaline Circulation: Implications for Climate

We have only recently begun to discover the intricate ways in which microplastics, increasingly pervasive across marine ecosystems, may affect the physical structure and circulation of the ocean. Of particular interest is the potential disruption of thermohaline circulation — the global conveyor belt of ocean currents, driven by gradients in temperature and salinity — through microplastic-induced modifications in water density and vertical stratification [57].

Microplastics, especially those ranging from 1 to 100 µm in size, tend to accumulate in the upper layers of the ocean. In semi-enclosed seas, such as the Baltic, thin microplastic-rich layers form within stable stratified water columns [58–60]. Reduced downward transport of particles and nutrients can alter thermohaline-driven processes. The buoyancy and chemical properties of microplastics contribute to their uneven distribution in the water column [61,62], potentially affecting the density gradients that underlie large-scale ocean circulation. Microplastics may penetrate into the ocean's interior layers, with smaller particles being transported below the surface by physical processes and biological activity [63]. This redistribution may not only interfere with the vertical flux of organic material but also impact the formation and sinking of deepwater masses critical to thermohaline dynamics.

Deep-sea studies reveal that bottom currents associated with thermohaline circulation (**Figure 3**) can concentrate microplastics in specific benthic regions, creating "microplastic hotspots". This suggests that microplastics are not merely passively distributed but may be influenced by, and potentially influence, abyssal circulation patterns through feedback mechanisms still under investigation [57]. While definitive causal links between microplastic accumulation and large-scale shifts in thermohaline circulation remain to be established, the existing evidence suggests a feedback loop wherein microplastics alter local water density and stratification, thereby modifying current behavior. Such effects could be especially pronounced in polar and subpolar regions, where deep water formation is particularly sensitive to surface conditions [58,64].

Thus, the current scientific literature supports the idea that microplastics are not merely passively transported by ocean currents but can actively interact with the structure and dynamics of the water column, both influencing and being influenced by ocean circulation patterns. The influence of microplastics on ocean-climate interactions could have far-reaching effects, as explained in the following paragraphs.

Changes in ocean circulation would have implications for global climate systems. A weakening of thermohaline circulation in the North Atlantic, due to altered density gradients, could reduce heat transport toward Europe, leading to colder winters in Western Europe and shifts in precipitation patterns [65]. The global climate system is intricately linked to the movement of ocean currents, which serve as critical drivers of heat, moisture, and nutrient distribution. Among the most influential is the thermohaline circulation, often referred to as the "global conveyor belt," which transports warm water from the tropics toward the poles and cold water from the poles back toward the equator (**Figure 4**). The dynamics of this system are governed by differences in water temperature and salinity, which determine the density of seawater. Changes in ocean circulation, particularly those resulting from alterations in these density gradients, could have profound and far-reaching impacts on global climate patterns.

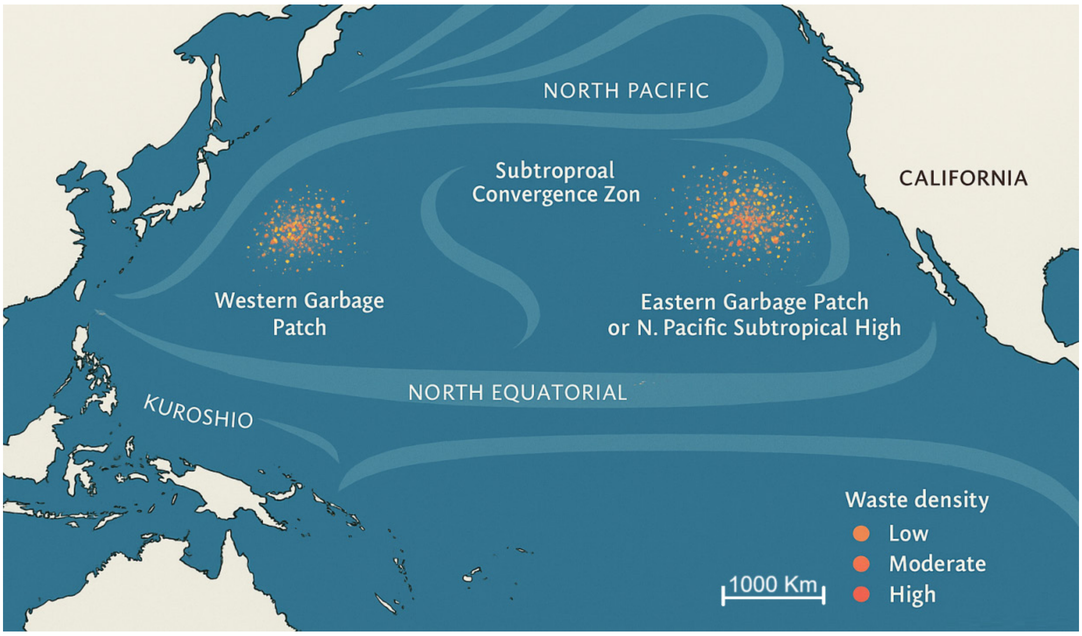

Figure 3. Accumulation of Marine Debris in the Pacific Ocean.

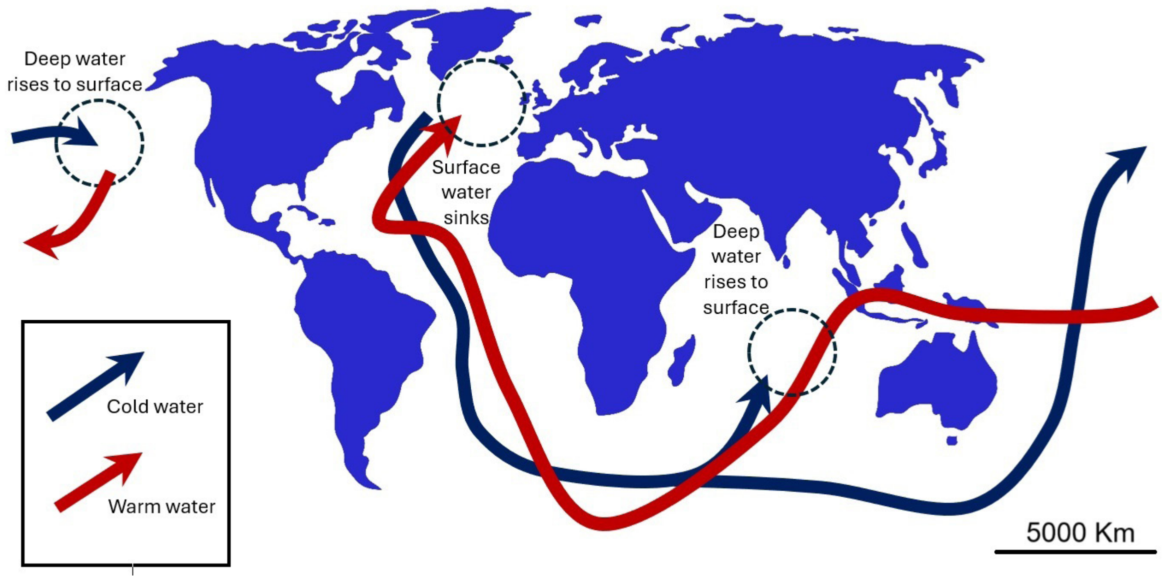

Figure 4. Major Surface Currents in the World's Oceans Play a Crucial Role in Global Heat Distribution. Cold Currents Carry Cooler Water from High-Latitude Regions toward Warmer Equatorial Zones, While Warm Currents Transport Heat from the Tropics to Higher Latitudes, Moderating the Climate of Cooler Areas.

One of the most concerning consequences of changes in thermohaline circulation is the potential weakening or even collapse of the Atlantic Meridional Overturning Circulation (AMOC). The AMOC is responsible for transporting warm water from the Gulf Stream into the North Atlantic, which significantly influences regional climate, particularly in Western Europe. A weakening of the AMOC, driven by factors such as increased freshwater influx from melting ice (assisted by the presence of microplastics within it) and altered salinity levels, could disrupt this vital heat transport mechanism. Europe could then experience reduced heat supply, leading to colder winters and altered precipitation patterns [65]. The potential for these disruptions is particularly concerning in the context of climate change, where such effects could be exacerbated by rising temperatures and changing precipitation patterns.

A weakening AMOC could also influence broader atmospheric circulation patterns, such as the position and strength of the jet stream. The jet stream, which is responsible for driving weather systems across Europe, is closely tied to the heat gradients between the tropics and the poles. As the AMOC weakens and the temperature differential between the equator and the poles diminishes, the jet stream may slow down or become more meandering, leading to prolonged weather patterns. This could result in extended periods of extreme weather, including cold spells and heavy rainfall, particularly in regions of Europe and North America [66].

Disruptions in ocean circulation can also have global implications. The shifting patterns of sea surface temperatures caused by changes in circulation could alter monsoon systems, which are critical for rainfall in tropical regions. A weakening AMOC has been linked to drier conditions in the Sahel and altered monsoon dynamics in South Asia, with potential consequences for agricultural productivity and water availability [67]. In addition, the redistribution of heat from the oceans to the atmosphere, influenced by changes in thermohaline circulation, could drive shifts in global temperature patterns, contributing to regional warming or cooling events that challenge existing climate norms.

The impacts of weakened thermohaline circulation extend beyond atmospheric weather patterns. The ocean itself is a massive heat sink, absorbing and redistributing heat across vast distances. Disruption in this system can impact marine ecosystems by altering the distribution of nutrients, affecting fisheries and marine biodiversity. Changes in the timing and intensity of upwelling, which brings nutrient-rich waters to the surface, could reduce the productivity of marine life in key areas, with cascading effects throughout the food chain. In the North Atlantic, studies show that a reduction in the strength of the

AMOC could lead to significant cooling, particularly in the northern regions of Europe [68,69]. This "cold event" could resemble the abrupt climate shifts seen during past glacial periods, when the AMOC weakened or shut down entirely. The "Little Ice Age" (roughly 1300–1850) is often cited as a historical example when a weakened AMOC coincided with cooler conditions in Europe and North America. Recent models suggest that we may be witnessing early signs of a similar pattern in modern times [70].

Thus the thermohaline circulation, particularly the AMOC, plays a central role in regulating the Earth's climate, especially in temperate regions. Disruptions to this system caused by factors like melting ice associated with microplastics' presence and changes in salinity could result in colder winters, altered rainfall, and changes in atmospheric circulation patterns, with profound implications for ecosystems and human societies [71]. Bellomo et al. used climate model experiments to determine the impact of a weakened AMOC on future climate conditions [71]. A decline in AMOC strength would lead to significant alterations in temperature and precipitation patterns. These changes would include cooling in the Northern Hemisphere, particularly in the North Atlantic and Arctic, a strengthening of westerly winds in the mid-latitudes, and an eastward shift of the jet stream in the North Atlantic, contributing to increased storm activity over Europe. Bellomo et al. predicted a widespread reduction in precipitation across the Northern Hemisphere [71].

The global interconnectedness of climate systems means that any alteration in ocean circulation would have cascading effects on weather patterns, water resources, and food security, highlighting the urgent need for continued research into the complex dynamics of ocean-climate interactions. The big question is whether atmospheric microplastics have already started to influence these systems, and if not, whether there is still time to halt this threat.

6. Research Gaps and Future Directions

Airborne microplastics are now recognized as a significant environmental concern. However, there are several key research gaps that must be addressed to fully understand their impacts on atmospheric processes, climate systems, and ecosystems. Current literature is limited, and much of the research is exploratory, requiring a more robust foundation to guide both science and policy.

6.1. Emission Quantification and Source Identification

A primary challenge is the quantification of microplastic emissions into the atmosphere. Although urban, industrial, and coastal areas are known to be major sources, the exact quantities of microplastics released and their spatial distribution remain poorly characterized. Future research must focus on comprehensive emission inventories for different regions and sectors. The identification of specific sources, such as various agricultural practices and new consumer goods, is also essential to better model microplastic fluxes into the atmosphere.

6.2. Characterization of Microplastic Properties

The physical and chemical properties of microplastics play a crucial role in determining their interactions with atmospheric processes. However, there is a lack of standardized methods to characterize airborne microplastics in terms of their size, shape, density, chemical composition, and surface characteristics. Future studies should focus on developing methodologies for the comprehensive analysis of microplastic particles across different environments, particularly in remote and high-altitude regions. Standardized protocols are urgently needed to ensure that results are comparable across studies.

6.3. Atmospheric Residence Time and Transport Dynamics

Another critical gap is the residence time of microplastics in the atmosphere and their long-range transport dynamics. While some studies have indicated that microplastics can travel long distances, their persistence in the atmosphere is still unclear. How long these particles remain suspended and how their transport varies depending on atmospheric conditions, such as wind speed, temperature, and humidity, are key factors that require more attention. Future research should aim to develop models to predict the behavior of microplastics under different climatic conditions.

6.4. Interactions with Atmospheric Processes

Despite increasing evidence that microplastics can influence atmospheric cloud formation and radiative forcing, these interactions are still not fully understood. The role of microplastics as CCN and INPs needs further exploration, particularly in terms of how they impact cloud properties and regional precipitation patterns. Additionally, the effects of microplastics on aerosol chemistry, including their role as carriers of other pollutants or biological agents, require more comprehensive studies.

6.5. Climate Modeling and Impact Assessment

Finally, the integration of microplastics into climate models must be a major area of attention. To assess the potential climate impacts it is essential to understand how airborne microplastics interact with other atmospheric components, such as aerosols, greenhouse gases, and particulates. Researchers should focus on incorporating microplastics into global and regional climate models to evaluate their potential role in radiative forcing, regional warming, and modulation of atmospheric circulation. The influence of microplastics on global precipitation patterns and ecosystem impacts must also be modeled to assess long-term effects on agriculture, water resources, and biodiversity.

6.6. Policy and Mitigation Strategies

As research into the atmospheric impacts of microplastics progresses, there is an increasing need for evidence-based policy and mitigation strategies. This includes regulations to limit the production and disposal of plastic waste, promote material innovations, and develop technological solutions for capturing airborne microplastics. For example, one of the potential ways suggested to reduce atmospheric MP levels has been phytoremediation — the use of protective forest belts that can trap airborne particulates. As yet, this has not been tested for microplastics' control, nor proven sufficiently effective for wide scale use. This remains a potential option for future research. Addressing the many issues concerned with reduction of microplastics in the atmosphere requires multidisciplinary collaboration among environmental scientists, engineers, policymakers, and public health experts.

7. Conclusions

Understanding the interplay between natural aerosols and microplastics in the atmosphere is crucial for comprehending the full scope of their impacts on climate systems. While natural aerosols have been studied extensively, the unique properties of microplastics, such as their resistance to degradation, long-range transport, and interactions with atmospheric processes, represent an emerging area of research that will require continued attention. Given their cumulative impact and persistence in the atmosphere, microplastics could be a significant factor in the evolution of climate systems and require further integration into global climate models.

Author Contributions

Conceptualization, methodology, formal analysis, investigation, resources, data curation, writing—original draft preparation, writing—review and editing, and visualization were jointly carried out by Estefan M. da Fonseca and Christine C. Gaylarde.All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement

Not applicable.

Data Availability Statement

No new data were created or analyzed in this study. Data sharing is not applicable to this article.

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Conflicts of Interest

The authors declare no conflict of interest.

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