The role of Ekman currents, geostrophy and Stokes drift in the accumulation of floating microplastic

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Key Points:

- Modeled microplastic distributions agree with observed distributions in the North Pacific and North Atlantic
- Ekman currents are the main process behind microplastic accumulation in the subtropical ocean gyres
- Stokes drift contributes to microplastic transport to the polar regions

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Abstract

Floating microplastic in the oceans is known to accumulate in the subtropical ocean gyres, but unclear is still what causes that accumulation. We investigate the role of various physical processes, such as surface Ekman and geostrophic currents, surface Stokes drift and mesoscale eddy activity, on the global surface distribution of floating microplastic with Lagrangian particle tracking using GlobCurrent and WaveWatch III reanalysis products. Globally, we find that the locations of the garbage patches are largely determined by the Ekman currents. Separate simulations of the North Pacific and North Atlantic show that the locations of the modeled garbage patches using GlobCurrent Total (Ekman + geostrophic) currents agree with observed microplastic distributions. Geostrophic currents and Stokes drift do not contribute to garbage patch formation in the subtropics, but Stokes drift leads to increased microplastic transport to the polar regions. Transport due to Stokes drift is found to be more sensitive to the temporal resolution of the dataset than the other current components. Since the WaveWatch III Stokes drift and GlobCurrent Ekman current datasets are not independent, combining Stokes drift with the other current components leads to an overestimation of the effects of Stokes drift and there is therefore a need for independent measurements of the different ocean circulation components. In the North Pacific, we find that microplastic tends to accumulate in regions of relatively low eddy kinetic energy, indicating low mesoscale eddy activity, but we do not see similar trends in the North Atlantic.

Plain Language Summary

Microplastic is a common form of pollution in the oceans, and high floating microplastic concentrations tend to be observed at the surface in the subtropical ocean gyres. These regions are commonly referred to as garbage patches. However, the physical processes that control the buildup in these regions are not yet fully understood. Therefore, we model microplastic transport with various surface current component that correspond to different physical processes. We do this with Lagrangian modeling, where microplastic is represented by virtual particles that are transported by ocean currents. We found good agreement between the modeled distribution with the full surface currents with observations in the North Pacific and North Atlantic and find that the microplastic accumulation is mainly due to the wind-driven Ekman currents. Meanwhile, wave-driven Stokes drift results in microplastic transport to the polar regions. Since Stokes drift has not consistently been included in microplastic transport modeling, microplastic contamination of the polar regions might be more severe than currently expected.

1 Introduction

The surface ocean circulation is driven by a large number of processes and is traditionally decomposed into various current components. These include the wind-driven Ekman currents, the geostrophic currents, and wave-induced Stokes drift. It has been shown that the Ekman and geostrophic currents play different roles in marine debris accumulation (Kubota, 1994; Kubota, Takayama, & Namimoto, 2005; Martinez, Maamaatuaiahutapu, & Taillandier, 2009), while Stokes drift has been shown to be important for kelp (Fraser et al., 2018) and oil (Drivdal, Broström, & Christensen, 2014) transport. However, the contribution of Stokes drift using reanalysis data to transport of floating plastic debris has not been studied.

Plastic debris has been found in a large number of marine habitats, such as in the open ocean (Cózar et al., 2014, 2017; Eriksen et al., 2014, 2013; Lebreton et al., 2018), on coastlines (Pieper, Ventura, Martins, & Cunha, 2015; Thompson et al., 2004; Young & Elliott, 2016) and on the sea floor (Galgani et al., 2000; Van Cauwenberghe, Vanreusel, Mees, & Janssen, 2013). The majority of plastic debris found at sea is non-biodegradable (Duhec, Jeanne, Maximenko, & Hafner, 2015; Morét-Ferguson et al., 2010) and can persist for decades in the open ocean (Lebreton et al., 2018), where it can cause harm to marine life through ingestion (Mascarenhas, Santos, & Zeppelini, 2004; van Franeker & Law, 2015), entanglement (Henderson, 2001) and by acting as a potential pathway for habitat invasion by alien species (Molnar, Gamboa, Revenga, & Spalding, 2008).

An estimated 4.8 - 12.7 million tons of plastic entered the ocean in 2010 (Jambeck et al., 2015), and buoyant plastic debris is known to accumulate in the subtropical ocean gyres in each of the ocean basins (Cózar et al., 2014; Eriksen et al., 2014; Law et al., 2010, 2014). For the Pacific basins, this accumulation has been found to be caused by surface Ekman currents (Kubota, 1994; Kubota et al., 2005; Martinez et al., 2009). The geostrophic currents contribute to debris transport, but due to their non-divergent nature do not lead to debris accumulation on their own Martinez et al. (2009). Kubota (1994) found that Stokes drift does not significantly contribute to debris transport, but parametrized Stokes drift as windage with climatological mean wind fields and as such did not take ocean swell into account, which is not locally generated. Windage represents the force of surface wind on exposed portions of an object above the ocean surface and windage effects have been found to have a significant impact on the trajectories of large objects (Trinanes et al., 2016). For microplastic, windage can play a significant role with low-density plastic such as polystyrene, but for higher density plastics the microplastic particles would be largely below the surface and thus not be exposed to much direct wind stress (Chubarenko, Bagaev, Zobkov, & Esiukova, 2016).

Comparisons of modeled microplastic distributions with observed microplastic concentrations were done by van Sebille et al. (2015), who modeled the global distribution of microplastic based either on drogued surface drifter trajectories (Maximenko, Hafner, & Niiler, 2012; van Sebille, England, & Froyland, 2012) or using HYCOM/NCODA surface currents (Lebreton, Greer, & Borrero, 2012) and compared the distributions with observations from surface-trawling plankton nets. It was found that the modeled distributions in the North Pacific closely correlate to spatial patterns in the observations, but that in the North Atlantic the agreement of the modeled distributions with observations is weaker. None of the models completely accounted for Stokes drift, which might therefore be a possible explanation for the observed discrepancies.

Processes that act on scales smaller than the mesoscale also play a role in microplastic accumulation. Martinez et al. (2009) found a tendency for debris in the South Pacific to accumulate in regions of relatively low eddy kinetic energy (EKE), which can be considered as a proxy for mesoscale eddy activity (Eden & Böning, 2002). Microplastic concentrations in an anticyclonic eddy have been found to be more than nine times higher than in a cyclonic eddy (Brach et al., 2018), while resolving mesoscale eddies increases the ability of microplastic to leave garbage patches in debris simulations (Maes, Blanke, & Martinez, 2016). However, the link between mesoscale eddy activity and plastic debris accumulation in the North Pacific and North Atlantic has not been considered so far.

Since different components of the the ocean circulations can change on different time scales, the temporal resolution of ocean circulation datasets can impact modeled transport. Maximenko et al. (2012) reported that temporal variability of the ocean currents has a strong influence of debris transport, as particles do not follow mean ocean current streamlines to reach debris accumulation regions. Particularly transport due to Stokes drift is dependent on the temporal resolution of the dataset, since Stokes drift is dependent on the wave field, which can change on very short time scales by changes in local weather conditions (Bennett & Mulligan, 2017; Montiel, Squire, Doble, Thomson, & Wadhams, 2018).

In this paper we study the contributions of the Ekman and geostrophic currents and Stokes drift on the location of microplastic accumulation regions (henceforth referred to as garbage patches) on a global scale, with particular focus on the North Pacific and the North Atlantic. This is done by means of Lagrangian simulations with ocean circulation data from reanalysis products (Rio, Johannessen, & Donlan, 2016; Tolman, 2009) including surface Ekman and geostrophic currents and surface Stokes drift. The recently proposed Sea surface KInematics Multiscale (SKIM) monitoring satellite (Ardhuin et al., 2018) would be able to measure ocean surface transport components such as Stokes drift directly. Therefore, the role of Stokes drift is of particular interest seeing how its effect on the transport of plastic debris has not been extensively considered (van den Bremer & Breivik, 2018). We also consider how transport is dependent on the temporal resolution of the datasets. Since windage has been used as a proxy for Stokes drift in the past Breivik and Allen (2008); Kubota (1994), we compare the transport due to Stokes drift from the WaveWatch III hindcast Tolman (2009) with various windage scenarios to investigate whether windage adequately captures Stokes drift dynamics. The modeled microplastic distributions in the North Pacific and North Atlantic are compared with observed microplastic concentrations measured with surface-trawling plankton nets from the dataset compiled by van Sebille et al. (2015). Finally, we examine the link between mesoscale eddy activity and microplastic accumulation.

2 Materials and Methods

2.1 Ocean Surface Current Datasets

We use several different reanalysis surface current data sets outlined in Table 1 for the period of 2002-2014. The Ekman and Geostrophic flow fields are from the GlobCurrent project (Rio et al., 2016), which combines satellite observations and in-situ measurements to obtain estimates of the surface circulation. Rio et al. (2016) make an initial estimate of the Geostrophic currents from altimeter maps and subtract this from surface velocities of ARGO floats to get an estimate of the non-geostrophic velocity of each drifter, which is referred to as the surface Ekman velocity. The Ekman velocities $\vec{u}_{ek}(z)$ are parametrized by Rio et al. (2016) with an amplification factor $\beta(z)$ and Ekman velocity angle $\theta(z)$ by applying a least squares fit between measured Ekman velocities from ARGO drifters and surface wind stress $\vec{\tau}$ data from ERA-Interim (Dee et al., 2011). Based on 841,746 ARGO drifter Ekman velocities, the surface Ekman currents are found by Rio et al. (2016) to be at an angle of $\theta(0) = 30.75°$ to the wind stress (to the right in the Northern Hemisphere, to the left in the Southern Hemisphere), with an amplification factor of $\beta(0) = 0.61$ m^2 s kg^{-1}. Using 15m-drogued drifters from the Surface Velocity Program (SVP), the Ekman current parameters at 15m depth are $\theta(15\text{m}) = 48.18°$ and $\beta(15\text{m}) = 0.25$ m^2 s kg^{-1}.

The Geostrophic velocities of 15m-drogued and undrogued surface drifters from the Surface Velocity Program (SVP) are found by subtracting the Ekman velocities from the drifter velocities. Rio et al. (2016) uses the measured Geostrophic velocities to update the initial geodetic mean dynamic topography (MDT) to determine the CNES-CLS13 MDT from which the final Geostrophic velocities are computed. This incorporation of in-situ observations provides missing short-scale information for the boundary currents and equatorial regions that would be missing with just a geodetic approach (Rio, Mulet, & Picot, 2014). The Total surface currents are the sum of the surface Geostrophic velocities and the surface Ekman velocities.

The surface Stokes drift is from the WaveWatch III hindcast dataset (Tolman, 1997, 2009), where the magnitude and direction of the Stokes drift is based on the wavenumber-direction spectrum (Webb & Fox-Kemper, 2015). The 2002-2014 temporal means of the GlobCurrent and WaveWatch flow fields are shown in Figure 1.

It must be noted that the GlobCurrent and WaveWatch III datasets are not independent. The parametrization of the GlobCurrent Ekman currents does not contain a

Table 1. Overview of the datasets used for particle advection in the simulations.

Flow Field	**Dataset**	**Spatial Resolution**	**Temporal Resolution**	**Source**
Ekman currents	GlobCurrent v3 Ekman Hs Currents	1/4°	3 h	Rio et al. (2016)
Geostrophic currents	GlobCurrent v3 Geostrophic Currents	1/4°	24 h	Rio et al. (2016)
Total currents	GlobCurrent v3 Total Hs Currents	1/4°	3 h	Rio et al. (2016)
Stokes drift	WaveWatch III Surface Stokes Drift	1/2°	3 h	Tolman (1997, 2009)
Windage	CFSR Surface Winds	1/2°	3 h	Saha et al. (2011)

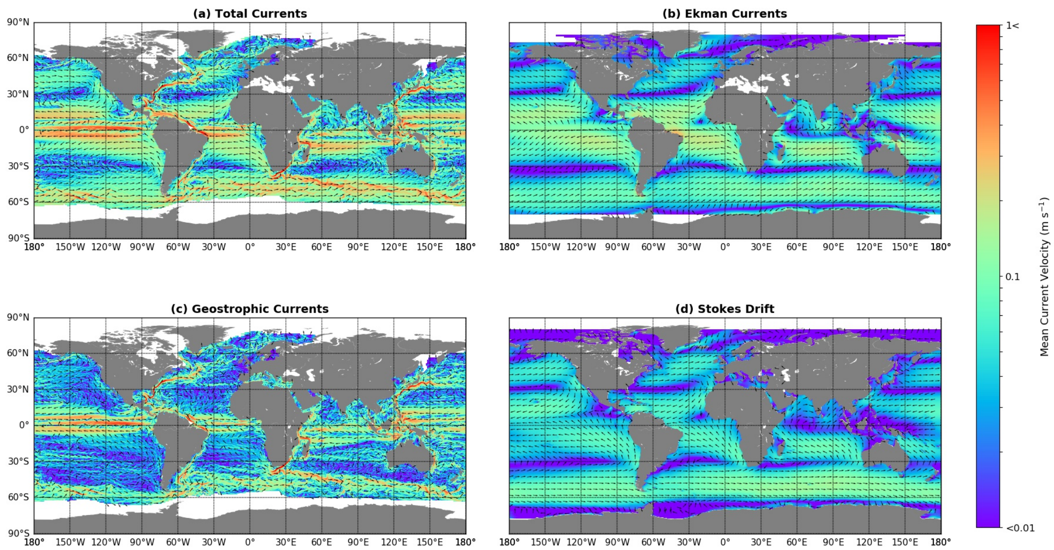

Figure 1. Temporal mean flow fields for the Total, Ekman and Geostrophic currents and the Stokes drift. Averages are taken for 2002-2014, with the normalized vectors indicating the mean direction and the colormap indicating the current magnitude. Note that the velocity scale is logarithmic.

correction for Stokes drift, and so summation of the flow fields will lead to an overestimation of the Stokes drift effect.

2.2 Windage Proxy

Windage effects are dependent on the object size, shape and buoyancy and the coupling strength between the local wind and the resultant windage velocity of the object is highly variable (Chubarenko et al., 2016). We use the windage classification used by Duhec et al. (2015), which classifies debris as either low windage (e.g. fishing nets and small plastic fragments), medium windage (e.g. polystyrene and partially filled PET bottles) or high windage (e.g. unfilled PET bottles and fishing buoys). We compare the Stokes drift with each of these windage scenarios, where the windage is 1%, 3% or 5% of the local wind vector, to investigate which would be most appropriate as a proxy for Stokes drift. We use the CFSR (Saha et al., 2011) wind fields for 2002-2014 (Table 1), which is the same wind field used for the WaveWatch III hindcast (Tolman, 2009).

2.3 Microplastic Observation Dataset

The dataset of microplastic measurements taken by surface-trawling plankton nets was compiled by van Sebille et al. (2015). 11,632 trawl measurements taken between 1979 and 2013 were considered by van Sebille et al. (2015), of which 6812 were collected in the North Atlantic, 2551 were collected in the North Pacific and the rest were spread out over the Southern Hemisphere and in the Mediterranean. While microplastic commonly refers to plastic debris <5 mm, van Sebille et al. (2015) refers to any plastic debris collected with a plankton net trawl as microplastic, as most of the plastic collected in plankton net trawls are small fragments. We use the same definition in all following references to microplastic.

Given that the samples were collected over a period of 34 years and that microplastic concentrations are sensitive to the vertical mixing due to surface wind stress (Kukulka, Proskurowski, Morét-Ferguson, Meyer, & Law, 2012), van Sebille et al. (2015) corrected for the sampling year and the variable wind conditions. All concentrations are ultimately expressed in terms of counts km^{-2} and are binned into 1° bins. Given that the observational record for the Southern Hemisphere is very limited, it is not possible to make meaningful comparisons between modeled microplastic distributions and observations for these regions. We therefore focus on the North Atlantic and the North Pacific.

2.4 Lagrangian Transport

We use Parcels (Probably A Really Computationally Efficient Lagrangian Simulator) (Lange & Van Sebille, 2017) to model microplastic as virtual particles which are advected using ocean flow field data. A change in the position $\vec{x}$ of a particle is computed by:

$$\vec{x}(t + \Delta t) = \vec{x}(t) + \int_{t}^{t+\Delta t} \vec{v}(\vec{x}(\tau), \tau)\mathrm{d}\tau \tag{1}$$

where $\vec{v}(t)$ is the velocity at $\vec{x}(t)$. The flow velocity $\vec{v}(\vec{x}(t), t)$ at the particle location is obtained through linear interpolation of the flow field data in space and time.

All simulations are carried out for 2002-2014. Since the Geostrophic current dataset has a temporal resolution of 1 day, we use daily mean fields for the Total currents, Ekman currents, Stokes drift and wind fields for consistency with the temporal resolution. We also carry out simulations with 3 hourly data to study the effect of current variations on sub-daily time scales.

For the initial microplastic distribution, we use a homogeneous distribution with particles placed at 1° intervals for the global simulations (34,515 particles). We also run separate simulations for the North Pacific and North Atlantic starting from a homogeneous distribution with particles placed at 1/2° intervals (30,091 particles for the North Pacific and 18,632 particles for the North Atlantic), to allow better comparisons of the modeled distributions with observations. The majority of marine plastic debris is thought to enter the oceans from the coastlines from rivers (Lebreton et al., 2017), direct littering at the coast (Jambeck et al., 2015) or as runoff from natural disasters (Prasetya, Black, De Lange, Borrero, & Healy, 2011). However, the input distribution remains highly uncertain (Lebreton et al., 2017). The input distribution is important for modeled concentrations. However, since the purpose of this study is to determine the processes determining the average spatial locations of the garbage patches, indicated by the spatial location of the peak microplastic concentration, it was assumed that the effect of the initial distribution is small. This is supported for the long-term distribution by the close agreement between the garbage patch locations modeled by Maximenko et al. (2012) (which started with particles with a initially homogeneous distribution) and those modeled by van Sebille et al. (2012) and Lebreton et al. (2012) (which released particles at the coasts scaled according to coastal population densities). The reported modeled concentrations are averaged over the final year of the 12-year simulation and binned into 1° bins to determine the average locations of the garbage patches.

The GlobCurrent datasets resolve some mesoscale eddies, and EKE is taken as a proxy for mesoscale eddy activity. Each particle samples the local EKE along its trajectory, where the EKE is computed from the Total surface current anomaly components u' and v', which are computed with respect to the time-averaged Total surface currents for 2002-2014. The EKE is computed according to:

$$EKE = \frac{(u')^2 + (v')^2}{2}. \tag{2}$$

Preliminary simulations showed that almost half the particles beached over the course of a 12 year simulation. Since the purpose of this study does not involve investigating particle beaching, we implement an artificial shore-normal boundary current with a velocity of 1 m s^{-1} that is non-zero only at the coast. This prevented the beaching of particles and allowed for more robust statistics. The anti-beaching current is not found to influence the microplastic distribution.

3 Results

3.1 Global

Simulations with the Total currents show the formation of garbage patches in each of the subtropical ocean gyres, as well as north of Russia around Novaya Zemlya (Figure 2a), which agrees with observations (Cózar et al., 2014, 2017; Eriksen et al., 2014). The garbage patch with the most particles is in the South Pacific, but this is an artifact of the large number of particles within the basin at the beginning of the simulation, as was similarly stated by Maximenko et al. (2012). The garbage patches form as a result of the Ekman currents (Figure 2b), with the locations of the garbage patches matching those of the Total current garbage patches. The Ekman currents on their own lead to a smaller surface area of the garbage patch than with the Total currents, which is due to Geostrophic currents. The Geostrophic currents counter microplastic accumulation in the subtropics and disperse the microplastic over a larger surface area. On their own, the Geostrophic currents only lead to elevated concentrations in the open ocean north of Brazil and west of New Guinea (Figure 2c). However, this is likely a product of the Geostrophic current dataset, as the equatorial region has the highest estimated error of the Geostrophic currents relative to observations (Rio et al., 2016).

In the Pacific basins, Stokes drift largely clears the subtropical gyres of microplastic, transporting it east toward New Guinea (Figure 2d). Microplastic is found in the subtropical ocean gyre in the South Atlantic, but with low concentrations relative to garbage patch concentrations in the Total current simulation. Outside the equatorial regions, the highest concentrations are found near Antarctica and north of Norway, indicating that Stokes drift contributes to poleward microplastic transport.

The influence of Stokes drift is also apparent by comparing the connectivity of the ocean basins when particles are advected solely by Total currents or by the sum of Total currents and Stokes drift (Figure 3). Tracking the initially uniformly distributed particles indicate connections between the different ocean basins over a 12 year period, which show that the ocean basins do not follow strict cartographic boundaries. This is especially the case for the southern hemisphere (Figure 3a), where the basins stretch westwards in bands in the simulation with Total currents (Froyland, Stuart, & van Sebille,

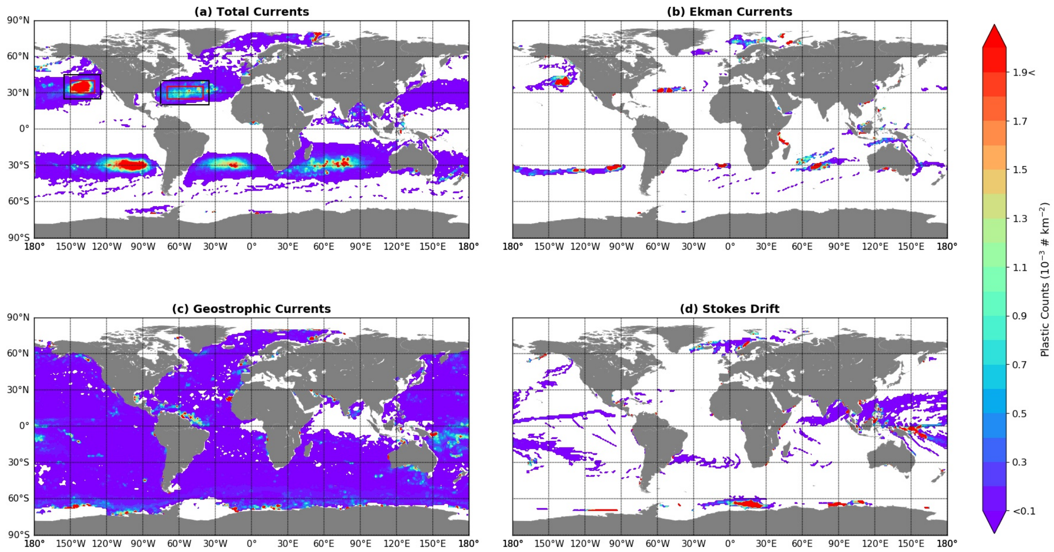

Figure 2. The average particle density of the final year of the global Lagrangian runs with the virtual particles advected by the daily mean Total, Ekman and Geostrophic currents and the Stokes drift. The red and black boxes in the North Pacific and North Atlantic in panel (a) indicate the garbage patch and extended garbage patch for that basin used in the EKE analysis.

2014). Only around half of all particles within the South Pacific, South Atlantic and Indian basins end within the same basin they originated from, compared to 96.0% and 82.0% for the North Pacific and North Atlantic (Table 2).

The inclusion of Stokes drift has a strong influence on these connections, particularly in the Southern Hemisphere (Figure 3b). The South Pacific has the greatest reduction in particle number from 26.6% of the total particles to 15.8%, with the majority of these particles going either to the South Atlantic or the Indian basin. The increased connectivity with the North and South Pacific leads to a large increase in the number of particles in the Indian basin, which rises from 20.4% of the total particles to 27.4% (Table 2). This transport compensates for the increased connectivity between the South Atlantic and Indian basins, indicated by the share of particles in the South Atlantic that originate from the Indian basin rising from 28.2% to 39.6%.

The poleward transport due to Stokes drift, shown in Figure 2, is apparent by the 213% increase in the total number of particles in the Southern basin at the end of the simulation relative to the simulation with just the Total currents. This increase is largely due to particles starting in the Southern basin being retained, although there are also increases in the number of particles reaching the Southern basin from the Indian, South Atlantic and South Pacific basins. There is also a slight increase of particles in the Arctic basin due to increased poleward transport from the North Atlantic.

Finally, the inclusion of Stokes drift increases cross-equatorial particle transport. With just the Total currents, only 0.4% of particles in the South Atlantic originate from the North Pacific, while in the Indian basin the North Pacific share is 6.5%. This respectively rises to 3.3% and 19.2% with Stokes drift included. No particles from the North Atlantic are within the Southern Hemisphere at the end of the simulation.

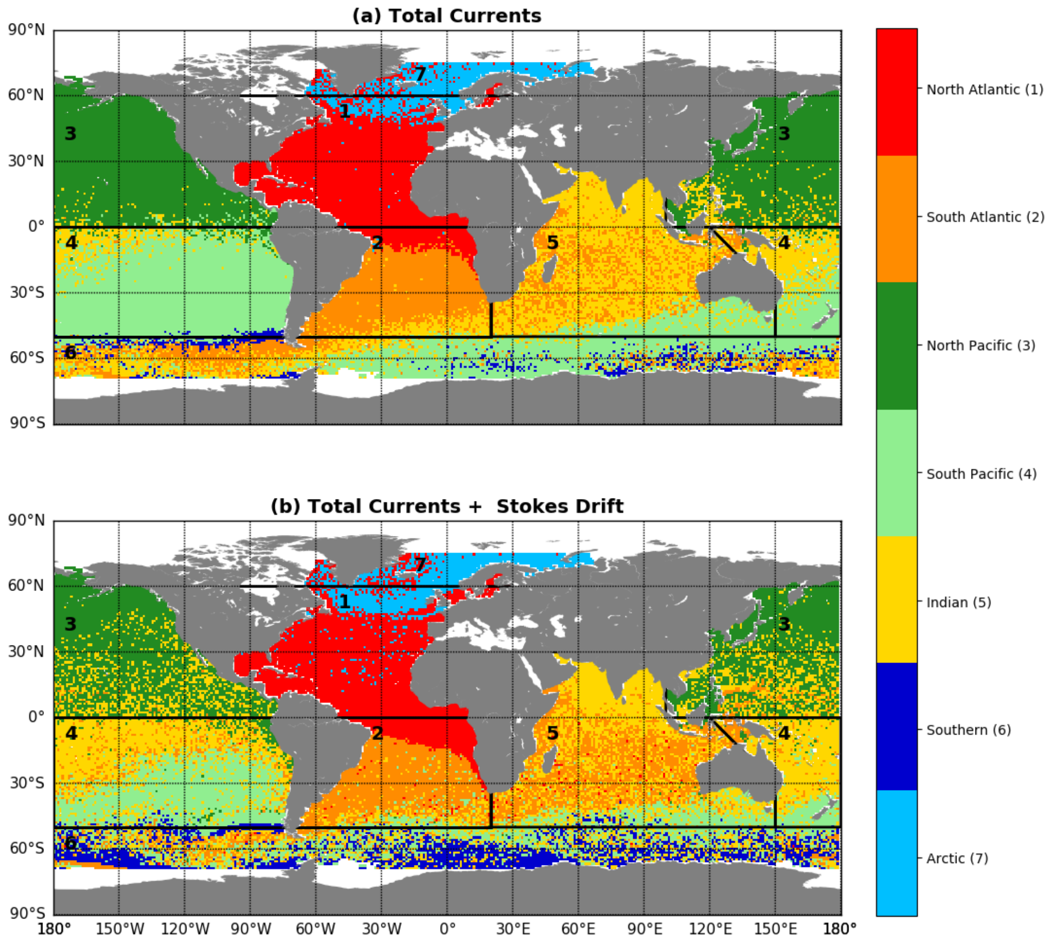

Figure 3. Connectivity of the ocean basins based on virtual particles advected with daily mean Total currents and the sum of the daily mean Total currents and Stokes drift. Particles are shown at their initial position colored according to their position at the end of the simulation. The coloring is based on the black boxes.

Table 2. The total number of particles within each basin (according to the definitions in Figure 3), at the end of the global simulations, with particles advected by either daily mean Total currents or the sum of the daily mean Total currents and Stokes drift. The left column indicates the basin of origin. Percentages indicate the fraction of total particles in the final basin that originate from the given basin of origin.

Basin of Origin	**North Pacific**		**South Pacific**		**North Atlantic**		**South Atlantic**	
	Total	Total + Stokes	Total	Total + Stokes	Total	Total + Stokes	Total	Total + Stokes
North Pacific	96.0%	93.4%	0.9%	0.0%	0.0%	0.0%	0.4%	3.3%
South Pacific	3.2%	5.1%	55.3%	46.6%	0.0%	0.0%	0.7%	9.2%
North Atlantic	0.0%	0.0%	0.0%	0.0%	82.0%	75.2%	0.0%	0.0%
South Atlantic	0.0%	0.1%	0.2%	3.5%	13.5%	17.2%	44.9%	34.3%
Indian	0.8%	1.0%	8.9%	12.6%	0.1%	2.0%	28.2%	39.6%
Southern	0.0%	0.4%	34.7%	37.3%	0.0%	0.4%	25.8%	13.6%
Arctic	0.0%	0.0%	0.0%	0.0%	4.4%	5.2%	0.0%	0.0%
Total Particles	7146	5809	9178	5452	4097	4205	4942	5603

Basin of Origin	**Indian**		**Southern**		**Arctic**	
	Total	Total + Stokes	Total	Total + Stokes	Total	Total + Stokes
North Pacific	6.5%	19.2%	0.0%	0.0%	0.0%	0.0%
South Pacific	18.1%	34.3%	5.0%	2.5%	0.0%	0.0%
North Atlantic	0.0%	0.0%	0.0%	0.0%	38.8%	48.3%
South Atlantic	5.3%	3.4%	0.0%	0.2%	0.7%	0.0%
Indian	50.1%	28.6%	0.0%	1.8%	0.0%	0.0%
Southern	20.0%	14.5%	95.0%	95.5%	0.0%	0.0%
Arctic	0.0%	0.0%	0.0%	0.0%	60.5%	51.7%
Total Particles	7028	9446	818	2557	1260	1405

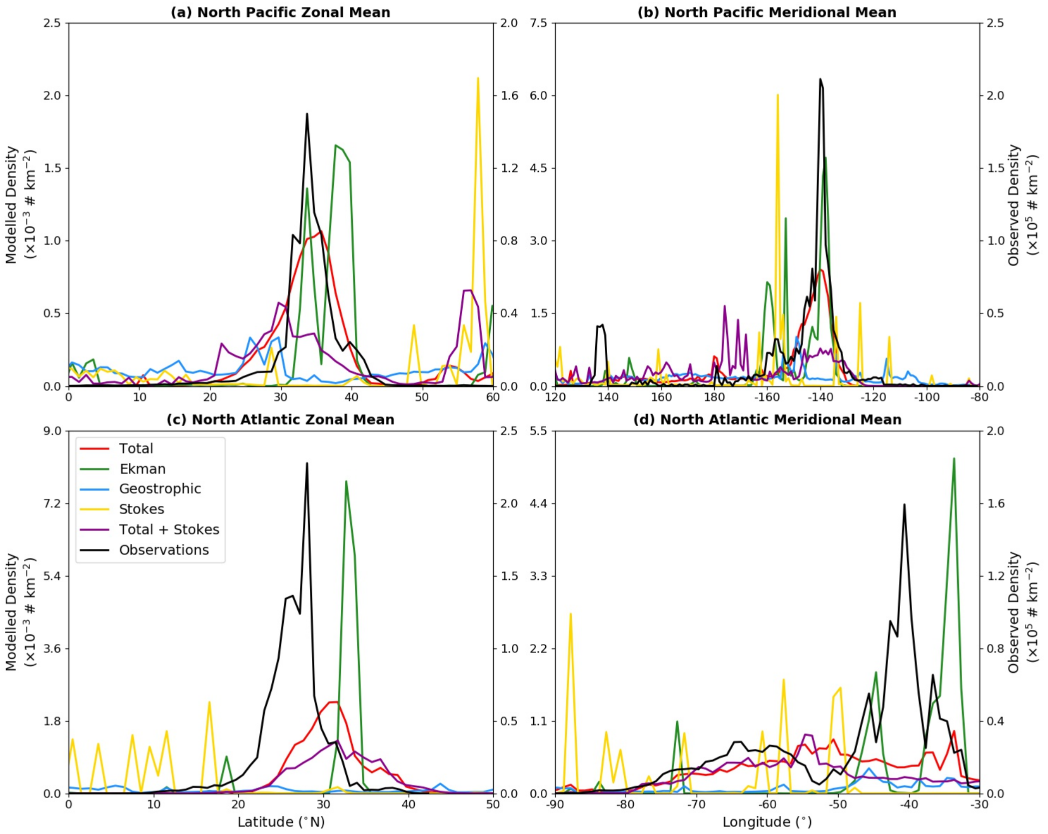

Figure 4. Zonal and meridional spatial means of observed (van Sebille et al., 2015) and modeled microplastic concentrations with various daily mean surface current components for the North Pacific and North Atlantic simulations. For the North Pacific the means are for the region of $0° - 60°$N and 120°E–80°W. In the North Atlantic the means are for the region $0° - 50°$N and $90° - 30°$W. In each subplot the left axis indicates the modeled concentrations while the right axis indicates the observed concentrations. Please note the different scales used in the subplots.

3.2 Comparison with Observations

We focus on the North Pacific and North Atlantic for the comparison of simulated distributions with observations as these are the only regions with a sufficient sampling density.

The North Pacific garbage patch with the Total currents shows good agreement with observations, with peaks in the meridional and zonal means of the microplastic concentration closely agreeing at (35°N, 140°W) (Figure 4a&b). In the North Atlantic the agreement is less clear. The model correctly predicts accumulation in the subtropics, but the highest concentrations are 5° farther north in the observations (Figure 4c). However, while the observational record has a pronounced peak in meridional mean microplastic concentration at 40°W, the elevated concentrations in the Total currents simulation are spread over $75° - 30°$W, with only small peaks at 34°W and $50° - 55°$W (Figure 4d).

The zonal and meridional mean of the Geostrophic current simulation distribution show no elevated concentrations in the subtropics in neither the North Atlantic nor the North Pacific (Figure 4a&c). In contrast, the Ekman currents do lead to strong peaks in concentration in the subtropics, with the location of the concentration peaks in the

North Pacific closely agreeing with the concentration peaks in the observations (Figure 4a&b). There is only a small shift in the position of the concentration peak relative to the concentration peak in the Total current distribution, indicating that Geostrophic currents have little impact on the location of maximum accumulation. We do observe that the Ekman current simulations show much higher concentrations than the Total current simulations, which is due to the lack of strong dispersion of microplastic by the Geostrophic currents (Figure 2c).

In the North Atlantic the Ekman currents lead to the formation of two subtropical microplastic concentration peaks at 35°W and 45°W (Figure 4d). These agree closely with the meridional concentration peak in the observations at 40°W. However, the addition of Geostrophic currents spreads out the microplastic and the westernmost peak is found at $50° - 55°$W. The location of easternmost peak is unaffected, but the concentrations are lowered by a factor of five.

The addition of the drift to the Total currents does not lead to closer agreement between observed and modeled microplastic distributions (Figure 4). In the North Pacific the addition of Stokes drift causes much greater temporal variance in the location of the garbage patch, leading to a less defined garbage patch as the temporal averaging spreads out the peak concentrations over a larger area. The peak concentration in the zonal direction has shifted further south relative to observations, while there is no clear peak at all in the meridional direction (Figure 4a&b). In the North Atlantic the general shape of the microplastic distribution is unchanged in the zonal and meridional directions, but the concentrations are consistently lower (Figure 4c&d).

3.3 Role of Mesoscale Eddy Activity

For the North Pacific and North Atlantic Total current simulations, time series of the average EKE are computed for all particles within the basins and for all particles whose final position at the end of the simulations are within the respective garbage patches. The garbage patches are selected such that they encompass the elevated microplastic concentrations in the subtropical ocean gyre, as shown in Figure 2a. The extended garbage patches shift the garbage patch boundaries by 5° in each cardinal direction.

In the North Pacific the average EKE for particles in the garbage patch at the end of the simulation is consistently lower than the average for all particles (Figure 5a), which at the end of the simulation has grown by an order of magnitude. This is unchanged by considering the extended North Pacific patch. The time series of the extended garbage patch shows a similar trend, and indicates that observed trend is not just a product of the selected garbage patch boundaries.

The North Atlantic average EKE time series for all particles and just the garbage patch particles do not show a strong correlation (Pearson $r=0.560$, $p< 0.01$) and the average EKE for the garbage patch particles is not consistently lower than the garbage patch as a whole (Figure 5b). There is a drop in the average EKE at the end of the simulation, but this is a product of the selected garbage patch boundaries as this drop is not visible when considering the extended North Atlantic garbage patch. There is therefore no indication that microplastic in the North Atlantic tends to accumulate in regions of relatively low mesoscale eddy activity.

3.4 Comparison of Windage with Stokes Drift

In the North Atlantic, particle advection in the two higher windage scenarios leads to particle distributions that are similar to the distribution from advection by Stokes drift in that particles are largely cleared from the subtropical open ocean in the higher windage scenarios (Figure 6). Furthermore we see most accumulation in the Carribbean or between Greenland and Norway. However, with Stokes drift particles in the polar regions

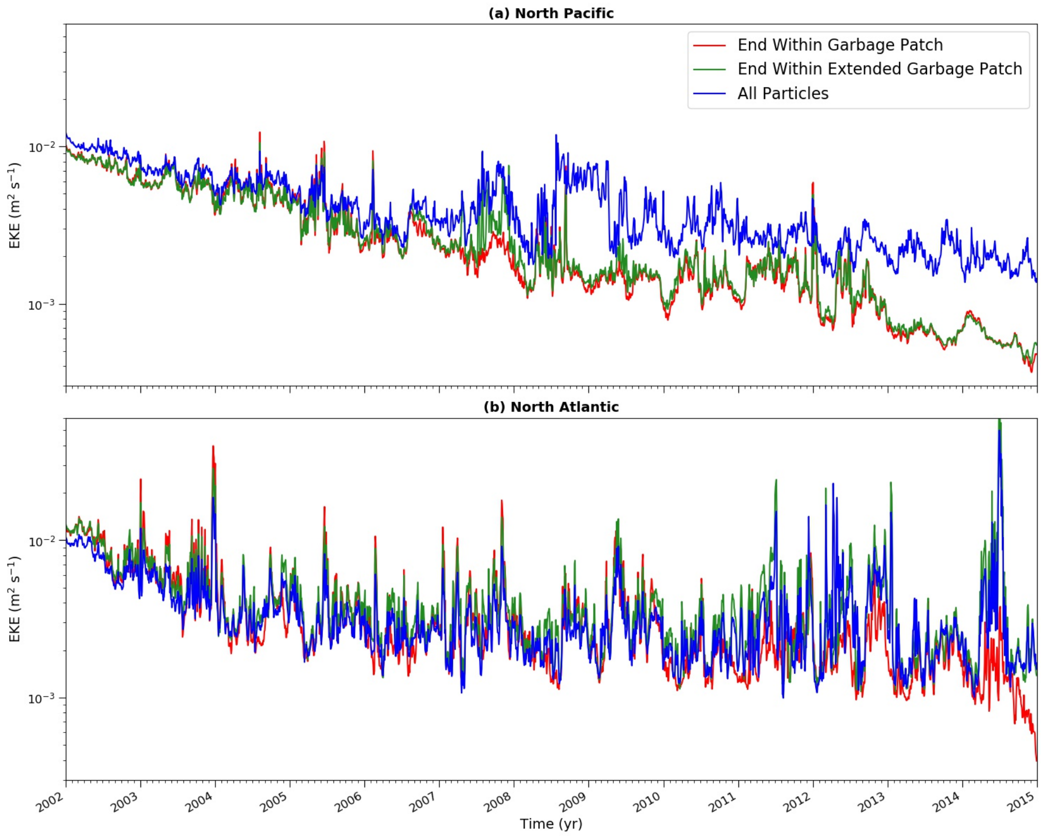

Figure 5. Average EKE over time of particles that end within the garbage patch, of particles that end within the extended garbage patch, and of all particles within the North Pacific and North Atlantic simulations. The particles are advected with daily mean Total currents. The North Atlantic garbage patch is defined as $25^\circ - 35^\circ$N and $40^\circ - 70^\circ$W, while the extended North Atlantic garbage patch is defined as $20^\circ - 40^\circ$N and $35^\circ - 75^\circ$W. The North Pacific garbage patch is defined as $30^\circ - 40^\circ$N and $130^\circ - 150^\circ$W, while the extended North Pacific garbage patch is defined as $25^\circ - 45^\circ$N and $125^\circ - 155^\circ$W, as shown in Figure 2a. Please note that the EKE axis is logarithmic.

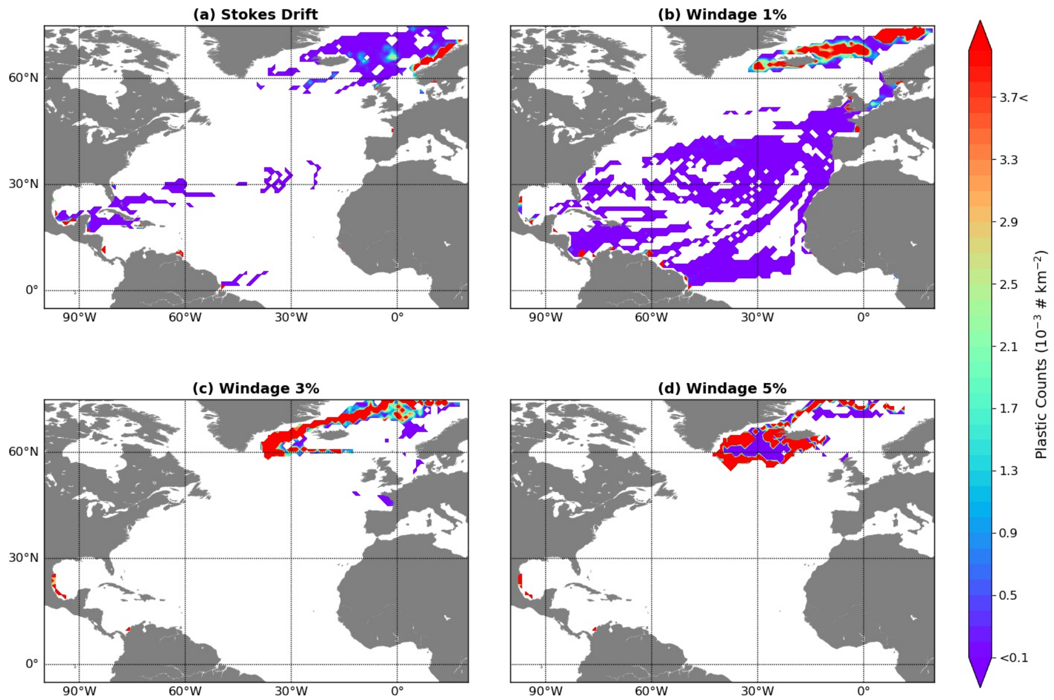

Figure 6. The average particle density of the final year of North Atlantic Lagrangian simulations with the virtual particles advected by daily mean Stokes drift and 1%, 3% and 5% windage from daily mean CFSR wind fields.

are largely driven towards the coast, while within the windage scenarios more particles tend to remain in the open ocean. Additionally, in the 1% windage scenario more particles remain in the subtropics than with Stokes drift. The high concentrations in the polar regions with each of the windage scenarios do not indicate a stable garbage patch, but are due to high numbers of particles passing through the region in the final simulation year.

All windage scenarios result in the same general microplastic distribution, but the 3% and 5% windage scenarios result in particle velocities that are much higher than Stokes drift. The global average Root Mean Square Error (RMSE) of the 3% and 5% windage scenario Eulerian velocity fields relative to the Stokes drift Eulerian velocity fields are 0.282 m s^{-1} and 0.225 m s^{-1}, while for the 1% windage scenario Eulerian velocity fields the global average RMSE is only 0.033 m s^{-1}. The RMSE is not globally uniform, with the smallest RMSE in the equatorial regions and the highest RMSE at $30° - 60°$ latitude and in the polar regions (Figure 7). The higher latitudes correspond to regions with a large amount of ocean swell, which have little correlation with local wind conditions (Fan, Lin, Griffies, & Hemer, 2014).

Considering the zonal and meridional velocity components of the Stokes drift and windage separately, there is a closer correlation between the zonal velocity components than the meridional components. With the zonal velocity, the coefficient of determination (r^2) for most of the open ocean is 0.8 or higher, with lower coefficients only being found in the polar and select equatorial regions. In comparison, the coefficients of determination for the meridional velocity components are consistently lower. This has implications for the direction of the windage, for low correlation for either velocity component, results in the direction of the windage Eulerian velocity field deviating from the direction of the Stokes drift Eulerian velocity field.

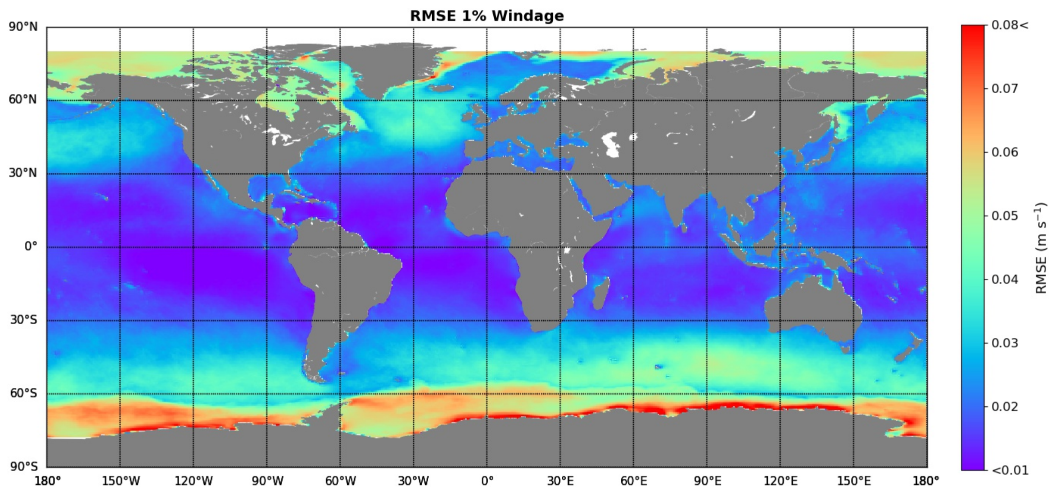

Figure 7. Root Mean Square Error (RMSE) between the speed of the Stokes drift and the 1% Windage scenario. The RMSE is computed on a 0.5° × 0.5° grid for 01-01-2002 to 31-12-2014.

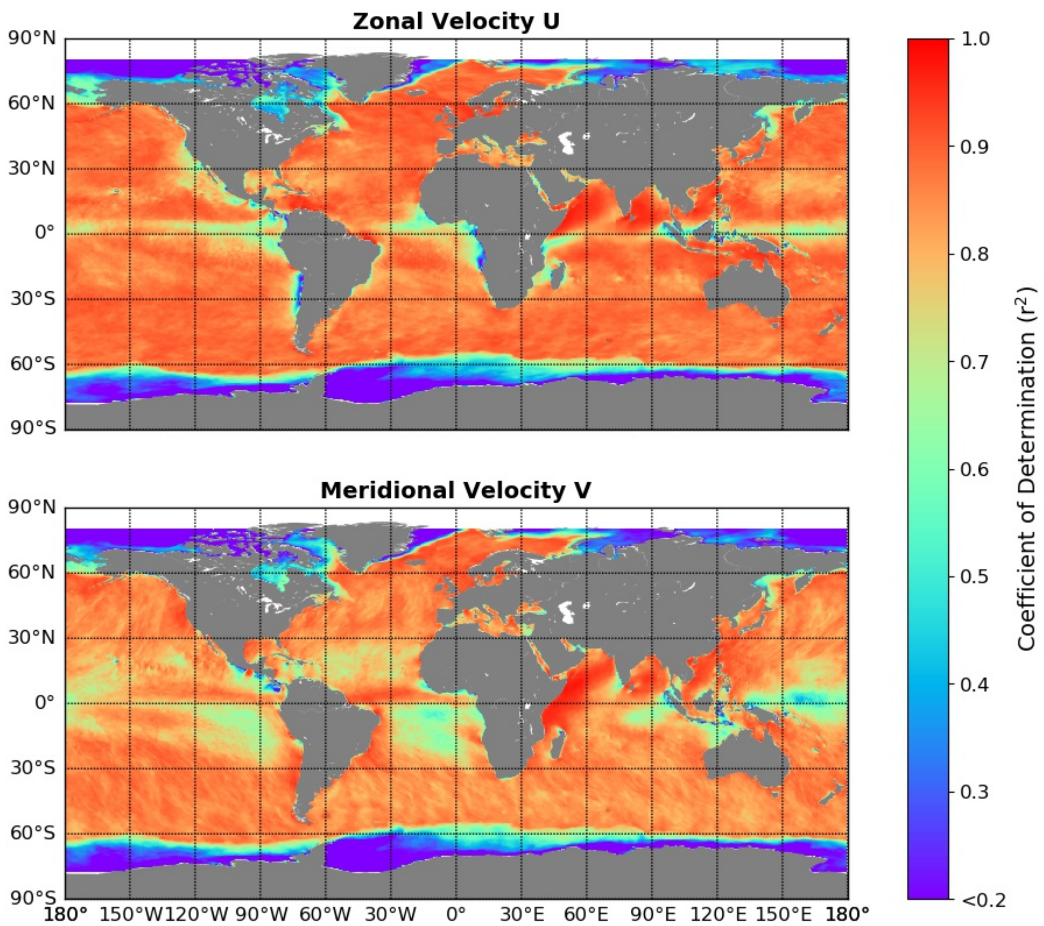

Figure 8. Coefficient of determination r^2 for the zonal and meridional velocity components of Stokes drift and windage. Coefficients are computed on a 0.5° × 0.5° grid for 01-01-2002 to 31-12-2014.

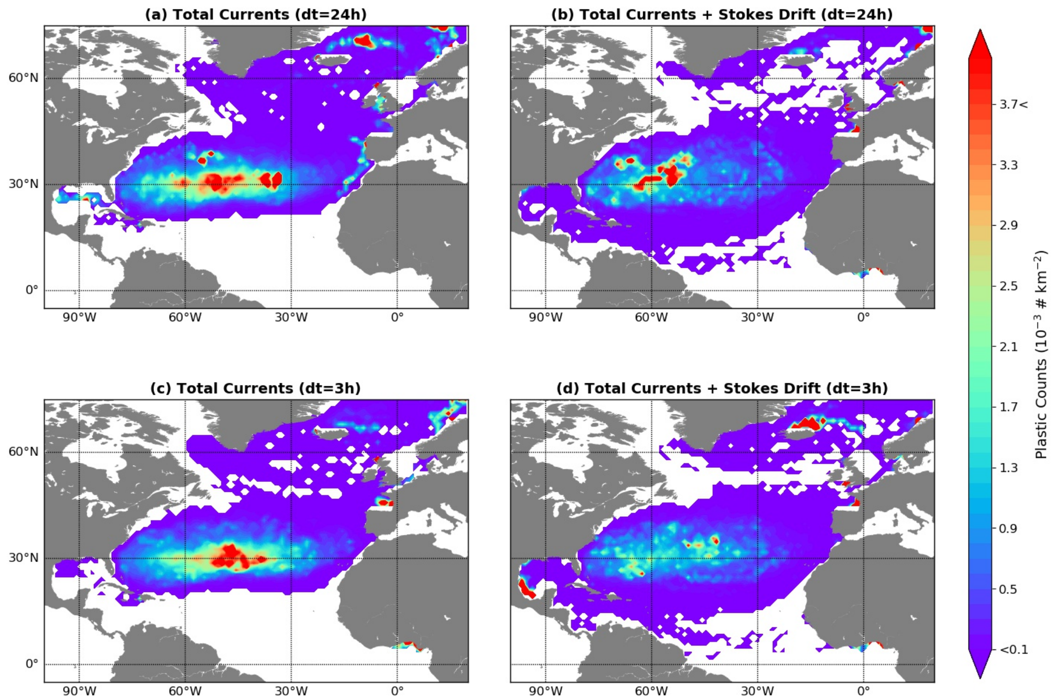

Figure 9. The average particle density of the final year of North Atlantic Lagrangian simulations with the virtual particles advected by Total currents or the sum of the Total currents and Stokes drift. The flow field datasets have a temporal resolution of either 24 hours or 3 hours.

3.5 Impact of Temporal Resolution of Flow Fields

Simulations of the North Atlantic where particles are advected using flow field data sets with a temporal resolution of 3 hours show that the higher temporal resolution of the Total currents does not have a strong impact on the modeled garbage patch (Figure 9a&c). The peak concentrations remain in the same location, although the zonal spread of microplastic is smaller when using the higher temporal resolution data set. In the case of the North Pacific the resultant microplastic distribution is similarly largely unaffected by the change in temporal resolution of the Total current dataset (Figure 10a&c).

The effect of the increased temporal resolution of the microplastic distribution is more apparent with the sum of the Total currents and Stokes drift. In the North Atlantic there is no clear peak in microplastic concentrations in the subtropics, as is the case when considering the daily mean flow field scenario (Figure 9b&d). There is also more microplastic in the Arctic regions, with high concentrations north of Iceland that are not visible with the lower temporal resolution. In the case of the North Pacific, the inclusion of Stokes drift with the daily mean datasets already results in there being no clear garbage patch in the subtropics, and increasing the temporal resolution does not change this (Figure 10b&d).

4 Discussion & Conclusions

In this study we investigate the role of various surface current components on the accumulation of microplastic in the subtropical ocean gyres. This is done by Lagrangian particle tracking with ocean circulation data from reanalysis products. The modeled microplastic distribution with the Total currents in the North Pacific, and to a lesser ex-

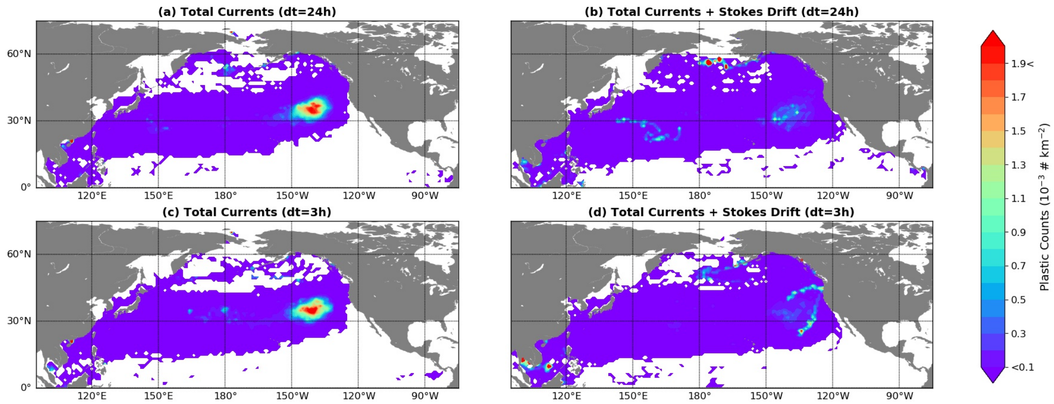

Figure 10. The average particle density of the final year of North Pacific Lagrangian simulations with the virtual particles advected by Total currents or the sum of the Total currents and Stokes drift. The flow field datasets have a temporal resolution of either 24 hours or 3 hours.

tent in the North Atlantic, show good agreement with the observational microplastic distribution, and the location of the garbage patches is largely determined by the Ekman currents. This agrees with earlier work on the Pacific basins by Kubota (1994); Kubota et al. (2005) and Martinez et al. (2009), which found Ekman current to lead to debris transport to the subtropics, where Geostrophic currents transport the debris eastward. In our simulations we find the Ekman currents able to account for the eastward transport on their own. This is due to the angle of the surface Ekman currents to the surface wind stress being 30.75° instead of 45° as predicted by Ekman theory and used by Kubota (1994); Kubota et al. (2005) and Martinez et al. (2009). In the subtropics this leads to a stronger zonal velocity component and therefore more zonal microplastic transport. Considering the close agreement with observations, especially in the North Pacific, the GlobCurrent parametrization of the Ekman currents based on ARGO float Ekman velocities is likely a better indicator of the real surface ocean circulation than Ekman currents computed solely based on Ekman theory.

Stokes drift has not been consistently considered in all global microplastic transport simulations, and this can lead to an underestimation of the microplastic contamination of polar regions. Our simulations showed that Stokes drift on its own does not contribute to microplastic accumulation in the subtropics, but we do observe high concentrations near Antarctica and Norway. In contrast, the Total current simulations show very little microplastic near Antarctica. This is supported by Fraser et al. (2018), who found that Stokes drift can lead to kelp crossing the strong circumpolar winds and currents to reach the Antarctic coast. Stokes drift therefore appears to be an important contributor to surface microplastic transport.

Unfortunately it is currently not possible to accurately determine the combined effect of the Total and Stoke currents from reanalysis flow fields alone. The GlobCurrent and WaveWatch III datasets are not independent and the sum of Total currents and Stokes drift leads to overestimation of Stokes drift effects. The GlobCurrent surface Ekman currents are parametrized based on the non-geostrophic velocities of ARGO drifters, and these drifter velocities contain a Stokes drift component (Rio et al., 2014). However, the parametrization of the Ekman currents is based on the local surface wind stress, and therefore does not properly account for the contribution of ocean swell to Stokes drift. This is shown by our comparison of Stokes drift with the windage scenarios, where regions with high amounts of ocean swell show a higher RMSE between the Eulerian velocity fields of Stokes drift and the 1% windage scenario. We also see that the windage direction does not always agree with the direction of Stokes drift, which can have important implications for transport modeling. This is especially the case for polar regions, which are most affected by transport due to Stokes drift but where we also see the greatest discrepancy between Stokes drift and windage scenarios.

There is a need for instruments capable of direct global measurements of Stokes drift in the open ocean. This would provide a global observation dataset of Stokes drift, which in turn can be used to correct for Stokes drift in the parametrization of Ekman currents. In this manner, summation of all current components would be possible and further analysis of the contribution of Stokes drift to microplastic transport would be possible. The recently proposed SKIM satellite would use near-nadir Ka-band Doppler radar with incidence angles of 6° and 12° to measure the directional wave spectrum, from which the Stokes drift can be derived (Ardhuin et al., 2018). The measured velocity fields would have a temporal resolution of 1 hour, which would be of great use for Stokes drift, since Stokes drift transport appears more sensitive to the temporal resolution of the datasets than the transport due to Ekman and Geostrophic currents. This is due to Stokes drift being dependent on the wave field, which responds quickly to changes in atmospheric conditions. In contrast, geostrophic balance responds to changes in conditions on timescales of days.

Martinez et al. (2009) first found that marine debris tends to accumulate in regions of low EKE, and for the North Pacific we verify similar behavior. Maes et al. (2016) showed the inclusion of mesoscale eddies results in more debris escaping the North Pacific garbage patch. Since mesoscale eddies can transport mass, our initial hypothesis was that higher microplastic concentrations are observed in regions of low EKE since these are regions where there is less mesoscale eddy activity. In regions of low mesoscale eddy activity, this would happen less frequently and therefore high concentrations can be maintained. In the North Pacific the region of low EKE coincides with the subtropical ocean gyre, and so Ekman currents can transport microplastic to the garbage patch. The low EKE can contribute to the maintenance of the elevated concentrations, since low mesoscale eddy activity would indicate that less eddies are present within the region to carry away microplastic. In the North Pacific this hypothesis remains plausible, but we would expect to see similar patterns in the North Atlantic. Theoretical work has suggested that the EKE of subtropical gyres scales with the basin size (Spall, 2000), and therefore it is possible that the smaller size of the North Atlantic basin leads to a less prominent role for mesoscale eddy activity. On the other hand, we see that the modeled North Atlantic garbage patch has a larger zonal extent than in the North Atlantic. This might be due to an absence of a local minimum in the EKE, with microplastic dispersion due to mesoscale eddy activity being constant throughout the subtropics. However, these remain hypotheses.

While we model transport as being purely two dimensional, biofouling of microplastic particles results in decreased buoyancy, which leads to sinking Kooi, van Nes, Scheffer, and Koelmans (2017). Additionally, we do not consider microplastic removal processes, such as beaching and ingestion. Therefore, future microplastic modeling might consider three dimensional flow fields with vertical microplastic dynamics and account for microplastic removal. Furthermore, in this paper we only compare our modeled distributions with observations in the North Pacific and North Atlantic due to insufficient sampling of the other ocean basins. There is therefore a great need for more microplastic sampling, especially outside the eastern North Pacific and the Western North Atlantic.

Acknowledgments

The code used for this work is distributed under the MIT license and can be found at https://github.com/OceanParcels/SKIM-garbagepatchlocations. The v3.0 GlobCurrent data can be found at http://www.ifremer.fr/opendap/cerdap1/globcurrent/v3.0/ and the WaveWatch III hindcast can be found at ftp://ftp.ifremer.fr/ifremer/ww3/HINDCAST/GLOBAL/.

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