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Title: Impacts of changing ocean circulation on the distribution of marine microplastic litter

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Abstract

Marine plastic pollution is currently a major scientific focus, with attention paid to its distribution and impacts upon ecosystems. With recent estimates indicating that the mass of plastic released to the marine environment will reach 250 million tonnes by 2025, the extent of these effects looks set to rise. Of increasing concern is the distribution of microplastics, those measuring less than 5 mm in diameter, which represent an increasing proportion of marine litter and are known to interact with numerous species of biota throughout the marine environment. The local abundance of microplastic is dependant on a complex interaction between the scale of local plastic sources and prevailing environmental conditions; as a result its distribution is highly heterogeneous. Circulation models have been utilized to predict plastic distribution; however, current models do not consider future variation in circulation patterns and weather systems caused by a changing climate. In this document we discuss the potential impacts of global climate change on the abundance and distribution of marine plastic pollution.

Introduction

The plastics circulating in the world's oceans have rich and diverse histories. In the wake of the Second World War disposable plastic items were developed and marketed as a tool to kick start global economies. The perpetuation of this mindset - in combination with the popularity of single-use products, uncontrolled disposal, and poor waste management and recycling practices - has resulted in the loss of large volumes of plastic to the environment (**Barnes et al. 2009; Bergmann et al. 2015**). Due to technological advances, population growth, and economic expansion, plastic production has increased; and since its development as an industrial component in the 1950's the annual production of plastics has risen to 322 million tonnes (**PlasticsEurope, 2016**). With greater volumes of consumer plastic in circulation loss to the environment has also risen, as a result, it is currently estimated that input of plastic waste from coastal countries will rise from 12.7 million metric tons to as high as 250 million metric tons by 2025 **(Jambeck et al. 2015).**

Plastic pollution has been divided into two functional subcategories: macroplastic debris, measuring over 5mm in size, and microplastic debris, which fall below this boundary. Microplastics are further divided into primary microplastics, which are manufactured to measure less than 5mm, and secondary microplastics, which achieve these dimensions through the breakdown of macroplastic litter once in the environment. The abundance of macroplastic debris and the scale of weathering factors have a great influence on the local level of secondary microplastics. The pathways through which these plastics enter our oceans are varied, including littering, landfill run-off, and loss at sea **(Browne 2015)**. While the scale and number of local sources of debris is of obvious importance, a number factors are responsible for the distribution of plastics in the marine environment.

Movement of Marine Plastic Debris

In addition to being highly resistant to degradation (known as recalcitrant), the density of the polymer greatly influences its distribution **(e.g. Ivar du Sol et al. 2013).** Polymers with a density higher than that of the surrounding water will sink, and those which are lower will float. These differences influence whether plastics remain in surface waters, become beached in coastal areas and estuaries, or sink to deep sea sediments **(Galgani et al. 2015)**. In areas with high levels of macroplastic debris, weathering may result in elevated local levels of microplastic. This breakdown is dependent on local environmental conditions including latitude, UV, and temperature **(Andrady 2015).**

Due to prevailing conditions, some areas accumulate both macro- and microplastics from a vast catchment. Suspended microplastics may be transported from their point of release to remote areas **(Ivar do Sul et al. 2013)** or accumulate in central ocean regions (or gyres) **(Cozar et al. 2014, 2015; Law et al. 2010)** (Figure 1.)**.** Studies in the North Pacific Subtropical Gyre and the South Pacific Gyre have shown densities of small plastic particles of 334,271 km² and 26,898 km² respectively (e.g. **Eriksen et al. 2013; Moore et al. 2001)**; and circulation models suggest that plastics can be present in all ocean gyres, as the gyres act as a conveyer to collect and accumulate plastic items **(Lebraton et al. 2012; Maximenko et al. 2012). Cozar et al. (2014)** suggested that accumulation as a result of gyre-circulation has led to the Pacific Ocean containing 33 to 35% of the global ocean plastic load. However, the vast majority of the sea surface, outside of subtropical gyres, has not been surveyed and therefore introduces potential errors to the global estimates.

Plastics and microplastics not entrained in gyre systems may reach remote oceanic regions and shorelines as a result of ocean transport. Transport of water between ocean basins is the product of complex interaction of forces, the key drivers of which are the temperature and salinity of water, known as thermohaline circulation (THC), the frictional effects of air currents, and the coriolis force **(Jonasson et al. 2007) (Figure 1)**. Observations of cargo lost from container ships have shown a strong relationship between the patterns of global circulation and those of debris distribution **(Ebbesmeyer et al. 2007; Karl 1999)**.

A more subtle influence on the distribution of floating plastics is that of the wind. Plastic debris riding at the water's surface are subject to the frictional effect of air currents which alter the path of the object, known as windage **(Shaw and Mapes 1979)**. The impact of windage on debris may result in the course of an object differing to that of the current alone (Figure 1). Comparisons of windward and leeward beaches have shown a distinct disparity in plastic abundance, with windward beaches experiencing plastic abundance raised by up to 24.2% **(Debrot et al. 1999)**. Similarly, in the Tamar estuary, England, downwind sites had raised levels of fragmented plastic debris **(Browne et al. 2010)**.

Mapping Microplastics

The combination of factors influencing plastic distribution have been used to develop models to provide an overview of the expected plastic load at a given time (e.g. **Cozar et al. 2014; Eriksen et al. 2014; van Sebille et al. 2015,**). In this way, researchers may predict areas of high plastic accumulation and potential threats of plastic debris to ecosystems. A Lagrangian tracking model, NEMO, was used to predict the movement of particles in the Mediterranean. This model assumed a homogeneous initial distribution of marine debris, with repeated one year predictions separated by 24 hours. This model has been used to predict both the accumulation of floating debris and its beaching points **(Mansui et al. 2015).** The model MEDSLIK-II was used to predict the movement of plastic debris in the Adriatic Sea, using an estimate of 10'000 tons of litter released each year. This model predicted increased volumes of plastic in the northwest boundary of the Adriatic but no defined aggregation points;

as a result, the authors suggest that the main sinks are the seafloor and shoreline stranding **(Liubartseva et al. 2016).**

While many of these models have proven effective in mapping current plastic distribution, they are subject to sources of uncertainty, such as variation in wind direction and force. Reconstructions of a decade of oceanic conditions in the North Sea have been used to simulate both pre-existing and subsequent distribution of floating debris. A Lagrangian particle tracking model, PELETS -2D, was used to predict the 90 day trajectories of debris from various locations. In this study wind drift was seen to greatly affect the distribution of particles away from the prevailing circulation patterns **(Neumann at el., 2014)**. In addition to the variability caused by short-term variation in abiotic factors, our oceans are currently undergoing a more marked period of uncertainty brought about by global climate change. These changes may not only affect the ability of models to predict the location of plastic aggregations, but also alter the geographic areas and habitats at risk of the negative effects of marine plastic pollution.

Changing climate and ice melt

Since the mid-19th century, there has been a mean increase in atmospheric temperature of 0.6 ± 0.2 °C (**Solomon 2007**). This warming has subsequently been linked to a range of effects on the marine environment; manifesting in the increasing reports of coral bleaching (**Hoegh-Guldberg 1999**), ocean acidification (**Doney et al. 2009**), and reduced sea ice (**Comiso et al. 2008**). The symptoms of climate change are not solely the result of a warmer atmosphere, but relate to an interaction between the thermal properties of the air, land and oceans. This relationship adds to an already complex picture of emissions and mitigation methods which cause uncertainty in both climate change projections and its impacts on the environment **(IPCC 2013**). One of the most widely discussed effects of temperature on circulation, salinity and sea temperatures is the increased rate of ice melt and reducing glacier extent. Increased freshwater input from terrestrial glaciers and the thermal expansion of seawater result in global rises in sea level. Previous projections of sea level change by 2099 rise indicated increases of 18 cm – 38 cm under the B1 and 26 cm – 59 cm under the A1FI climate scenarios (**Solomon 2007**). More recent estimates range from a conservative 28 cm - 56 cm and a potentially disastrous 57 cm - 131 cm (**Mengel et al. 2016**).

Ice melt in polar regions is predicted to have a range of effects on the distribution of marine plastics. Firstly, seasonal expansion and contraction of the ice sheets is believed to contribute to the flux of microplastic, as particles are trapped as water freezes and are released as it melts **(Lusher et al. 2015) (Figure 2)**. It has been suggested that melting ice may result in the release of entrained plastic **(Obbard et al. 2014)**; however, the bulk of the large ice sheets and glaciers formed before the proliferation of plastics and plastic litter, and the scale of such releases are predicted to be relatively minimal. Secondly, the density of many polymers is equal to or lower than that of seawater, causing plastics to float and be carried for long distances on ocean currents. Reduction in the density of seawater at sites of freshwater input is expected to reduce the relative buoyancy of marine debris, increasing the rate at which plastics sink (Figure 1). Correspondingly, areas of high evaporation will experience increased water densities, resulting in plastics persisting in the water column and/or surface waters. When predicting the movement of plastic at the water's surface, researcher's must take into account the residence time of plastics in the neustonic zone; in low water density areas, the transport time of plastics will be reduced, and in high density areas it will be increased.

Climate and Circulation

Freshwater inputs from melting glaciers are predicted to have effects beyond increasing the volume of water in our oceans. In addition to its role in the transport of heat from low latitude upwelling areas to high latitude sites of overturning (**Wunsch 2002)**, THC is directly affected by climate. Meridional Overturning Circulation - the process by which warm water is cooled, increasing its density and causing it to sink. Freshwater inputs in polar regions reduce the salinity, and therefore the density, of surface waters. This lessens the rate at which these waters sink, slowing formation of cold deep waters (**Broecker 1987**). Further freshwater inputs result from changes in the hydrological cycle, including increased rain events at higher latitudes (**Rahmstorf 1995**). It is believed that a fourfold increase in CO_2 is required to cause a collapse of THC (**Manabe and Stouffer 1994**); however, a reduction in transport of up to 50% has been observed in a number of models (**Rahmstorf 1999**). Atlantic Water Overturning is thought to be slower now than at any point in the previous century (**Rahmstorf et al. 2015**). Reducing the speed of deep water formation also slows down the rate at which fresh water is removed from these sinking regions, again reducing the seawater density (**Toggweiler and Key 2001**).

In addition to the effect of salinity on deep water formation, overturning is also influenced by the circulation of surface waters (**Pasquero and Tziperman 2004**). Surface water movement is primarily wind driven, which is driven by uneven heating of the earth's surface. Climate change is predicted to influence the pattern of global heating, one result of which will be altered wind patterns. Melting of the sea ice will reduce the albedo effect (the heat reflective capacity of the earth's surface) (**Curry et al., 1995; Holland and Bitz, 2003; Ingram et al., 1989**); these areas will be more readily heated, resulting in the formation of new low pressure areas as the newly heated - less dense - air rises upward. As wind patterns are governed by the movement of air from areas of high to low pressure, this change will alter prevailing wind conditions. Variation in wind patterns will affect the movement of surface waters, as well as the position of eddies and convergences, changing the distribution of floating micro- and microplastic. In addition to altering the effect of windage on plastic at the water's surface, increased wind speeds will result in increased vertical mixing, raising the abundance of plastics found at depth **(Reisser et al 2014, Kulkula et al. 2012)** (Figure 1). Debris that have previously settled in the sediment may also be re-suspended by wind driven mixing in near-shore waters **(Floderus and Pihl 1990),** increasing their abundance in the water column. These changes in coastal systems could also facilitate the transport of plastics to offshore areas (Figure 2).

Climate and Weather

Changes in sea surface temperature may also affect the scale and patterns of precipitation, in particular tropical storms, cyclones and tornadoes. Global warming intensifies along-shore wind stress on the ocean surface, resulting in accelerated coastal upwelling **(Bakun 1990**). It has been suggested that, as temperatures increase, torrential rain, flooding droughts and storms will become more frequent **(Christensen et al. 2004; Coumou and Rahmstof 2012)**. Furthermore, ocean subsurface temperatures, and thermohaline depths and thickness are predicted to affect the activities of natural climatic variations; an effect currently believed to be visible in the increasing frequency of El Niño events **(Cai et al. 2014; Johnson 2014).** Rising sea surface temperatures also increase the frequency of hurricanes, which are fuelled by warm tropical waters. Uncertainty in wind conditions may best be addressed by increasing the integration time of models, smoothing the effect of this short term variation **(Liubartseva et al., 2016**).

In addition to the increasing annual mass of plastic released from land or lost at sea, the input, distribution, and accumulation of marine plastic debris will also be affected by changes to global circulation and the morphology of coastal regions (**Figure 2**). Not only is increased wind strength predicted to facilitate the transport of windblown plastics from terrestrial environments into waterways, but more frequent rain events will increase flooding and surface water runoff further increasing plastic input **(Moore et al. 2002; Lattin et al. 2004)**. Movement of plastic from the terrestrial to the marine environment is also enabled by coastal flooding, as sea levels rise in response to melting ice and changes in water density. Debris littering shorelines will also become available for transport as these areas are inundated by rising seas.

Conclusions

Distinct relationships have previously been recorded between microplastic aggregation and both marine circulation and weather conditions. The impacts of a changing climate on ocean salinity and volume, and the movement of air and water suggests that there will be significant changes to the current pattern of distribution. The predicted increase in the mass of marine plastic debris indicates that the threat posed by microplastics will only rise in the coming decades. The ability to predict areas of plastic input and deposition would enable the identification of at risk species, and efforts to reduce and remove plastic debris to be targeted to specific locations. The current uncertainty as to the effects of global warming on our oceans is the greatest challenge in predicting the future patterns of plastic aggregation and accumulation in relation to global circulation. With future models of climate-ocean feedback expected to produce more accurate predictions of circulation patterns, including the impacts of a variable climate is vital in forecasting potential microplastic hotspots and "garbage patches".

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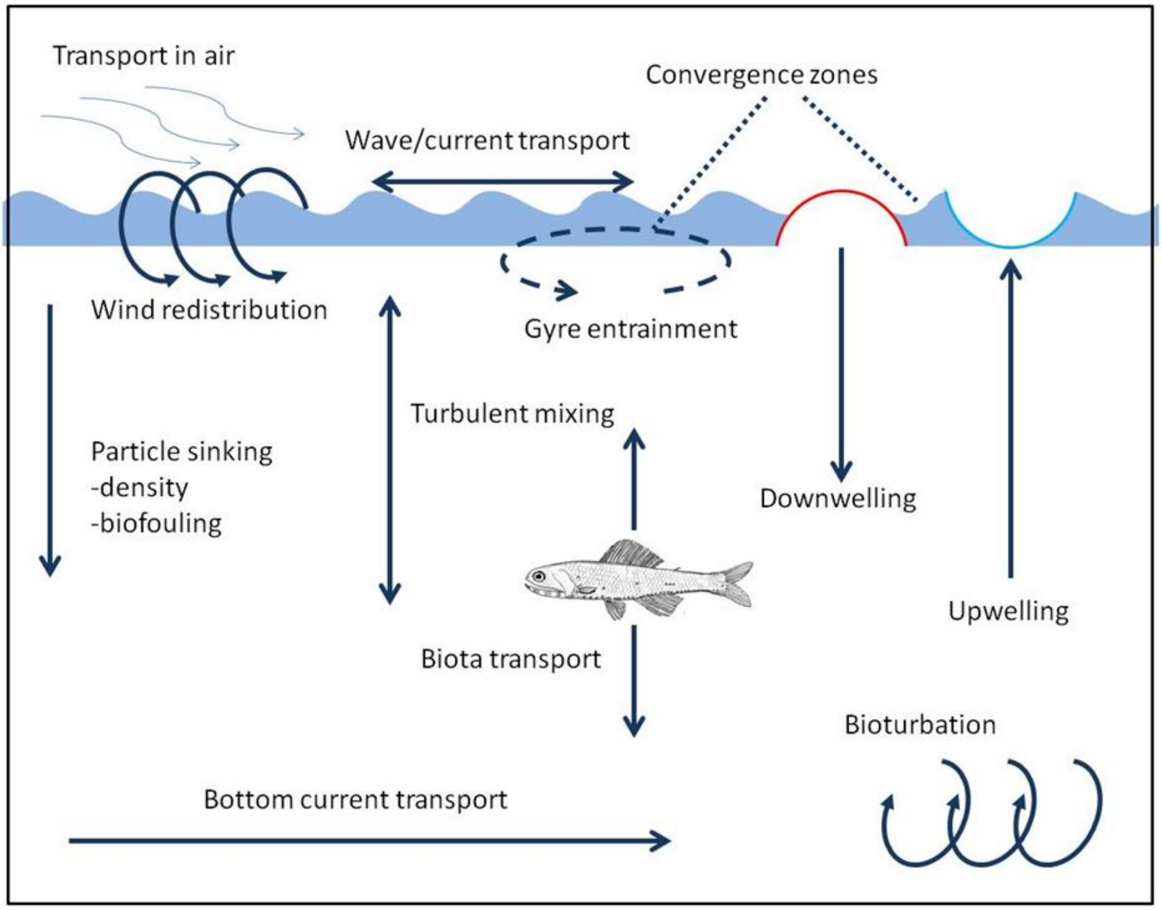

Figure 1. Factors influencing the distribution of plastic and microplastics within and between the zones of the marine environment and biota (adapted from Lusher 2015)

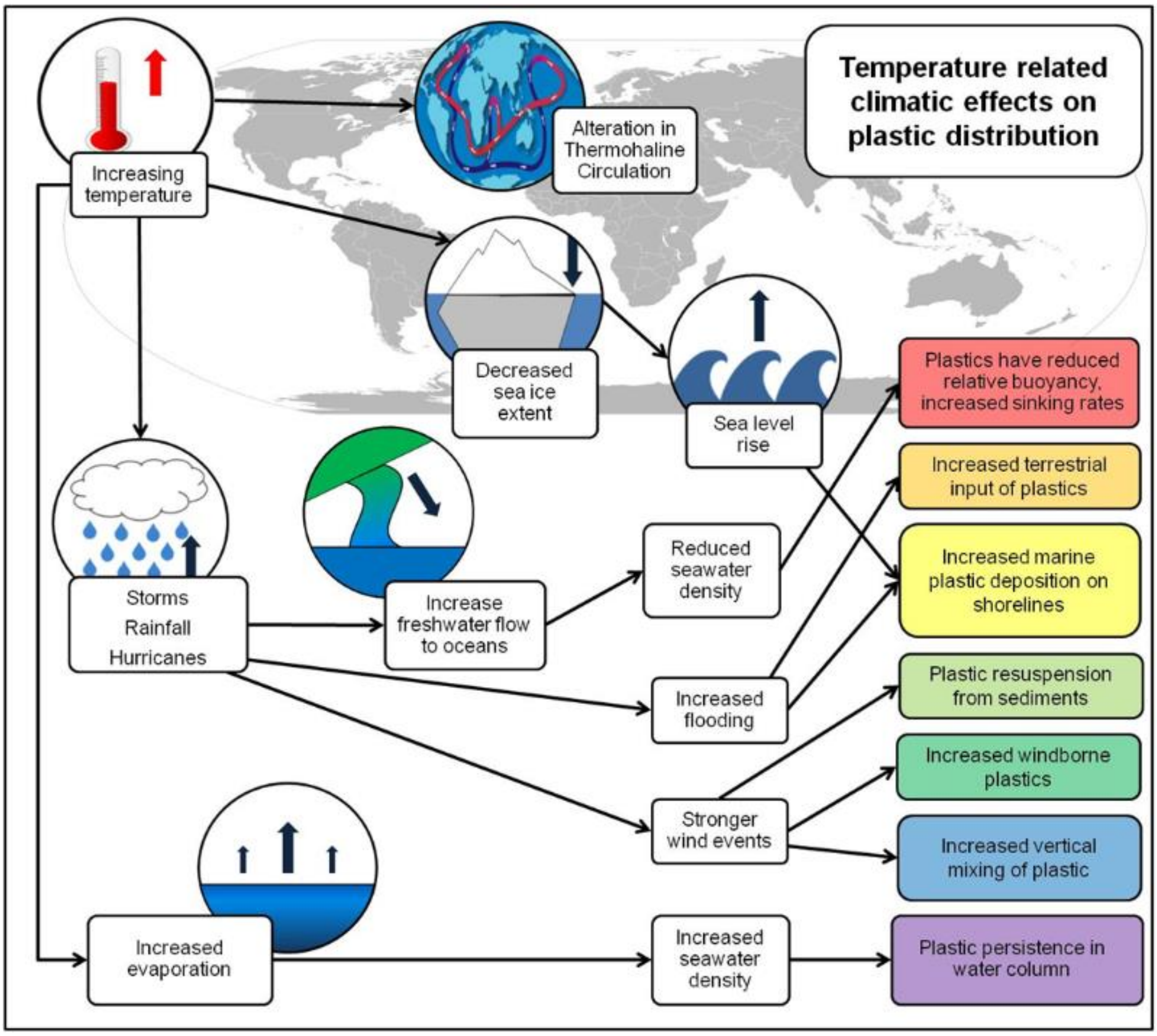

Figure 2. Schematic diagram of the predicted effects of climate change on the marine environment, and the potential impacts of such variation on plastic input, distribution and accumulation