LIMNOLOGY
and
OCEANOGRAPHY

Limnol. Oceanogr. 9999, 2025, 1–12

doi: 10.1002/lno.12814

RESEARCH ARTICLE

Marine snow as vectors for microplastic transport: Multiple aggregation cycles account for the settling of buoyant microplastics to deep-sea sediments

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Abstract

Many studies have reported the paradoxical observation of high concentrations of low-density microplastics (plastic particles < 5 mm) in deep-sea sediments despite their buoyancy. The incorporation of buoyant microplastics into marine snow has been observed to enhance microplastic settling. Previous studies on the vertical movement of buoyant microplastics have been unable to theoretically account for these ocean observations and no study has comprehensively elucidated microplastic transport pathways in the ocean from the surface to seafloor. Here, we establish a one-dimensional theoretical model, that embraces key elements of the flocculation process, to explain how marine snow acts as a vector to transport buoyant microplastics to deep water and the ocean bottom. Microplastics reach the ocean floor through multiple cycles of aggregation, settling, and disaggregation between marine snow and microplastics. Each settling cycle results in a net settling of 200–400 m. We demonstrate that microplastics with different sizes show distinct vertical settling behaviors and only microplastics less than 100 μm in diameter can reach the ocean bottom. This theoretical model refines our ability to predict and understand the global and long-term fate, transport, and inventory of microplastics in the ocean interior, the influence of microplastics on the biological carbon pump and the efficacy of plastic management policies.

Plastic waste, especially microplastics (plastic particles < 5 mm), have been detected in every corner of the world (Browne, Galloway, and Thompson 2010; Cózar et al. 2014; Allen et al. 2019; Hartmann et al. 2019), and deep-sea sediments are considered the final resting place of microplastics (Woodall et al. 2014; Bergmann et al. 2023; Tsuchiya et al. 2023). High concentrations of small microplastics (mainly < 100 μm) have been consistently detected within different ocean basins (Bergmann et al. 2017; Tekman et al. 2020; Tsuchiya et al. 2023) comprising disproportionate concentrations of buoyant microplastics, while large buoyant microplastics (> 500 μm) rarely reach the ocean bottom. However, there is no clear mechanism explaining how, or over what timescales, these small and buoyant microplastics from the ocean surface reach the deep-sea sediments, and why large and buoyant plastic particles do not settle to the ocean bottom.

Settling of marine snow aggregates is a critical process to transport nutrients such as inorganic minerals and organic detritus from the ocean surface to the deep ocean and is a key element of the biological carbon pump in the ocean (Alldredge and Gotschalk 1988). Marine snows are organic-rich aggregates made up of organic detritus and inorganic minerals and normally have higher settling velocities than individual particles (Turner 2002). The incorporation of microplastics into marine snows makes these aggregates an important pathway for transferring these buoyant particles from the ocean surface to deep-sea zones. This acts as a natural removal process for buoyant microplastics from the upper ocean

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Associate editor: Christelle Not

Data Availability Statement: The code used to generate the analyses presented in the paper can be found here: https://zenodo.org/records/14780376.

(Kvale et al. 2020; Zhao et al. 2023). Of note, the flocculation process is often considered an important stage in developing the structure of aquatic mineral–biological aggregates (Droppo 2001; Spencer et al. 2022). Once microplastics are incorporated into the marine snows, it is the physical characteristics of the marine snow, rather than the microplastic particle, that dictates transport dynamics, and marine snows could be important vectors for microplastics across different layers of the ocean (Alldredge 1998; Ransom et al. 1998; Turner 2015). The incorporation of small microplastics into marine snows has been verified through laboratory experiments (Michels et al. 2018; Porter et al. 2018) and field monitoring studies (Zhao et al. 2018; Galgani et al. 2022). Zhao et al. (2017, 2018) detected elevated concentrations of microplastics in marine snow samples, and Tekman et al. (2020) also reported a high correlation between microplastics and particulate organic matters at different depths of marine waters. Galgani et al. (2022) detected high mass concentrations of small microplastics ($< 100\ \mu$m) in sediment trap samples from ocean water column, suggesting that the marine snow aggregates is an important pathway to transport microplastics to deep ocean.

The trajectories of microplastics transported by marine snows across the full depth of the ocean remain cryptic, even though we have direct observations from in situ measurements, supported by laboratory experiments. None of these studies have addressed the following questions: (1) What is the trajectory of buoyant microplastics in the ocean interior influenced by marine snows? (2) By what mechanism do marine snows transport buoyant microplastics to the deep ocean? Resolving this process is crucial to understand the flux of microplastics in the water column, which remains an open question (van Sebille et al. 2020), as well as understanding the potential influence of microplastics to ocean biogeochemistry (Kvale and Oschlies 2023). Thus, it is essential to comprehend the interactions between marine snows and microplastics throughout the water column.

The overall aim of this study is to explain how marine snows transport buoyant microplastics vertically in the ocean from surface to seafloor. The objectives are:

1. to establish a theoretical model to explain how buoyant microplastics are incorporated into and settle with marine snows in the ocean interior.
2. to reconstruct the sedimentation trajectory of buoyant microplastics from the ocean surface to the seafloor, identify the timescales involved, and discuss the mechanisms enabling microplastics to reach the ocean floor.
3. to examine how the size of microplastics affects the incorporation and sedimentation processes described in objectives 1 and 2, and discuss the implications for different-sized microplastics.

Methods

A theoretical one-dimensional model was established to simulate the buoyant microplastics' vertical transport influenced by aggregation and disaggregation with marine snows. The particle (microplastics and marine snows) movement vertically including rising and settling is determined by the density difference with ambient seawater (Kooi et al. 2017; Lobelle et al. 2021). Once the buoyant microplastics are incorporated into marine snows, they settle alongside marine snows (Porter et al. 2018). This model uses established concepts and parametrizations for most of the components (Kooi et al. 2017; Fischer et al. 2022), and the theoretical framework is shown in Fig. 1a.

Physical and marine snow parameters

Physical oceanography dataset

We used the North Pacific Subtropical Gyre as a representative ocean environment to investigate the vertical transport of microplastics in the water column. The depth of the water column is 5100 m, a representative value for water depth in this region. The biogeochemistry dataset was acquired from Subhas et al. (2020). This is an ideal location for this study because ocean gyres concentrate high levels of plastic waste at the ocean surface in North Pacific Subtropical Gyre (Cózar et al. 2014; van Sebille, Wilcox, et al. 2015), and understanding the sedimentation of microplastics in this area would be beneficial to global ocean plastic waste management. The thermohalocline and density distribution with depths for this location were acquired from the World Ocean Database (Mishonov et al. 2024).

Marine snow concentrations

The total particulate matter (TPM) concentration was estimated from Subhas et al. (2020) and transformed into the number of marine snows. We assumed a uniform size of 1 mm for marine snows because this size falls within the most frequently detected size range and exhibits higher stability (Alldredge and Gotschalk 1988; Monroy et al. 2017). The TPM was calculated based on the ratio between particulate organic carbon (Subhas et al. 2020) and this ratio is 15 in this study (Harms et al. 2021). The TPM mass of aggregates can be found in Alldredge and Gotschalk (1988) and the average weight of TPM in each marine snow is 2.5 μg ($\mathrm{TPM_{agg}}$). Therefore, the number of marine snows (N_{MSA}) can be calculated according to the concentration of TPM ($\mathrm{TPM_{con}}$) and the marine snow TPM mass (Eq. 1). In this study, we assumed all of the TPM is aggregated (Guidi et al. 2009), or ready to be aggregated when calculating the number of marine snows at each depth (Fig. 1b).

$$N_{\mathrm{MSA}} = \mathrm{TPM_{con}} / \mathrm{TPM_{agg}} \tag{1}$$

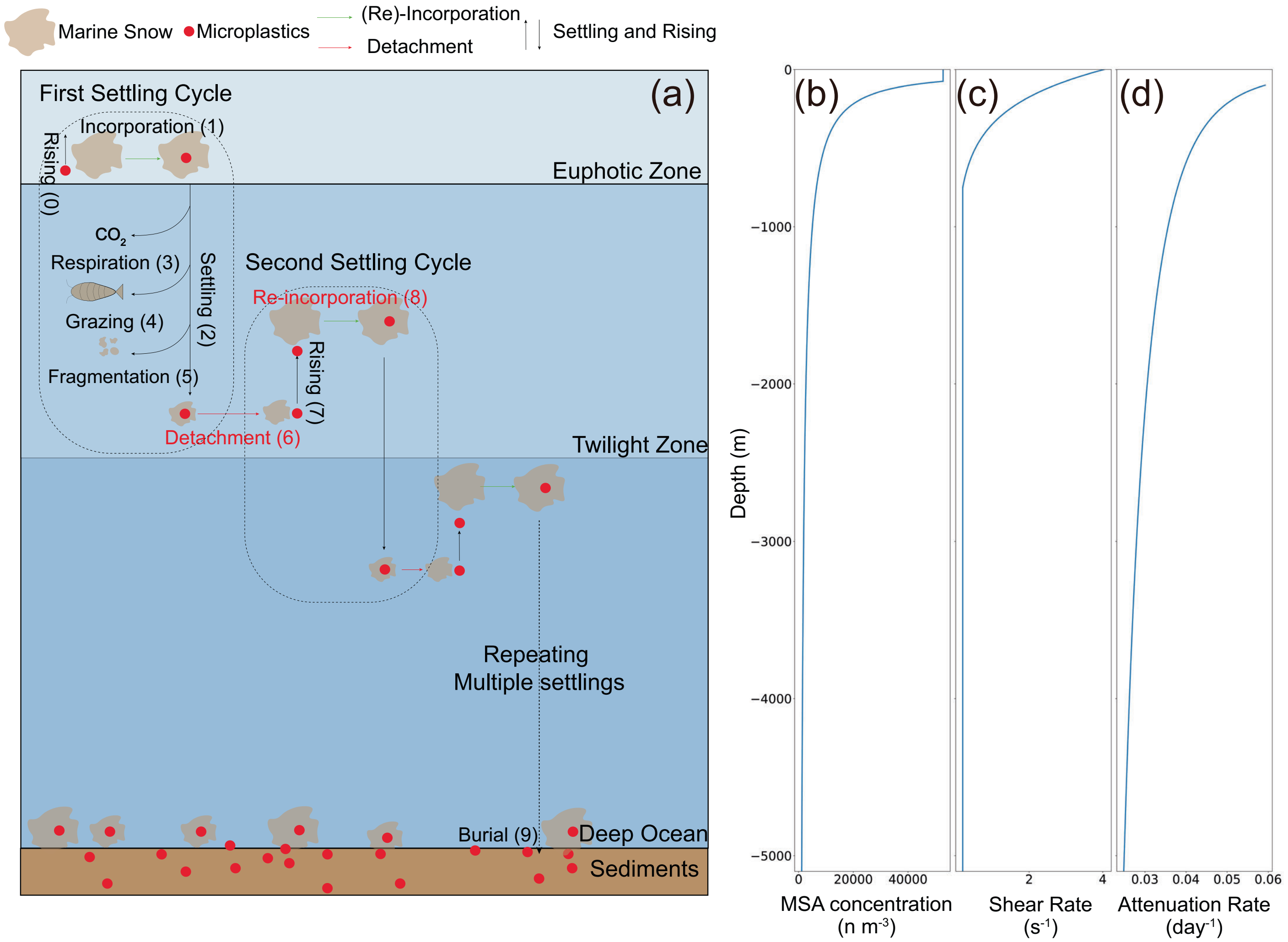

Fig. 1. The schematic diagram for the model framework. (**a**) The model shows multiple incorporations of microplastics into marine snow is the main mechanism for transporting buoyant microplastics to the deep ocean. The processes include the rising and settling of microplastics due to the density difference between microplastics with ambient seawater (from routes 0 to 9). (**b**) The numerical concentration of marine snow aggregates (MSAs) is based on the dataset from North Pacific Ocean (Subhas et al. 2020) and the mass of marine snows (Alldredge and Gotschalk 1988). (**c**) Shear rates with different depths (Alemán, Pelegrí, and Sangrà 2006). (**d**) The marine snow attenuation (d^{-1}) with different depths (Fischer et al. 2022). Euphotic zone (0–100 m), Twilight zone (100–1000 m), and Deep ocean (> 1000 m).

Aggregation dynamics

First incorporation of microplastics into marine snows

Individual microplastics are available for interaction with marine snows at the water surface, and the microplastics were released initially at the depth of 0.5 m, as is a convention in such models (Lobelle et al. 2021; Fischer et al. 2022). Microplastics rise in the water column firstly because they have a lower density than seawater (Fig. 1a, Route 0), and incorporation can occur when microplastics and marine snows are brought together and collide through turbulence and differential settling (Eqs. 2a, 2b). This collision leads to the incorporation of microplastics into marine snow (Fig. 1a, Route 1), which is used to calculate the flocculation rate of microplastics (Besseling et al. 2017; Burd 2024). The collisions and interactions between microplastics and marine snows are induced by shear (β_{shear}), differential settling (β_{settling}), and Brownian motion (β_{Brownian}) based on established flocculation theory (Burd and Jackson 2009; Kooi et al. 2017; Fischer et al. 2022):

$$\beta_{\text{shear}} = 1.3\ \gamma\ \left(r_{\text{MSAs}} + r_{\text{MPs}}\right)^3 \tag{2a}$$

$$\beta_{\text{settling}} = \frac{1}{2}\pi r_{\text{MSAs}}{}^2 \left(v_{\text{MSAs}} - v_{\text{MPs}}\right) \tag{2b}$$

Brownian motion refers to the random movement of particles due to thermal energy in a fluid medium, and in this study, the β_{Brownian} is negligible as this mainly affects nanoparticles (Besseling et al. 2017), and the β_{Brownian} is

7 orders of magnitude lower than the β_{shear} and β_{settling} induced collision frequency as the marine snows are orders of magnitudes larger than the upper boundary size for Brownian motion. The unit for β_{Brownian}, β_{shear}, and β_{settling} is $\text{m}^3\ \text{s}^{-1}$. Shear-induced collisions occur due to the relative motion of fluid parcels that bring particles into contact and facilitate interactions. The shear rate (γ, gradient of velocity in the fluid) is used to describe how the rate of shear-induced collisions varies with depth, as shown in Fig. 1c (Burd and Jackson 2009), and the unit is s^{-1}. Differential settling is when particles of different settling velocities interact, leading to faster settling particles sweeping up slower settling particles (Burd and Jackson 2009). r_{MSAs} is the radius of the marine snow aggregates (unit: m). r_{MPs} is the radius of microplastics (unit: m). v_{MSAs} and v_{MPs} are the settling (or rising) velocities in the seawater (unit: m s^{-1}). And this can be calculated based on the Stokes' law for aggregates/flocs (Manning and Dyer 2002):

$$v_{\text{MSAs}} = \frac{(\rho_{\text{MSAs}} - \rho_{\text{sw}})\, d_{\text{MSAs}}{}^2 g}{18\mu} \tag{3a}$$

$$v_{\text{MPs}} = \frac{(\rho_{\text{MPs}} - \rho_{\text{sw}})\, d_{\text{MPs}}{}^2 g}{18\mu} \tag{3b}$$

The ρ_{MSAs}, ρ_{sw}, and ρ_{MPs} represent the density of marine snows, seawater, and microplastics, respectively. The unit is kg m^{-3}. d_{MSAs} and d_{MPs} are the diameters of marine snows and microplastics, and the unit is m. μ is the viscosity (unit: kg $\text{m}^{-1}\ \text{s}^{-1}$). g is the gravitational acceleration, and this value is $9.81\ \text{m s}^{-2}$. The shear rate is a key parameter to influence the collision and incorporation of microplastics into marine snows, and a shear rate profile with depth was acquired from a previous study that calculates the shear rate from the ocean surface to seafloor (Alemán, Pelegrí, and Sangrà 2006) (Fig. 1c). Biological shear (nonphysical shear), such as animal swimming was also considered, and this contributes to the background shear rate that is set at $0.2\ \text{s}^{-1}$ (Dilling and Alldredge 2000; Fakhraee, Planavsky, and Reinhard 2020). The shear rate distribution can be found in Fig. 1c.

Quantification of microplastic incorporation rates into flocs/aggregates (e.g., marine snow aggregates) and which size fractions can be incorporated has been unanswered for over a decade (Koelmans et al. 2022). The most significant contributions of this model, are that we incorporate both an empirical model to predict the flocculation of microplastics with marine snows (Wu et al. 2024), and the aggregation of microplastics and subsequent settling with marine snows across the entire ocean depth (Fig. 1a, Route 1). Our mathematical model can predict which size fraction can be incorporated into marine snows (Eq. 4; boundary curve) (Wu et al. 2024). Only small-sized microplastics can be incorporated into the marine snows, and the size relationship can be used further to explain the duration a microplastic particle can reside within a marine snow (Fig. 1a, Routes 3, 4, and 5).

$$\begin{gathered} x \le 900\ \mu\text{m}, y = -0.0002x^2 + 0.36x \\ x > 900\ \mu\text{m}, y = 162 \end{gathered} \tag{4}$$

where x is the size of marine snows (d_{MSAs}), and y is the size of microplastics (d_{MPs}) that can be incorporated into the marine snows. For microplastics below the boundary curve (Eq. 4), they can be incorporated into the marine snows. This is used to determine whether microplastics can be incorporated into the marines, and also for the detachment/disaggregation of incorporated microplastics from marine snows. Therefore, a microplastic particle with a diameter of $75\ \mu$m (d_{MPs}) is used in this study to explore its settling behaviors as this size is under the boundary curve (Eq. 4). Aside from the testing size of $75\ \mu$m, other sizes of microplastics (25 and $150\ \mu$m) and nanoplastics (100 nm, plastic particles $< 1\ \mu$m; Koelmans et al. 2022) are also used to explore how the size influences the settling behaviors. In this study, we assume that microplastics remain undegraded as most of the time plastic particles stay subsurface of the ocean which has negligible degradation rates due to ultraviolet radiation attenuation, and the modeling time scale is much shorter compared with the degradation time scales of plastics (O'Brine and Thompson 2010; Min, Cuiffi, and Mathers 2020).

Microplastics settling with marine snows

Once incorporated, the microplastics settle with marine snows (Fig. 1a, Route 2) based on Stokes' law (Eqs. 3a, 3b). Laboratory results suggest that the settling behavior of marine snows is not meaningfully influenced by incorporated microplastics (Kvale et al. 2020; Rillig, Leifheit, and Lehmann 2021), and hence, this model assumes that the marine snows' settling velocity is not influenced by microplastics in this scenario (Porter et al. 2018; Andersen et al. 2021). In this study, we set the effective density ($\rho_{\text{MSAs}} - \rho_{\text{sw}}$) at $1.2\ \text{kg m}^{-3}$, and the resulting settling velocity of marine snow is also in the range of in situ measurement which is $1\text{–}368\ \text{m d}^{-1}$ (Alldredge and Gotschalk 1988). In this study, we consider only the fast-sinking marine snows as the only ones that can take buoyant microplastics to the deep sea (Fakhraee, Planavsky, and Reinhard 2020).

Marine snow attenuation

When marine snows settle below the euphotic depth, respiration by microbes within the marine snow consumes organic carbon, and the fragmentation reduces the integrity of marine snow (Fig. 1a, Route 3). These lead to the mass and volume of marine snows decreasing with settling. We assume marine snows are not experiencing attenuation above the euphotic zone boundary at 100 m of depth, and it occurs in the twilight zone (Buesseler et al. 2007) (Fig. 1a, d):

$$L_{\text{loss}} = Q_{10}{}^{(T-20)/10} R_{20} A \tag{5}$$

where $R_{20}A = 0.1$, and the unit is d^{-1} with the coefficient, $Q_{10} = 2$, which represents how much the attenuation increases by every 10°C increase in temperature (Kooi et al. 2017; Lobelle et al. 2021; Fischer et al. 2022), where T is the seawater temperature (°C) from World Ocean Database (Mishonov et al., 2024). Recent studies have demonstrated that fragmentation (Briggs, Dall'Olmo, and Claustre 2020) and surface erosion (Alcolombri et al. 2021) are key processes driving the mass loss of fragile marine snow aggregates, leading to faster degradation than accounted for by respiration alone in traditional models like the Martin curve (Briggs, Dall'Olmo, and Claustre 2020; Bressac et al. 2024). Therefore, in this study, the attenuation (L_{loss}, Fig. 1d) is modeled as being directly linked to the diameter of marine snows, assuming that fragmentation and settling-induced erosion is a first-order process proportional to the marine snow diameter rather than the volume (Silver, Shanks, and Trent 1978; Alcolombri et al. 2021; Kvale et al. 2021).

Breakup

The marine snow size decreases during settling. When the marine snow is too small to hold the microplastics based on the boundary curve (Eq. 4), the microplastics are detached and regain the buoyancy to rise in the ocean water. Or the mass loss of marine snows is over 40% of the initial value (Fig. 1a, Route 6), and this happens only below the euphotic zone (Kooi et al. 2017). After detachment, the microplastics are released back into the water and start rising in the water column as the density of microplastics is now lower than seawater (Fig. 1, Route 7).

Reincorporation into marine snows

In previous biofouling modeling frameworks (Kooi et al. 2017; Lobelle et al. 2021), following disaggregation microplastics regain buoyancy and return to their starting positions near the ocean surface. This oscillation ensures that microplastics never reach the deep sea, and ignores the fact that microplastics are available to be reincorporated while rising through the water column (Ransom et al. 1998). In this study, the detached buoyant microplastics are still available to be captured by ambient marine snows immediately after detachment at all depths (Fig. 1a, Route 8) based on the same collision functions in Fig. 1a, Route 1. Previous modeling frameworks have considered only the interaction between marine snows with ocean particulate matter within the upper ocean, and this hampers our understanding of the transport of microplastics in the deeper ocean interior (Kooi et al. 2017). Our new framework fills a clear theoretical gap which explains the presence of buoyant microplastics at the ocean floor.

Repeating settling cycles

One settling cycle describes the process of rising suspended microplastics (Fig. 1a, Route 0), incorporation by and settling with marine snows (Fig. 1a, Routes 1 and 2), marine snow size decreasing (Fig. 1a, Routes 3, 4 and 5), and detachment of microplastics releasing them back to suspension (Fig. 1a, Route 6). The second settling cycle begins with detached buoyant microplastics rising again (Fig. 1a, Route 7) and the reincorporation into marine snows (Fig. 1a, Route 8). Each settling cycle results in microplastic settling for a certain depth and repeats until microplastics hit the ocean bottom or reach the stable oscillation in the deep ocean.

Burial

Once microplastics reach the bottom of the ocean, the model deposits them on the seafloor, and the model stops tracing the microplastics and marine snows (Fig. 1a, Route 9). The long-term fate of microplastics once they reach the bottom of the ocean may be controlled by burial and resuspension (Waldschläger and Schüttrumpf 2019b; Kane et al. 2020; Waldschläger et al. 2022), but this is not in the scope of this study.

Results

The settling process of microplastics

This study shows that buoyant microplastics are vectored to the seafloor by marine snows in the ocean column, and this is the first study to elucidate the entire trajectory of microplastics from the ocean surface to the deep sea (Fig. 2a). This whole process takes 416.7 d of 17 settling cycles for a 75-μm diameter microplastic. The first incorporation is rapid and takes only 0.2 d. This is because of the high concentrations of marine snows and stronger turbulence at the ocean surface (Fig. 1b, c). The incorporated microplastics are transported with marine snows, while the size of marine snows is decreasing because of microbial respiration, fragmentation, and erosion (Briggs, Dall'Olmo, and Claustre 2020; Alcolombri et al. 2021). The size of marine snow continues to decrease with depth until the marine snow aggregates are not large enough to incorporate microplastics (Fig. 1a, Routes 3, 4, and 5) (Wu et al. 2024). This is the first detachment of microplastics from the marine snow. Marine snows transport microplastics downward 413.1 m from the ocean surface in this settling cycle, and this cycle takes 10.2 d (Fig. 2b). The net settling distance of the first settling cycle is 410.0 m.

The detached microplastics regain buoyancy and hence rise in the water column, but the microplastics are then available to collide with other marine snows. The reincorporation takes 1.6 d, and this is a much longer time frame than the first incorporation of 0.2 d, as the concentrations of marine snows and the shear rate are significantly lower in the deeper ocean water (Fig. 1b, c). In this process, the rising distance is 31.2 m, and this is much shorter than the first net settling distance (410.0 m) (Fig. 2b). The re-incorporated microplastics start settling in the second settling cycle, and the second settling cycle ends after 10.0 d of settling with a settling distance of 379.6 m, which is lower than the first settling as the first settling is an exception with the part of distance within

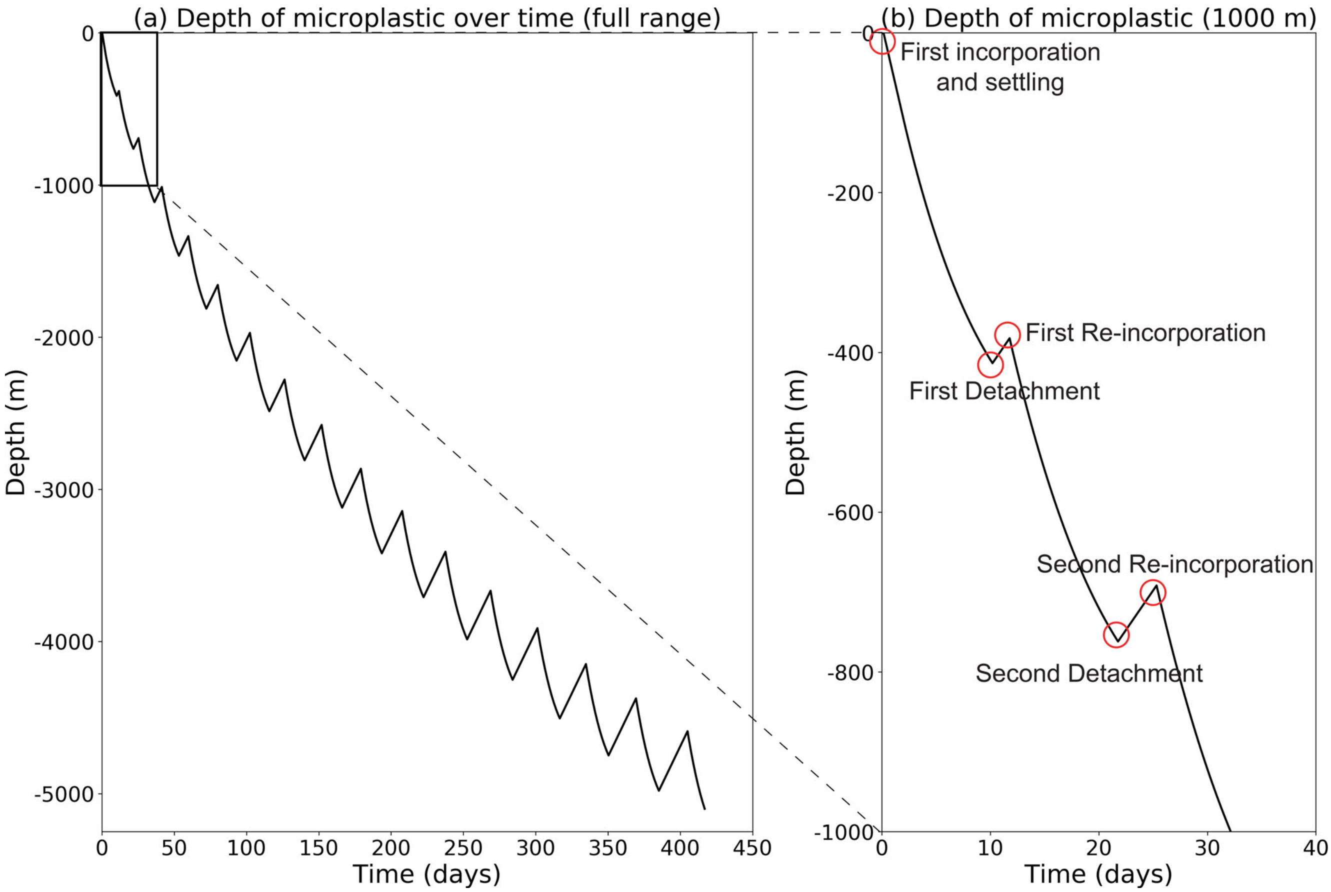

Fig. 2. Modeling output for the trajectory of the microplastics (75 μm) in the ocean from surface to sediment. (**a**) The trajectory of microplastics in the ocean interior with time. (**b**) Enlarged area of the microplastic trajectory in the depth range of 0–1000 m.

no-respiration zone (depth of 0–100 m). The second settling cycle contributes a net settling distance of 348.4 m, and this settling cycle takes 10.0 d (Fig. 3a, b). After repeating 17 settling cycles, the microplastics finally reach the ocean sediment floor (Fig. 2a).

Settling distances of different settling cycles

The setting/rising distances for each settling cycle are shown in Fig. 3. The different settling cycles will operate over different settling distances (Fig. 3). Rising distances increase with depth (Fig. 3a) because the rising time (from the time of microplastic releasing to the next incorporation) is longer as the concentrations of marine snows and shear rate both decrease, which delays released microplastics that rise in the water column to collide to another marine snow. The settling distance also increases with depth (Fig. 3b) as the degradation of marine snows decreases with depth (Fig. 1d). While the first settling cycle is an exception as this first settling includes the euphotic zone where the marine snows are not saturated. The net settling distance (Fig. 3c) is the sum of settling and rising distances in each settling cycle and decreases with depth because the increase of settling distance is lower than the decrease of the rising distance in each settling cycle (Fig. 3a, b).

The status of microplastics in the ocean water

The total time needed for the buoyant microplastic particle (75 μm) to travel from the ocean surface to the ocean floor sediment at 5100 m is 416.7 d, and the suspended time in this process is 188.7 d, while the duration of incorporation in marine snows is 228.0 d. In this study, we consider only the settling of one microplastic particle, so we cannot estimate the distribution of microplastics in different layers. The microplastic residence time within the euphotic zone (0–100 m) is 1.8 d. The upper twilight zone (100–500 m) is 12.1 d, and the average residence time for 100 m depth is 3.3 d, which is higher than the euphotic zone. The residence time in the lower twilight zone is 18.2 d, and the average residence time is 3.7 d/100 m. The mid-layer (1000–2000 m) residence time is 57.3 d, and the average is 5.7 d/100 m. The residence time in the deep sea (2000–5100 m) is 327.4 d, and the average is 10.6 d/100 m. Therefore, the average residence times in different layers are increasing because the low marine snow concentrations and low shear rate are counterproductive to

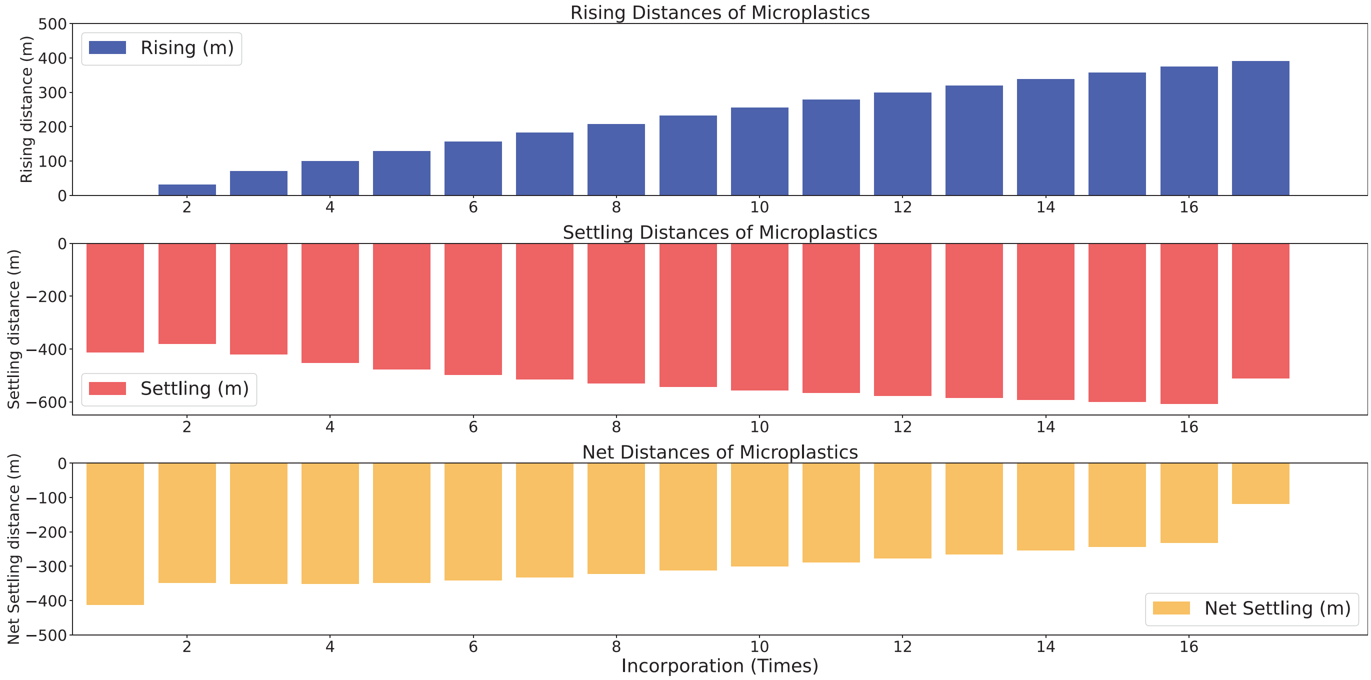

Fig. 3. The microplastic (75 μm) dynamic in the ocean water column. (**a**) The rising distance of each settling cycle for microplastics. (**b**) The settling distance of each settling cycle for microplastics in the marine snows. (**c**) The net settling distance for microplastics in each settling cycle.

incorporation and settling, this makes microplastics rise longer distances in the deep-sea depths (Fig. 3a). The residence time across different layers plays a crucial role in predicting the depth-dependent distribution of microplastics, and there is scope for future work to explore these patterns more fully.

The influence of microplastic size

We also investigated the sedimentation of the different sizes of plastic particles from ocean surface to the deep ocean. We found that smaller sizes of microplastics (25 μm) and nanoplastics (100 nm) settle more quickly to the deep ocean when contrasted to larger ones. This is because the smaller ones remain incorporated within flocs for a longer time, and their rising velocity is slower than larger microplastics when they are released from marine snows (Fig. 4). Whereas the large microplastics (150 μm) cannot reach the bottom (Fig. 4, green curve) because of the high buoyancy of large and buoyant microplastics, and this results in a higher rising distance. This makes the settling and rising distance reach equilibrium, with a net settling distance of zero after 600 d of simulation. This makes microplastics of 150 μm oscillate in the deep sea with a depth of around 2500 m (Fig. 4).

Discussion

The vertical sedimentation in the ocean from surface to sediment for buoyant microplastics has been unclear (van Sebille et al. 2020; Fischer et al. 2022). Although several studies have proposed marine snows as the most promising solution to answer this research question (Kvale et al. 2020; Tekman et al. 2020; Tsuchiya et al. 2023), two main gaps in our understanding persisted: (1) the limited information on the size-selective mechanism of microplastics, and (2) continuous interaction between microplastics and marine snows throughout the different depths in the ocean.

Size-selective mechanisms

The sedimentation of microplastics involves size-selective mechanisms, which consist of two size-selection processes. The first is the incorporation of microplastics into marine snows: only microplastics under the boundary curve (Eq. 4) can be incorporated by and settled with marine snows, which was hitherto not understood (Wu et al. 2024). Previous studies that model the fate and transport of microplastics influenced by flocculation assume that all size ranges can be incorporated into flocs/aggregates (Besseling et al. 2017; Kvale et al. 2020; Kvale and Oschlies 2023), which is not practical. With this boundary curve, we can estimate the size range of microplastics that can be incorporated into marine snows.

The second selection process happens within the settling process of microplastics with marine snows: larger microplastics (150 μm) have higher rising velocity in the water (Fig. 4). This makes the rising and settling distance equal, and microplastics oscillate in the deep ocean at the depth of ~ 2500 m (Fig. 4). This is the second selection process for microplastics, which can be incorporated by marine snows

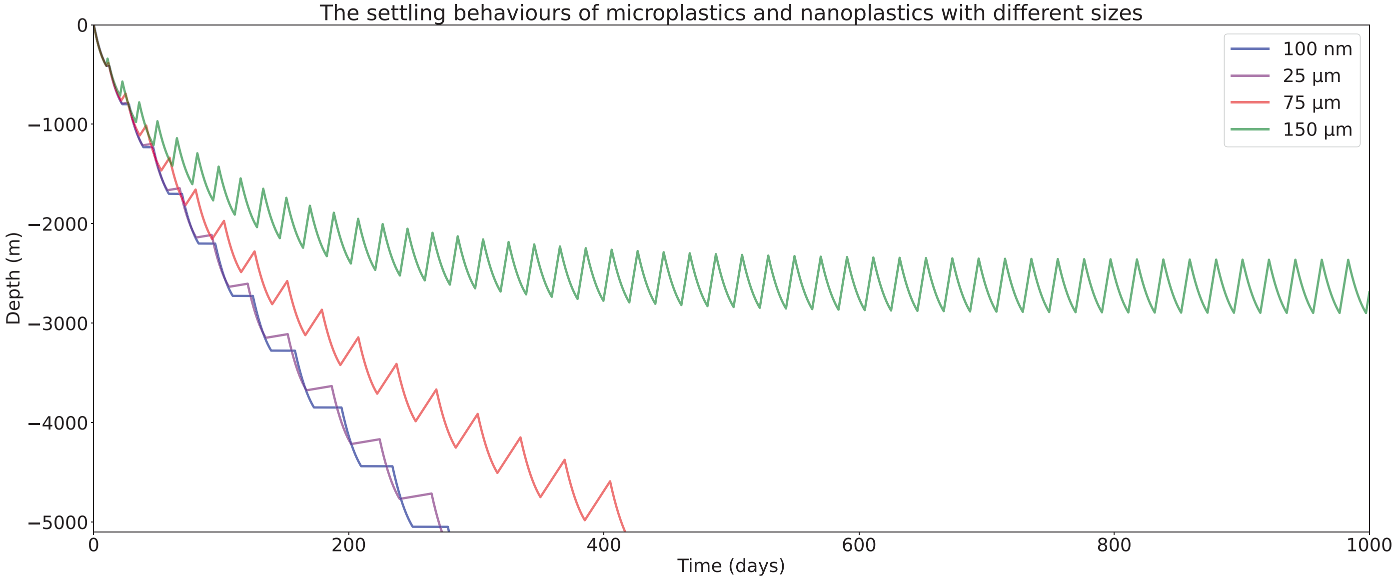

Fig. 4. The settling behaviors of microplastics and nanoplastics with different sizes. The green line is for 150 μm, the red line is for 75 μm, the purple line is for 25 μm, and the blue line is for nanoplastics of 100 nm.

but cannot reach the deep-sea sediments because of their high rising velocity. The modeling output also aligns with environmental monitoring studies that have detected only buoyant microplastics smaller than 200 μm, but not large buoyant microplastics as the settling of buoyant microplastics is driven by sedimentation of marine snows (Zhao et al. 2018, 2023; Galgani et al. 2022). Additionally, the size of microplastics ($< 200\ \mu$m) in the sediment samples is slightly smaller than the microplastics in the water column because the second size selection allows only smaller microplastics ($< 100\ \mu$m) to reach the sediment (Bergmann et al. 2017; Tekman et al. 2020).

The continuous incorporation mechanism across all depths

Marine snow settling is a very complicated process in the ocean interior (Ransom et al. 1998; Dilling and Alldredge 2000; Buesseler et al. 2007; Kvale et al. 2020). The size and mass are dynamic, especially size decreasing below the euphotic zone. This size reduction in marine snows leads to the detachment of microplastics after a certain time of mass loss of marine snows. After the detachment, the central idea of this theoretical model is that microplastics are immediately available to be captured and incorporated into other marine snows (Fig. 2b), and this happens in all depths of the water column because marine snows are present at all depths of the ocean in different concentrations (Ransom et al. 1998; Turner 2002, 2015). This continuous interaction with marine snows at all depths allows microplastics to be incorporated multiple times, and each time settles a certain depth depending on the properties of marine snows. This is because marine snows present at all depths of the ocean in different concentrations (Ransom et al. 1998). Normally, the concentration of marine snows is proportionally decreasing with the depth (Fig. 1b). Previous studies focused only on interaction at the ocean surface, which determines whether microplastics can be taken out of the surface (Lobelle et al. 2021). While the mid-layer concentration is more important in whether the microplastics can reach the bottom (Fig. 4).

This continuous interaction between microplastics at all depths is also consistent with previous field studies. Galgani et al. (2022) found the concentrations of microplastics highly correlated with the particulate organic carbon concentrations from the surface to the depth of 600 m, driven by the incorporation of microplastics into marine snows. Tekman et al. (2020) reported a significant correlation between particulate matter concentrations and small microplastics ($< 100\ \mu$m) in the ocean interior. Zhao et al. (2022, 2023) reported similar behaviors between microplastics and marine snows through a large-scale field investigation in the Pacific Ocean across all depths (Zhao et al. 2022, 2023). All the above evidence shows that microplastics are interacting with the marine snows at all depths, and this has been applied to the modeling framework. More importantly, a recent monitoring study reported up to 3% of carbon in the sediment trap samples is from plastic carbon (Galgani et al. 2022), and this significant amount suggests that marine snows settling is the mean pathway to transport microplastics compared with biofouling (Kaandorp et al. 2023). The climate model (Kvale et al. 2020; Kvale 2022) shows that the concentrations of modeled microplastic concentration driven by marine snows are highly consistent with measured microplastic concentration by (Zhao et al. 2022) in

Atlantic Ocean, which further verifies settling with marine snows is the main driver that controls the vertical transport of microplastics in the ocean.

The model uncertainty and limitations

There are some uncertainties in this theoretical model, mainly from two aspects, the settling dynamics of microplastics and the aggregation between microplastics and marine snows. These uncertainties and limitations are discussed as follows:

1. Microplastic characteristics: The model categorizes microplastics primarily by size and considers only one type of microplastics with the same properties such as shape, density, weathering, and polymer type (Kooi et al. 2021; Koelmans et al. 2022). The shape affects rising and settling behaviors, and hence the settling dynamics (Waldschläger and Schüttrumpf 2019a; Waldschläger et al. 2022). In addition, the interaction between different shapes and marine snows also changes, and this significantly changes the time microplastics remain associated with the marine snows and the detachment time scales (Wu et al. 2024). The density and polymer type, weathering conditions, and biofouling also influence both the settling velocity and aggregation behaviors. Therefore, in future studies, models need to consider including the influence of other characteristics by parameterizing the most updated research output in the model.
2. Modeling assumptions and simplifications: The one-dimensional modeling approach simplifies the complex multidimensional nature of oceanic currents and turbulence. Temporal changes in oceanic conditions, such as seasonal variations and climate-driven changes in ocean circulation patterns, are not considered, which could affect the settling dynamic (advection) and aggregation behaviors (shear rate) of microplastic distributions. Some studies have tested the influence of 3D ocean currents and show that ocean mixing by wind and vertical currents both show different influences on particle settling (Fischer et al. 2022).
3. Variability in marine snow characteristics: The model assumes certain uniformity in the size and composition of marine snows at different depths in the ocean, and this leads to deterministic settling velocity of marine snows. However, in reality, these aggregates are highly variable entities influenced by numerous local environmental factors including biological activity, material composition, water chemistry, and temperature (Turner 2002, 2015). This leads to a wide range of sizes and compositions of marine snows and hence varies the settling velocity. Additionally, the different composition of marine snows (e.g., transparent exopolymer particle) is the parameter that significantly influences the aggregation with microplastics, especially for attachment efficiency (Burd and Jackson 2009; Besseling et al. 2017). This is the probability of two particles becoming attached when they collide, which has not been considered in marine models. In addition, breakup is simply based on the ratio in size loss, and this needs to be enhanced with the support of lab experiments in the future. More importantly, seasonal changes are influencing not only the ocean current but also the biogeochemistry, such as algal blooms, which could change the composition and the abundance of marine snows, and this also substantially influences (Mishonov et al., 2024) interactions between marine snows and microplastics (Bergmann et al. 2023). Future studies need to consider different sizes and compositions of microplastics from different regions by combining more complicated flocculation models and in situ measurements within available 3D biogeochemistry models alongside the 3D ocean current simulations.
4. Empirical data and validation: The model is heavily dependent on empirical data from limited geographic areas and depth profiles. The availability and quality of data concerning microplastic concentrations and marine snow characteristics across different oceanic regions are inconsistent. This lack of comprehensive data limits the application of this model to global ocean conditions and reduces the confidence in extrapolating findings to areas beyond the study sites. We are urging microplastic communities to collect and share more data on microplastic concentration in different layers of the ocean, alongside detailed biogeochemistry data to allow the relationships between marine snows and microplastics to be studied across environments. The collection and sharing of these data will facilitate a comprehensive understanding of microplastic settling from the ocean surface to the deep sea, which will be critical in future efforts to manage ocean plastic pollution.

Summary and perspectives

This theoretical model incorporates fundamental flocculation processes to provide mechanistic understanding of how buoyant microplastics settle from the ocean surface to the seafloor through repeated cycles of incorporation and disaggregation with marine snows. This continuous interaction between microplastics and marine snows is the key mechanism that facilitates marine snows as vectors. This process is size-selective—with only microplastics $< 100\ \mu$m being incorporated into marine snows and reaching the seafloor. This study fills a theoretical gap in our understanding of the mechanisms contributing to the vertical sedimentation of marine snows and accounts for global observations of small buoyant microplastics in deep-sea sediments. These insights are critical for predicting the fate, transport, and inventories of microplastics in the ocean interior. Small and buoyant microplastics at the ocean surface are quickly scavenged and settle to the seafloor within 2 years with implications for the long-term management of microplastic pollution. These scavenging mechanisms may also help account for missing plastic waste from our global ocean budgets.

It includes only one environmental condition for one-dimensional modeling, and the hydrodynamics and marine snow concentrations are also varied across orders of magnitude. This leads to variability differences in the settling behaviors when considering incorporation into marine snows, so more modeling settings in a three-dimensional framework are needed to fully constrain global microplastic settling behaviors. More importantly, small microplastics account only for < 1% of total ocean plastic mass according to recent modeling output (Lebreton, Egger, and Slat 2019; Egger et al. 2020; Kaandorp et al. 2023), and the longevity of large plastic waste is the key to filling the last puzzle in understanding the ocean plastic inventory.

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Acknowledgments

This study was supported by Lloyds Register Foundation, UK; Queen Mary University of London, UK; HR Wallingford Company Research FineScale Project (ACK2-13_062), and EU INTERREG France (Channel) England Project "Preventing Plastic Pollution" co-financed by the European Regional Development Fund.

Conflicts of Interest

None declared.

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Submitted 11 July 2024
Revised 02 December 2024
Accepted 19 January 2025