



Summer Hydrodynamics as a Dual Driver of Microplastic Retention and Settling in Shallow Water Columns

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Abstract In shallow lakes, wind-driven turbulence and thermally induced convection control water mixing. Together, and depending on depth, they interact with microplastic (MP) settling to determine how particles are distributed throughout the water column. To investigate these processes, two MP addition experiments were conducted in a 112 m³ aquatic mesocosm during summer using 1–5 µm microspheres. High resolution data on MP concentrations, water velocities, wind speeds, and water and air temperatures were collected. Additionally, using OpenFOAM, a three-dimensional CFD model

incorporating fluid–particle interactions was configured to quantitatively interpret the experimental data of MP transport. The results indicated that although Stokes’ settling velocity predicted MP would take up to 182 days to reach the mesocosm bottom, MP of all sizes was detected just above the bed (3 m) within only 3 days. The vertical distribution of MP, characterized using the Péclet number (Pé, settling velocity/turbulent diffusion), increased with depth but remained < 1. In the near-surface layer (< 0.25 m), approximately 10% of MP remained in suspension by forced convection (wind-induced turbulence) and particle–fluid interactions. Free convection dominated MP transport between 0.25 and 3 m depth. Pé values < 1 indicate that, despite increasing gravitational settling with depth, free convection remains the dominant process. These results demonstrate that MP

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transport in shallow water columns is not governed by gravitational settling alone but is fundamentally controlled by the interplay of wind-driven turbulence and thermally induced convection. This generates depth-dependent mixing regimes and redistributes MP across the water column, increasing the likelihood of exposure to aquatic organisms at all depths.

Keywords Microplastic · Forced convection · Free convection · Peclet number

1 Introduction

Microplastic (MP) has emerged as a major environmental concern due to its ubiquity and long-term persistence in natural ecosystems (D'Avignon et al., 2022; Ziani et al., 2023). This is particularly relevant in lakes and reservoirs, which often act as temporary or permanent sinks of MP due to their low-energy hydrodynamic regime.

When MP enters lake systems, either through point or diffuse sources (Bellasi et al., 2020; Sun et al., 2019) it can reside in the lake water column from few days to years before reaching the lake sediment (Ahmadi et al., 2024; Elagami et al., 2022). The long residence time of MP in the water column combined with its small size (<5 mm) results in a very high uptake probability by key lake organisms (e.g. filter feeders such as zooplankton) (Gilfedder et al., 2023). Once MP is ingested, it can migrate through the food chain via various processes (such as predation), potentially harming species at higher trophic levels (Li et al., 2019). This can also disrupt ecological balance in aquatic ecosystems by negatively affecting food quality for aquatic animals, reducing growth, altering migration and reproductive patterns, and blocking the digestive tracts of organisms (Cole et al., 2016; Coppock et al., 2019).

The transport and accumulation of MP within the lake water column is governed by the interplay between multiple, often interrelated or opposing processes. These include factors affecting the gravitational settling of MP, such as the physical properties (density, size and shape) (Khatmullina & Isachenko, 2017; Waldschläger & Schüttrumpf, 2019), aggregation between various MP particles (Lempart-Drozd et al., 2025) or with naturally suspended matter present in the lake (Parrella et al., 2024), and uptake by

aquatic organisms followed by release through fecal pellets (Gilfedder et al., 2023; Nelms et al., 2018). The transport of MP is also largely governed by lake hydrodynamics, which can vary on daily to seasonal scales (Guo et al., 2024). Recent studies have shown that variations in MP buoyancy significantly influence transport pathways and retention times, with strong interactions between settling velocity and vertical mixing processes (Summers et al., 2023). These findings emphasize that MPs' fate is governed by the interplay between hydrodynamics and particle properties. However, most of this understanding originates from marine and estuarine systems (Cai et al., 2023; Summers et al., 2023; Zhao et al., 2025), while freshwater environments, particularly lakes, remain comparatively overlooked.

In large deep lakes, the water column is typically structured into epilimnion, metalimnion, and hypolimnion during the summer, where hydrodynamic conditions differ largely between layers (Wüest & Lorke, 2009). Turbulent mixing processes affect the epilimnion and, to a lesser extent, hypolimnion (due to internal seiches), while the metalimnion remains largely laminar (Ahmadi et al., 2024). In contrast, shallow lakes (e.g., polymictic lakes) are highly responsive to diurnal heating, cooling, and forced convection (wind-induced turbulence) due to their limited depth. Wind, however, supplies mechanical energy that promotes mixing and can partially overcome this stratification (Ahmadi et al., 2024). During the night, surface cooling increases the density of the upper layer, diminishing or removing stratification and frequently generating convective cells, in which denser surface water descends and lighter water ascends (Bouffard & Wüest, 2019; Yang et al., 2018). The interplay between these diurnal variations in hydrodynamics, wind forcing, and gravitational settling of MP creates transport processes that differ from those in deep stratified lakes (Wendt-Potthoff et al., 2025). The settling velocity of MP results from the balance between their weight, buoyant force, and the drag exerted by the surrounding water. The surface area-to-volume ratio of MP particles directly determines the drag force acting on the particle body and thus the settling velocity at which drag, weight, and buoyancy reach hydrostatic equilibrium (Ahmadi et al., 2022). This ratio increases sharply as particle diameter decreases, with a notable jump below 1 mm (Ahmadi et al., 2022). This means that small MP experiences disproportionately higher drag forces,

especially for irregularly shaped particles with an enhanced surface area, causing them to settle slower than larger MP (Khatmullina & Isachenko, 2017). In turbulent flows, such MP particles are trapped in eddies and closely follow fluid motion but also impart an equal and opposite drag force on the surrounding water. For very low MP concentrations, particle feedback is negligible, and the fluid is assumed to be unaffected, which is the basis of one-way coupling assumptions (Fouda, 2021). However, when MP concentrations are sufficiently high, the cumulative momentum exchange can modify the particle's surrounding water's velocity. This defines the two-way coupling regime, where particles are not only transported by the fluid but also feedback on the carrier dynamics (Fouda, 2021). This transition continuum from one-way to two-way coupling is typically explained as a function of particle loading. While most surface water MP concentrations are low (usually $< 130,000$ items/m³) (Chen et al., 2024), localized zones of high concentration (e.g. MP concentrations entering through point sources) can reach the two-way threshold (Goniva et al., 2015; Hadian et al., 2024). Recent studies have begun incorporating two-way coupling in aquatic models to capture momentum exchange between MP and water, demonstrating that even small particle sizes with high concentrations can significantly alter local hydrodynamics (Lehmann et al., 2021). Such findings highlight the necessity of considering two-way MP-fluid interactions to better understand particle transport and fate across lake depth profiles once MP is introduced into the water column. This may be especially important in experimental systems where MP concentrations are high to ensure that concentrations are above detection limits (Elagami et al., 2023; Rochman et al., 2024).

Although research on MP transport and accumulation in lentic freshwater systems has increased in recent years (Ahmadi et al., 2024; Elagami et al., 2023; Guo et al., 2024; Pan et al., 2023; Rochman et al., 2024; Yan et al., 2021), studies investigating the relationship between lake hydrodynamics and MP transport remain limited. This is particularly relevant for small lakes or ponds, where diurnal hydrodynamic variations and the associated spatiotemporal variations in turbulent conditions can strongly influence MP transport and settling behavior. This highlights the need to connect the processes driving turbulence (such as temperature gradients or wind forcing) with

gravitational settling, and feedback between particle and fluid to better understand MP transport dynamics quantitatively. Also, the effects of introducing large MP concentrations into the water column, leading to increased particle–fluid momentum exchange, which in turn may require a two-way coupling approach to adequately describe the hydrodynamic regime, remain poorly understood (Lehmann et al., 2021).

In this study, two MP addition experiments were conducted in a $7.5 \times 5 \times 3$ m (length x width x height) aquatic mesocosm between July and September 2024. Green fluorescent MP microspheres with a size range of 1–5 μm were added in large numbers to ensure detectability. The mesocosm setup was equipped with high-resolution instruments to capture MP concentrations, water and air temperature, wind speeds, turbulent fluxes at water surface, and water velocities. The field experimental boundary conditions were used to conduct computational fluid dynamics (CFD) simulations using OpenFOAM. This aimed to quantify how summer mixing of shallow water columns (largely driven by wind and temperature gradients) affects MP transport and to identify the key physical mechanisms controlling its transport. Investigating these processes will contribute to our understanding of the spatiotemporal distribution of MP in shallow lakes, and subsequently, exposure to aquatic organisms and subsequent transport through the food chain.

Despite the limited size of the mesocosm compared to a real lake, which can restrict large-scale circulation and enhance wall effects, it offers distinct advantages for studying MP transport. The controlled environment allows for precise monitoring of meteorological drivers, water temperature, and velocity fields, as well as for maintaining detectable and reproducible MP concentrations, conditions difficult to achieve in natural systems where numerous uncontrolled processes affect measurements. Thus, the mesocosm provides a suitable compromise between environmental realism and laboratory experiments.

2 Methodology

2.1 Mesocosm Setup

The experiments were conducted in the $5 \times 7.5 \times 3$ m (112 m³) aquatic mesocosm located at the University of Bayreuth, Germany (Fig. 1). The mesocosm was

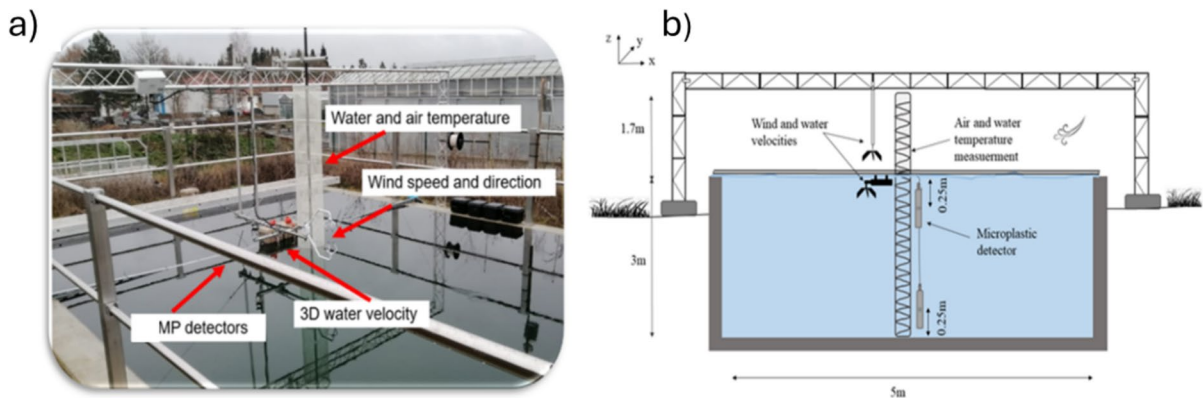


Fig. 1 **a** The real mesocosm with installed equipment, and **b**) Sketch of the mesocosm and instrumentation

initially filled with filtered lake water, obtained from the botanical garden at the University of Bayreuth, and then processed through a fine sand filter. The water was then left to stabilize for four weeks before the start of the experiments.

2.2 Experiments, MP Characterization, Preparation, and Addition

Two MP addition experiments were conducted: Experiment 1, starting at 10:40 on 17 July 2024 and ending on 30 July 2024, and Experiment 2, beginning at 15:40 on 20 September 2024 and ending on 30 September 2024. For each experiment, 5 g of green MP microsphere produced by Cospheric LLC (a thermoset amino formaldehyde polymer with density 1.3 g cm^{-3}) were used. The microspheres have diameters ranging from 1 to $5 \mu\text{m}$, with a median diameter (d_{50}) of $2 \mu\text{m}$. These specific particles have often been used in literature due to their stable fluorescence signal, precise size range, and resistance to photobleaching (Barboza et al., 2018; Bringer et al., 2020; Gerdes et al., 2019). Also, the requirement to use high MP concentrations to maintain a strong and stable detector signal during mixing makes them a particularly cost-effective choice (Elagami et al., 2023).

The maximum excitation and emission wavelengths of the MP was 414 and 514 nm, respectively, and were supplied as dry powder. The MP distribution (Fig. 2), measured using a Multisizer (Beckman Coulter 4e), was best described by the Rosin–Rammler model (Vesilind, 1980). The stock

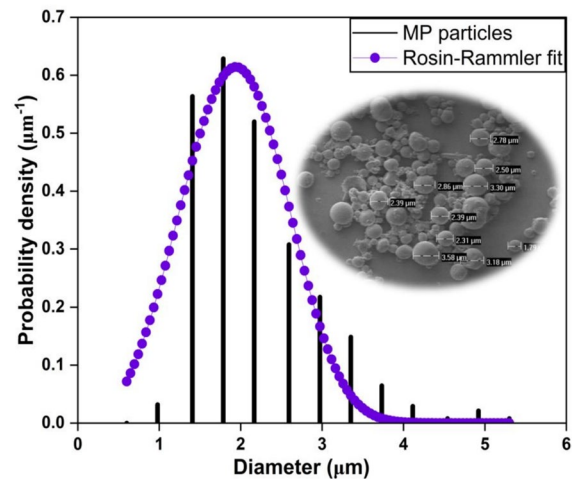


Fig. 2 Size distribution of the MP used in the experiments vs. the Rosin–Rammler model (Vesilind, 1980). This model was adopted in the CFD simulations to capture realistic size variability rather than a single mean diameter

suspensions were prepared in deionized water following, with a small amount of Tween® 20 (Sigma-Aldrich) added to minimize heteroaggregation of the MP (Elagami et al., 2023). In total, 100 L of stock solution was prepared at a concentration of $5 \times 10^4 \mu\text{g L}^{-1}$. This solution was divided equally into five clean buckets and stored at mesocosm ambient temperature for at least 48 h before experimentation.

The stock solutions were added as a single pulse from the top of the mesocosm using five metal watering cans equipped with wide sprinklers to ensure a uniform distribution of the solutions. The addition

process lasted approximately 10 min. The two experiments were carried out to test the repeatability of the results across the summer season and to provide datasets for model development, with Experiment 1 used for calibrating the model and Experiment 2 for validating its predictions.

2.3 In-Situ Measurements

Air and water temperatures were measured in and above the mesocosm using a fiber optic cable wrapped around a fiberglass tube with a diameter of 32 cm and height of 4.7 m (Thomas & Selker, 2021). The cable was read by a distributed temperature sensing (DTS) instrument (ULTIMA DTS, 5 km variant, Silixa, London, UK). Calibration of the raw data during post-processing was done using data from two solid-phase reference baths made from pure copper, set to temperatures spanning the range observed during the experiment (Thomas & Selker, 2021). The lower ~3 m were submerged below the water surface, with the remaining 1.7 m exposed to the air above the water. The column was capable of continuously capturing changes in water and air temperatures sampled at a frequency of 0.2 Hz and an effective vertical resolution of 2.5 mm with an accuracy of ± 0.04 K (Thomas et al., 2022).

Turbulent wind measurements were recorded at the center of the mesocosm using a 3D sonic anemometer (model CSAT3, Campbell Scientific, Logan, UT, USA), positioned roughly 30 cm above the water surface at 20 Hz sampling frequency. The instrument recorded 3-dimensional wind speed and the predominant direction, with a resolution of 0.001 m/s and accuracy < 0.1 m/s (Mauder et al., 2007). Raw data were processed and averaged over 10-min intervals following established procedures in (Thomas et al., 2009) to align with the water turbulence measurements from the ADV.

A Nortek Vector 300 Acoustic Doppler Velocimeter (ADV) was deployed at the mesocosms center to capture three-dimensional flow velocities. The probe was mounted roughly 0.25 m beneath the water surface, aligned so that the positive X, Y, and Z axes corresponded to the orientation shown in Fig. 1b. Measurements were recorded in bursts captured every 600 s, with each burst comprising 100 readings collected at 8 Hz. According to the manufacturer's specifications, the instrument's uncertainty is the greater of $\pm 0.5\%$ of the recorded velocity or ± 1 mm s⁻¹.

The fluorescence signals of the MP concentration were measured at the center of the mesocosm using two submersible field fluorometers (GGUN-FL24, Albillia) (Bailly-Comte et al., 2018), installed at 0.25 m and 2.75 m below the water surface. The fluorescence signals were captured in the green channel (470 nm excitation) at intervals of 60 s. The fluorometers were calibrated in the laboratory following Boos et al. (2021) using at least six calibration points between 10 and 3000 $\mu\text{g L}^{-1}$, with a detection limit of ~ 1 $\mu\text{g L}^{-1}$. The upper fluorometer was placed near the surface to capture the input pulse of MP, but slightly submerged (0.25 m below the surface) to avoid disturbances from MP addition. The lowest fluorometer was positioned at 2.75 m, approximately 0.25 m above the mesocosm bottom. This placement allowed us to monitor when particles had settled near the bottom.

2.4 CFD Simulations: Hydrodynamic and MP Tracking Configurations

Hydrodynamics in the mesocosm were simulated using OpenFOAM v24.06 (Weller et al., 1998) using the *buoyantBoussinesqPimpleFoam* solver, which resolves transient, incompressible, buoyancy-driven flows under the Boussinesq approximation (Abbasi et al., 2017). In this formulation, density is treated as constant except in the buoyancy term, as expressed in Eq. 1:

$$-\rho_0\beta(T - T_0)g \quad (1)$$

where ρ_0 is the reference water density (kg m^{-3}), β is the thermal expansion coefficient (K^{-1}), T and T_0 are the local and reference temperatures (K), respectively, and g is the gravitational acceleration (m s^{-2}). Turbulence was represented with the realizable k- ϵ model (Abbasi et al., 2017), which solves transport equations for turbulent kinetic energy (k) and its dissipation rate (ϵ), improving stability and accuracy for buoyancy-driven, wall-bounded flows compared to the standard k- ϵ formulation. To ensure that the CFD results were independent of numerical discretization, a mesh independence study was conducted, confirming that further grid refinement did not significantly affect the simulated flow and transport patterns. The thermal expansion coefficient (β) was prescribed as a constant value corresponding to water at 20 °C ($\beta \approx 2.04 \times 10^{-4}$ K^{-1}) (Takenaka & Masui, 1990). Model

performance was evaluated by comparison with measured temperature and velocity fields, ensuring that the simulations reliably reproduce the observed hydrodynamic conditions within the mesocosm.

To represent the MP transport, we coupled the Lagrangian particle tracking module to this solver. Particle paths were advanced with the standard kinematicCloud model, with an optional two-way coupling to account for feedback on the carrier flow. In one-way mode, particles experience hydrodynamic forces (e.g., drag) and gravity but do not influence the fluid. When two-way coupling is enabled, the fluid–particle momentum exchange is included in the carrier momentum equation via a cell-wise source term (Eq. 2):

$$S_{P \rightarrow F} = -\frac{1}{V_c \Delta t} \sum_{i \in \text{cell}} m_i (u_{p,i}^{n+1} - u_{p,i}^n) \quad (2)$$

where V_c is the control-volume size, Δt is the time step, m_i is the particle mass, $u_{p,i}^n$ is the particle velocity at the start of the step, and $u_{p,i}^{n+1}$ its updated velocity at the end of the step (Goniva et al., 2015; Hadian et al., 2024). This formulation ensures that the momentum acquired by the particles through drag and other forces is transferred back to the fluid with opposite sign, thereby representing MP not only as passive tracers but also as active momentum sources when their concentration is sufficient to influence the internal water velocity field. For numerical stability and robustness, the feedback term was included using

OpenFOAM's semi-implicit treatment (semiImplicit U option in the cloud dictionary). In this approach the momentum source is decomposed into an explicit contribution (S_u) and a linearized implicit part ($S_p u$), which is added directly to the diagonal of the momentum equation. This linearization increases diagonal dominance of the matrix and thereby improves the stability and convergence of the iterative pressure–velocity coupling. In practice, it allows moderately larger time steps than a fully explicit formulation while maintaining accurate two-way momentum exchange.

The mesocosm geometry (Fig. 3) was discretized using a structured mesh generated in SALOME 9.13 (IEEE Computer Society 2007) with local refinement near walls, the bottom, and the free surface to resolve boundary layers and wind-induced shear (mesh resolution ranged from 0.001 m at boundaries to 0.04 m in the central region). Simulations were initialized from a quiescent state one week before MP addition, with uniform temperature (4 °C), pressure (0 Pa), and velocity (0 m s^{−1}), allowing the system to spin up and develop realistic density gradients and turbulence fields before particle release. No-slip velocity conditions were imposed on the walls and the bottom. At the free surface, two time-varying boundary conditions were applied: (i) surface water temperature prescribed with a timeVaryingMappedFixedValue boundary condition, updated every 5 s from near-surface sensor data, and (ii) wind forcing applied as

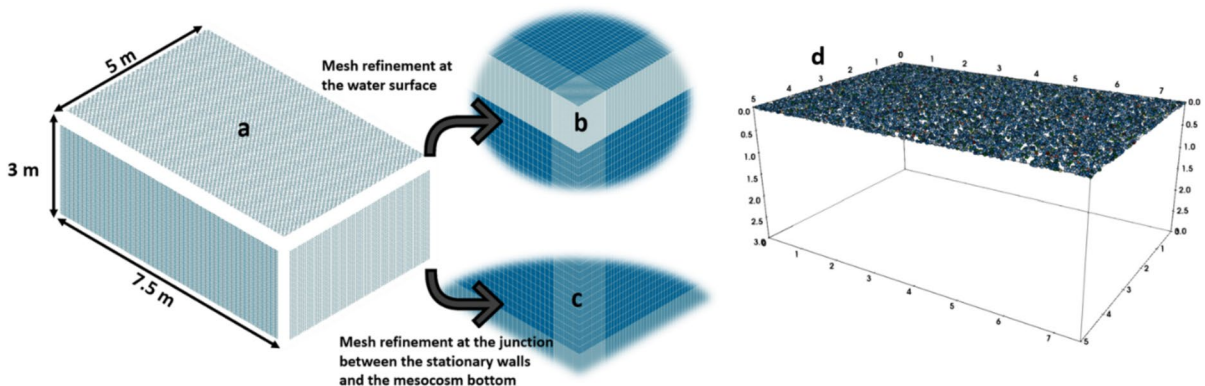


Fig. 3 **a** Computational mesh of the mesocosm, illustrating local refinements near the walls, bottom, and water surface. **(b)** and **(c)** mesh cell sizes ranged from 0.001 m near the boundaries to 0.04 m in the central region, where boundary effects

were minimal. The mesh was generated using SALOME 9.13 and imported into OpenFOAM for applying boundary conditions and solving the governing flow equations; **d**) Randomly distributed MP on the water surface at $t=0$

a dynamic shear stress using groovyBC, with measured wind velocity components converted into $\frac{\tau}{\mu}$ gradients, which represent the vertical shear of horizontal velocity at the air–water interface and thus provide the correct mechanism for transferring wind momentum into the water column. The boundary condition input files were derived directly from the experimentally recorded temperature, wind velocity, and wind direction data.

Releasing 5 g of MP per experiment corresponds to roughly 64 million individual particles based on the Rosin–Rammmler distribution. This is computationally unfeasible to resolve each particle directly in OpenFOAM. To overcome this, the particles were represented as 10,000 numerical parcels, each statistically equivalent to ≈ 6400 MP (Fig. 3d, particles randomly distributed across the surface at $t=0$). In this framework, the parcel's center of mass is tracked through the flow domain according to the forces and velocities acting on it, providing a computationally efficient yet physically consistent representation of the particle population. The addition of Tween 20 minimized particle aggregation during the experiments, ensuring that individual particles remained well-dispersed. This improved the consistency between the experimental conditions and the Lagrangian particle-tracking simulations assumptions.

2.5 The Ratio Between Mixing and Settling Timescales

The time required for particles to mix uniformly in the water column can be approximated from the mixed layer thickness H (m) and vertical eddy diffusivity K_z ($\text{m}^2 \text{s}^{-1}$), giving a homogenization timescale T_m (Ahmadi et al., 2024; Deleersnijder et al., 2006), as expressed in Eq. 3:

$$T_m = \frac{H^2}{K_z} \quad (3)$$

In contrast, the settling timescale T_s (s^{-1}), describes the time required for particles to travel through the mixed layer under the influence of gravitational settling W (m s^{-1}) alone. This T_s is given by Eq. 4:

$$T_s = \frac{H}{W} \quad (4)$$

The ratio of these two processes is expressed by the dimensionless Péclet number ($Pé$), as presented in Eq. 5:

$$Pé = \frac{T_m}{T_s} = \frac{WH}{K_z} \quad (5)$$

which compares gravitational settling, assuming that turbulence diffusion is negligible, against turbulent mixing (Deleersnijder et al., 2006). Here, the settling velocity is analogous to the advective velocity typically used when calculating the $Pé$ number in hydrology, while the turbulent diffusion represents the dispersive velocity. When $Pé \gg 1$, settling dominates and vertical concentration gradients are expected; when $Pé \ll 1$, dispersion dominates, leading to a more homogeneous, dispersive particle distribution. The vertical eddy diffusivity (K_z) used in the $Pé$ number calculation originates from the turbulence closure model, which accounts for both forced convection (shear), mechanically generated turbulence driven by wind stress at the air–water interface, and free convection (buoyancy driven), turbulence induced by surface heating, cooling, and associated density gradients. In both cases, vertical transport is represented as turbulent (eddy) diffusion through the effective diffusivity K_z .

3 Results

3.1 Measured and Simulated Temperature Profile in the Mesocosm

In Experiment 1 (Fig. 4a), air temperature varied between 10 and 35 °C, which translated into water column temperatures of 12 and 25 °C. Distinct day–night oscillations were observed in the surface layer: daytime warming raised surface waters to 22–25 °C, while nighttime cooling dropped them to 18–20 °C, yielding an average diurnal amplitude of about 12–15 °C. Below ~ 1.5 m depth, water temperature remained comparatively constant (15–20 °C), but still showed the daily temperature cycle.

In Experiment 2 (Fig. 4c), the air temperature ranged from 6–29 °C, leading to water temperatures between 7 and 20 °C. The surface layer still responded to daily heating and cooling, but with reduced intensity compared to Experiment 1: daytime peaks reached 16–22 °C, nighttime cooling

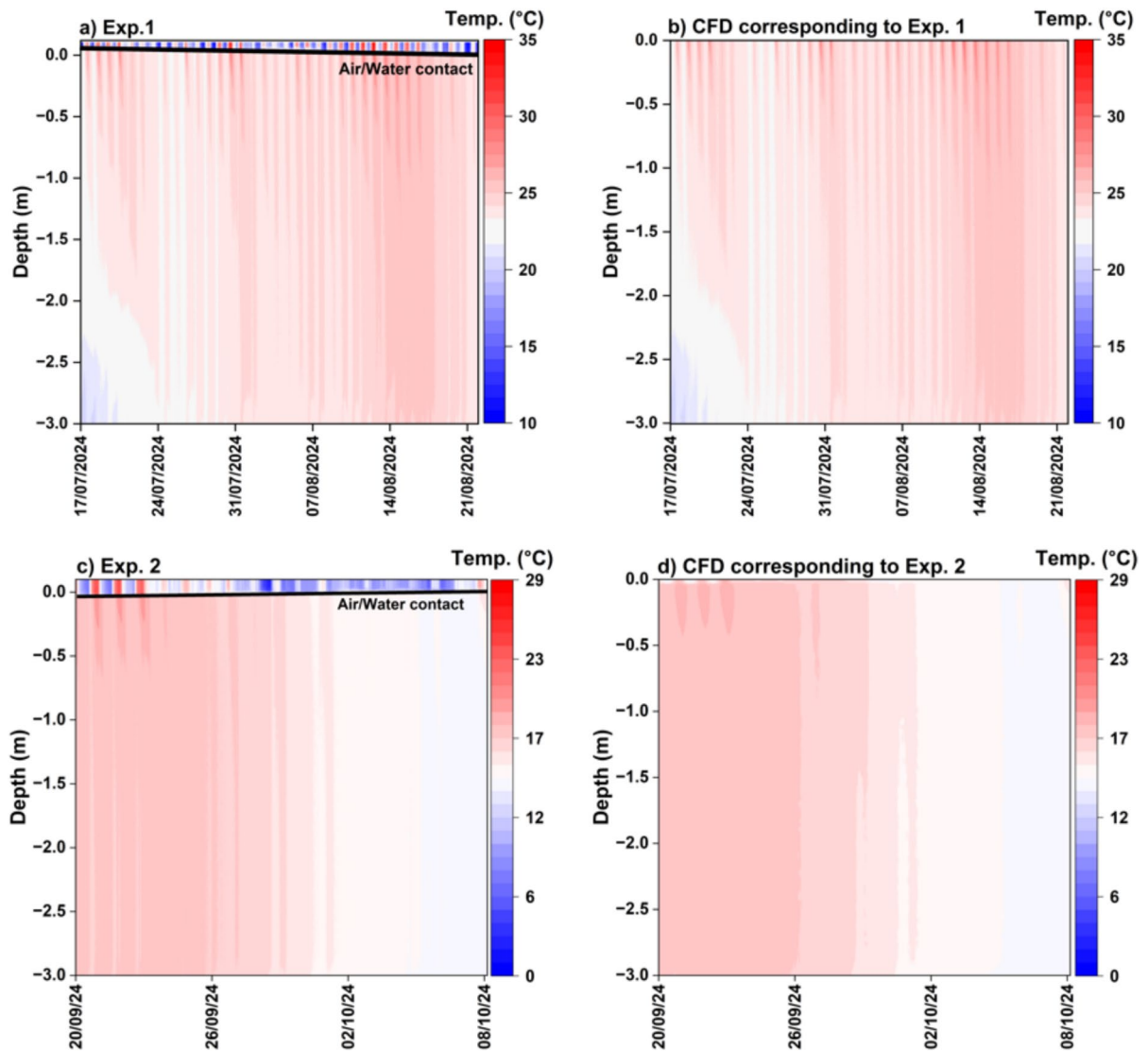


Fig. 4 Panels a and b show the measured and CFD-simulated temperature profiles for Experiment 1 (17 July–21 August 2024), while panels c and d show the measured and CFD-simulated profiles for Experiment 2 (20 September–08 October 2024)

lowered the surface to 14–18 °C, corresponding to a diurnal amplitude of about 6–9 °C. Waters deeper than ~1.5 m remained nearly constant at ~12–15 °C.

Calibration of the CFD model against Experiment 1 (Fig. 4b) produced an R^2 of 0.89 for the temperature profiles. Validation using Experiment 2 (Fig. 4d) showed an R^2 of 0.94. Furthermore, the simulated hydrodynamics matched the measured water velocities measured using the Nortek velocimeter closely ($R^2=0.84$), confirming that the model accurately reproduces the mesocosm dynamics and provides a

robust basis for the Lagrangian particle tracking of MP (cf. Supplementary Information (SI), S1).

3.2 Spatiotemporal Distribution of MP in the Mesocosm

Experiment 1: After the addition of the MP, the fluorometer at 0.25 m depth (Fig. 5a) detected a maximum concentration of ~370 $\mu\text{g L}^{-1}$ within 3–4 h of the addition. Concentrations then dropped to <50 $\mu\text{g L}^{-1}$ after 30 h, followed by a further but slow decrease

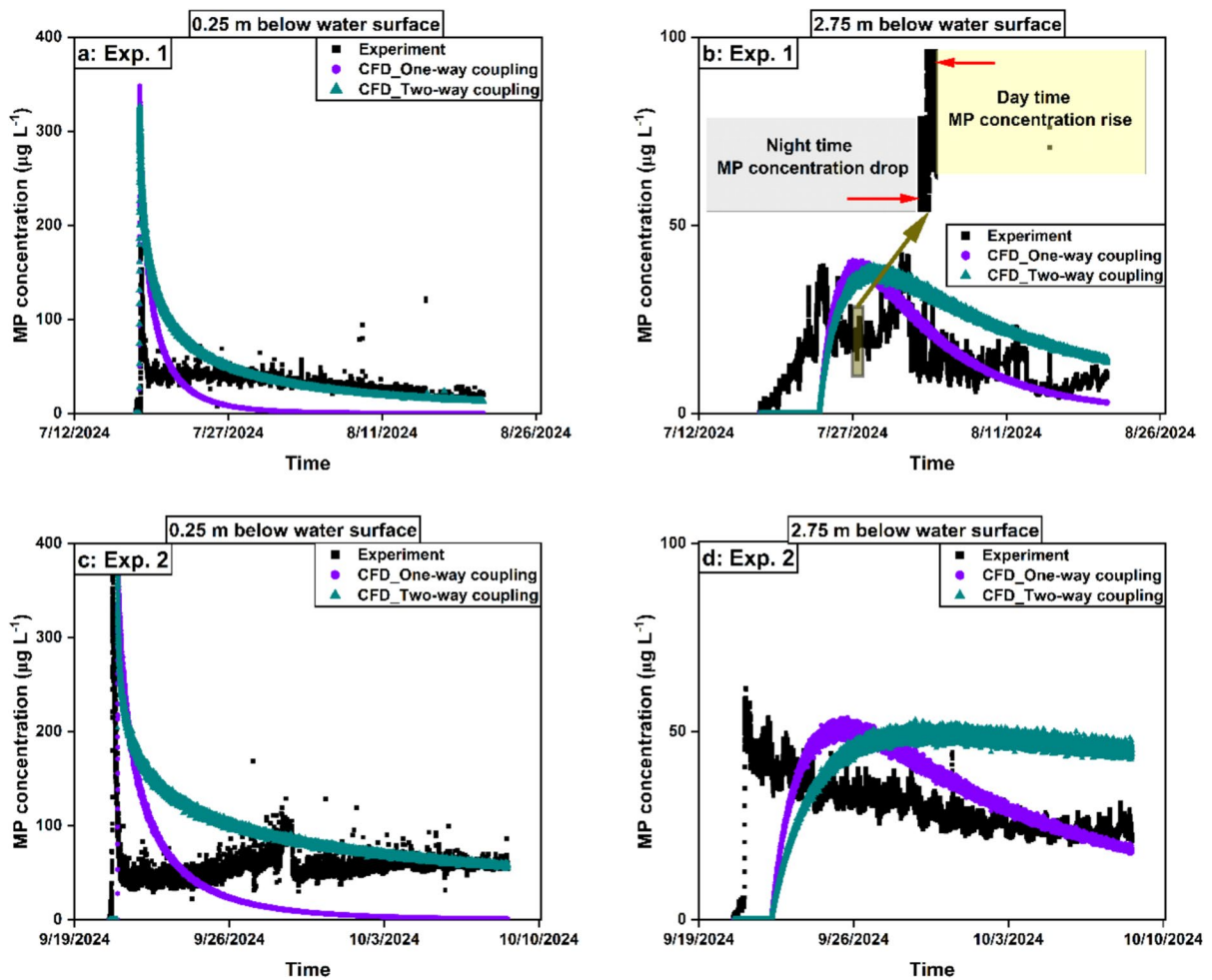


Fig. 5 Experiment 1: MP concentrations at **a)** 0.25 m and **b)** 2.75 m below the water surface. Experiment 2: MP concentrations at **c)** 0.25 m and **d)** 2.75 m below the water surface

over time with fluctuations showing a coefficient of variation (CV, cf. SI, S2) of 0.48 after the MP concentration curves levelled off (i.e., the concentration curves were still changing slightly but fluctuations became smaller as their rate of change approached zero) (Fig. 5). The CFD simulations reproduced this behavior: both one-way and two-way coupling showed similar peak concentration ($\sim 380 \mu\text{g L}^{-1}$). During the decline phase, the two-way coupling closely matched the experimental data (Figs. 5 and 6), with a Mean Absolute Error (MAE, cf. SI, S2) of $\sim 9\%$, whereas the one-way coupling deviated more strongly ($\sim 20\%$).

At 2.75 m depth (Fig. 5b), the MP concentration reached a maximum concentration of $\sim 45 \mu\text{g L}^{-1}$ after ~ 10 days, followed by a gradual decline to $\sim 20 \mu\text{g L}^{-1}$ by the end of the experiment. Clear diurnal variations were detected, with higher concentrations during the day and lower at night, resulting in a CV of ~ 0.73 (with a day–night oscillation up to $\pm 20 \mu\text{g L}^{-1}$). At this depth, simulations with one-way coupling provided a closer match to the experimental data, with $\sim 5.3\%$ lower error than the two-way coupling (Figs. 5 and 6). However, the modeling results showed a rise in MP concentration

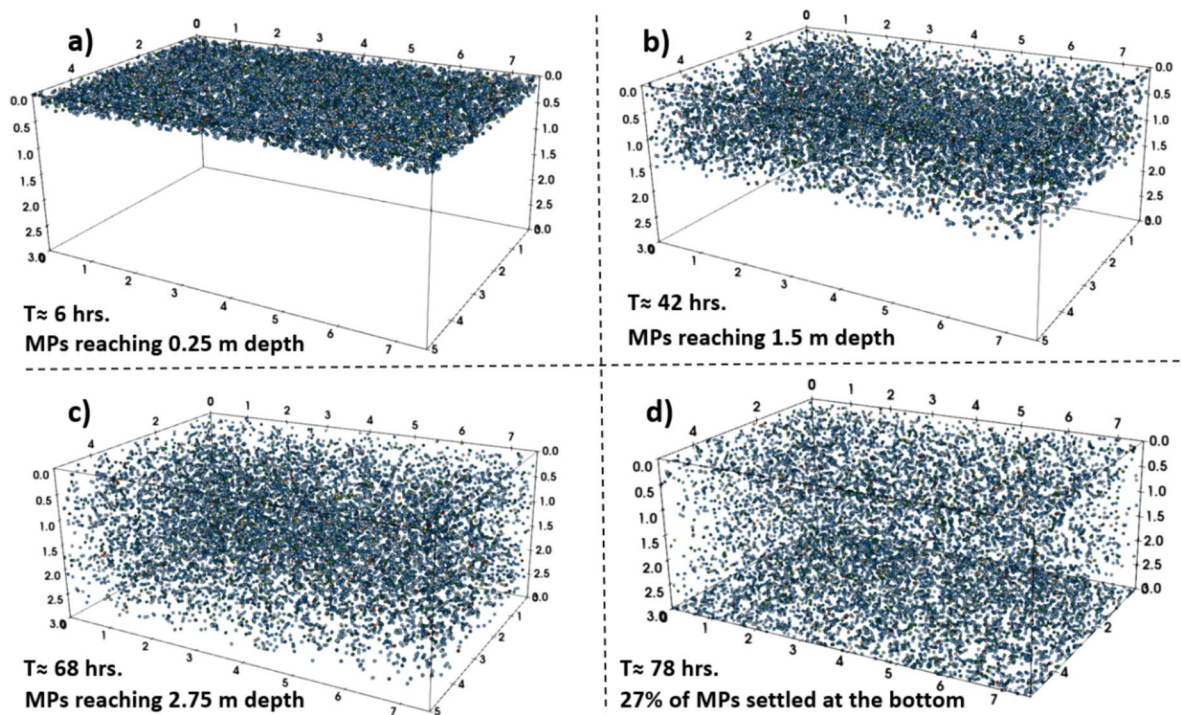


Fig. 6 MP distribution at: a) 0.25 m, b) 1.5 m, c) 2.75 m, and d) when the first particles settle on the mesocosm bed

approximately three days later than the experimental time series.

Experiment 2: The fluorometer at 0.25 m depth (Fig. 5c) also showed a maximum concentration of $\sim 350 \mu\text{g L}^{-1}$ within 3 h after MP addition. This was followed by a decline with a CV of 0.32, lower than in Experiment 1. After ~ 10 h, a steady secondary plateau formed at $> 70 \mu\text{g L}^{-1}$, with a CV of 0.18. As in Experiment 1, the two-way coupling reproduced the 0.25 m depth behavior more accurately than the one-way coupling, with a MAE of 12.3%.

At 2.75 m depth (Fig. 5d), concentrations gradually stabilized, with no strong secondary peak but with a day–night oscillation up to $\pm 10 \mu\text{g L}^{-1}$. Here, the one-way coupling achieved a better fit to the experimental data, with a MAE of 7.7%. However, similar to Experiment 1, the modeling results showed a rise in MP concentration approximately three days later than the experimental time series. A detailed comparison of MAE and CV for all

experimental and simulated cases is provided in Table S2.

3.3 Penetration Depth of Forced and Free Convection

The simulated temperature and velocity fields demonstrated that, throughout the 33 days of Experiment 1 and 19 days of Experiment 2, vertical mixing in the mesocosm was maintained by the combined effects of forced and free convection. Figure 7 shows results from July 31, 2024 (Experiment 1), the day with the maximum daily temperature difference ($\approx 18.2^\circ\text{C}$; cf. SI, Figure S3) and an average wind velocity of 0.62 m s^{-1} (CV=0.58). Figure 7b shows how the combined action of wind forcing and surface cooling shaped the velocity field within the mesocosm while also promoting the development of wall-related eddies (to further illustrate the development of the convective and diffusive heat-transport patterns shown in Fig. 7a, additional time-sequence snapshots are presented in

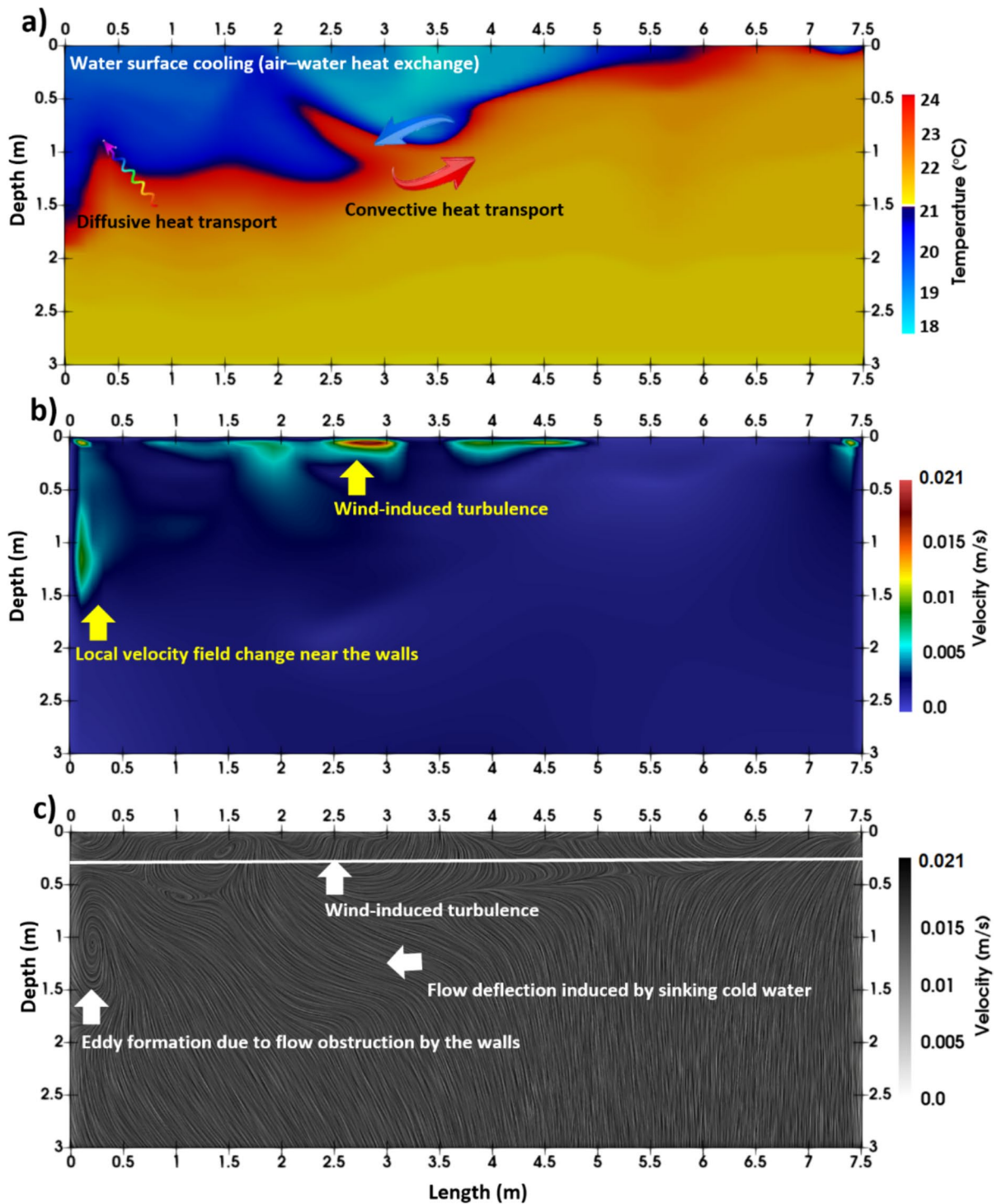


Fig. 7 Simulation snapshots for points with $x=[0,7.5]$, $y=2.5$, and $Z=[0,3]$ (visualized by ParaView 5.13) for the 31 st of July, 2024, at 20:40; **a)** water temperature field show-

ing the simultaneous diffusive and convective heat transfer across the mesocosm, **b)** water velocity field under the effects of wind and temperature forcing

the SI, cf. S4, Figure S4). Wind shear consistently induced shallow turbulent flows that mixed the upper water column, with the depth of influence generally ranging between 0.05 and 0.25 m and averaging around 0.20 m throughout the study period (Fig. 7c). In conjunction, diurnal surface cooling operated over longer timescales, driving free convection that periodically enhanced vertical homogenization of the water column (Fig. 7a). This periodicity corresponds to the transitional phases of the diurnal cycle, when surface temperature begins to rise in the morning and decline during the late afternoon and evening, during which convective mixing intensifies. The simulations also presented localized turbulence near the mesocosm walls, where velocity field changes and eddy formation were apparent (Fig. 7b and c).

3.4 Péclet Numbers at 0.25 m and 2.75 m Depths

Figure 8 presents the calculated Péclet numbers for particle settling vs turbulent transport in the two experiments. Pé values are shown for depths corresponding to the fluorometer positions: 0.25 m (Fig. 8a1 and

c for experiments 1 and 2, respectively) and 2.75 m (Fig. 8b1 and Fig. 8d for experiments 1 and 2, respectively). In general, the average Pé numbers were lower at the upper sensor located at 0.25 m (0.027 in Experiment 1 and 0.034 in Experiment 2), compared to the deeper sensor at 2.75 m (0.47 and 0.51 for Experiment 1 and Experiment 2, respectively) (Fig. 8).

The 6th of August 2024 was selected as a representative day to illustrate the transport processes occurring in the mesocosm. Figure 8a2 and b2 show zoomed-in snapshots of Fig. 8a1 and b1 for this day, revealing a slight decrease in modeled Pé numbers around midday at 0.25 m, followed by a similar response about half an hour later at 2.75 m. Similar patterns were consistently observed across all days of both experiments during the midday period.

3.5 Difference in Concentration Predictions: One- vs Two-Way Coupling

Figure 9 presents the vertical profiles of the difference in volumetric average MP concentrations between the one-way and two-way coupling simulations (i.e.,

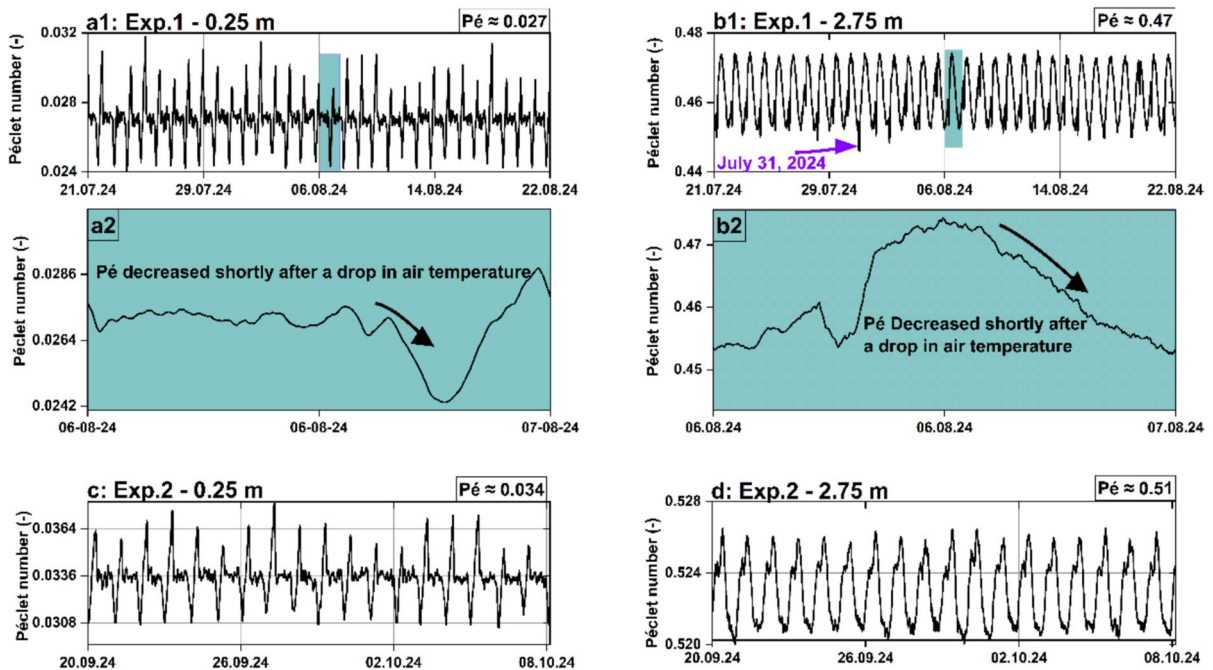
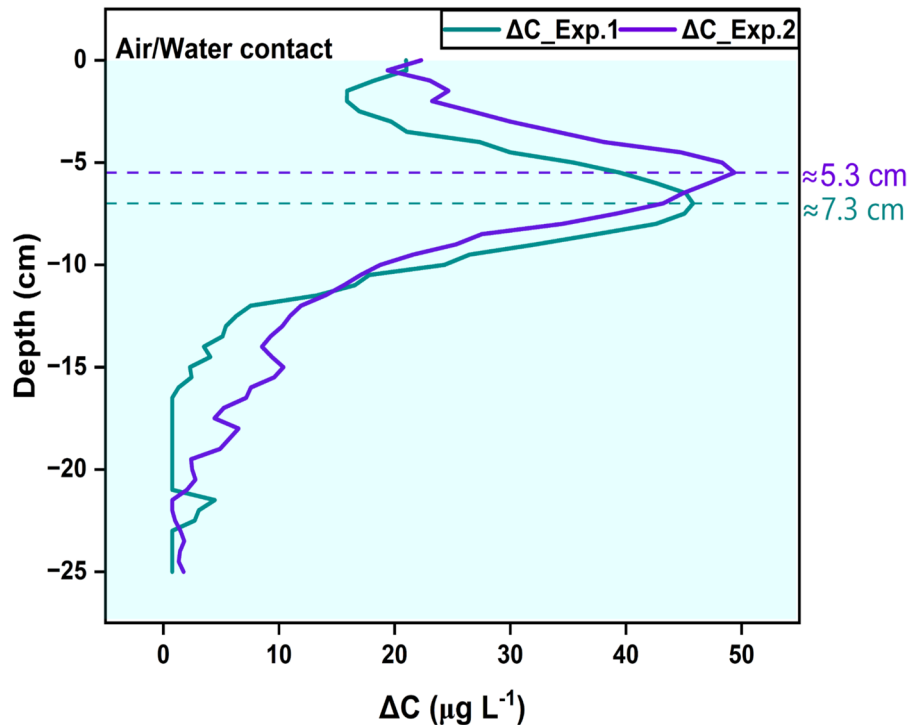


Fig. 8 Pé numbers were calculated at depths of 0.25 m and 2.75 m below the water surface for Experiment 1 (panels a and b) and Experiment 2 (panels c and d). Panels a2 and b2

illustrate the temporal variations of the Pé number on 6 August 2024, shown as examples for the locations indicated by the blue boxes in a1 (for a2) and b1 (for b2)

Fig. 9 The difference in the MP concentrations with and without the effect of fluid-MP coupling (i.e., $C_{\text{two-way}} - C_{\text{one-way}}$), right before reaching the first sensor located at 0.25 m below air/water contact



$\Delta C = C_{\text{two-way}} - C_{\text{one-way}}$) of Experiment 1 (green line) and Experiment 2 (purple line) for depths down to 0.25 m. In both experiments, the two-way coupling produced only minor differences at the surface, which increased with depth and peaked between 5 and 7 cm. Below this, the difference gradually declined, approaching zero at approximately 20 cm depth.

4 Discussion

Investigating the effect of summer mixing on MP transport in a real lake water column is challenging due to various technical limitations, legal restrictions on deliberate MP release and the complexity of real systems (Elagami et al., 2023; Rochman et al., 2024). Studying MP transport and accumulation in the aquatic mesocosms can provide a useful (simpler) tool for understanding the fundamental hydrodynamic processes that govern MP movement and are often used to bridge the gap in complexity between laboratory experiments (e.g. laminar settling column) and real-world lakes (Elagami et al., 2022; Rochman et al., 2025). Our mesocosm experiments best represent small, shallow lakes and ponds. These small water bodies, although

often overlooked compared to larger lakes, are crucial components of the freshwater hydrosphere, supporting nutrient cycling, carbon storage, and diverse communities of plants, invertebrates, and microbes (Zoboli et al., 2023). Their small size and high connectivity make them sensitive to pollution and influential in contaminant dynamics across aquatic networks.

Our results demonstrate that MP presented a distinct behavior across different depths of the mesocosm, reflecting the combined effects of free and forced convection and gravitational settling. The interplay between wind and temperature forcing impacts not only control the hydrodynamic structure of the mesocosm but also governs how MP is resuspended, redistributed, or allowed to settle. The following sections interpret how these depth-dependent hydrodynamic regimes provide the framework for understanding how MP is redistributed, retained, or transported within the water column.

4.1 Controlling Factors of MP Dynamics in the Near-Surface Layer (between 0 and 0.25 m)

After MP addition, concentrations peaked about 3–12 h and remained elevated ($> 50 \mu\text{g L}^{-1}$) throughout

both experiments, indicating that ~10% of the added MP was retained in the near-surface layer (above 0.25 m). This retention can be attributed to two main factors. First, forced convection generated by wind produces alternating upward and downward motions that can either suspend or promote the settling of MP, depending on particle size and the local turbulence structure. The smallest particles (1–5 μm), owing to their very low inertia (Ahmadi et al., 2024), respond almost instantaneously to turbulent fluctuations and therefore tend to move with the surrounding water. Within the upper shear layer, this causes a portion of the MP to remain mixed and continuously redistributed, behaving partly like passive tracers rather than independent settling bodies (Dichgans et al., 2023). However, strong downward motions within the same shear field, when combined with gravitational settling, periodically transport some particles out of this turbulent layer and into deeper zones that are less affected by forced convection (Figs. 7 and 9, close to air/water contact).

Second, at depths greater than 0.05 m (Fig. 9), where the direct wind effect diminished, the locally high particle concentrations dampened the local hydrodynamics through momentum exchange. This feedback slowed MP settling, making them less mobile and more persistent in the upper layer. Consequently, within the depth of 5–7 cm below the water surface, the two-way coupling provided a closer match to experimental observations (Fig. 5a), whereas the one-way coupling lacked particle-water interactions and therefore allowed particles to settle more rapidly (Fig. 5a, c, Fig. 9). The combined effects of upward component of the forced convection near the surface and particle-water interactions in the two-way coupling (in the depth between 5 to 7 cm) led to sustained concentrations above the 0.25 m sensor, explaining why two-way simulations better matched observations and why concentrations remained quasi-steady and relatively high throughout the experimental period (Fig. 5a and c).

Above 0.25 m, turbulence was driven by both wind and diurnal temperature changes, the latter acting on longer timescales. This was reflected in the average Péclet numbers for the shallow layer, 0.027 in Experiment 1 and 0.024 in Experiment 2, both well below 1, showing that turbulent diffusion dominated transport. The slightly higher value in Experiment 1 indicates stronger turbulent strength, consistent with its larger day-night temperature difference compared to Experiment 2 (13.1 °C vs. 9.5 °C; cf. SI, Figure S3).

4.2 Factors Controlling MP Dynamics at Greater Depth (between 0.25 and 2.75 m)

At greater depth, MP concentrations became lower than at the near-surface layer, reflecting the shift in dominant hydrodynamic processes and their influence on particle transport. Although transport remained dominated by turbulent diffusion, the relative influence of settling became stronger (Fig. 8, comparing panels b and d to a and c). In this region, one-way and two-way coupling simulations converged, with their differences diminishing to nearly zero below ~0.25 m (Fig. 9). The result indicates that particle feedback on the flow became negligible once gravitational settling increasingly separated the concentrated MP within the deeper layers.

In the deeper layers, where wind forcing is largely absent (Fig. 7b and c), convective water transport from diurnal heating and cooling became the primary driver of variability. Because these thermal processes act on longer timescales than wind forcing, settling has gained relative importance compared to the shallow region. The competition between turbulence and settling timescales produced the MP concentration fluctuations observed at 2.75 m, which were larger in Experiment 1, consistent with its greater day-night temperature difference, yielding a higher CV for MP concentration (0.73) compared to Experiment 2 (0.32) (cf., SI, S3, and Fig. 5b and d).

The difference in Pé numbers further illustrates this depth-dependent behavior. While values at both 0.25 m and 2.75 m remained well below one, confirming turbulent diffusion-dominated transport, the higher values at depth (0.47 in Experiment 1 and 0.51 in Experiment 2) indicate an increasing contribution of settling. For example, under stable conditions, before surface cooling intensified convective water transport, MP settled more effectively and yielded higher concentrations at 2.75 m (Fig. 8 b2). By contrast, during cooling phases, convective water transport enhanced vertical diffusion, counteracting settling and redistributing particles in both upward and downward directions. This interplay explains the day-night differences in MP concentration signals at the deep sensor (Figs. 5b and d) and the associated fluctuations in Pé numbers (Figs. 8b and d). However, the simulations under-represent these fluctuations because the closure model only resolves the mean turbulence and does not fully capture the intermittent shear bursts and convective plumes. Thus, the Lagrangian particles are exposed to a smoother

velocity field than the actual particles present in the mesocosm. In addition, spatio-temporal averaging and numerical diffusion in the mesh/time step further smooth short-lived events, and the parcel representation of millions of MP particles by fewer numerical parcels reduces stochastic variability. Together, these factors yield lower variability in the model than in the observations (cf., SI, Table S2).

4.3 Deposition Dynamics of MP at the Mesocosm Bed

Using Stokes' law, the 1–5 μm particles have laminar settling velocities of $\sim 1.9 \times 10^{-7}$ to 4.8×10^{-6} m s^{-1} , requiring ~ 7 –182 days to travel through the 3 m water column. Observations from the mesocosm and the CFD simulations showed MP reached the bottom by day 3 (cf. SI, S5). This rapid sedimentation resulted from the combined effects of gravitational settling, the downward components of forced and free convection, which enhanced the net downward transport of MP, while sporadic shear near the walls introduced additional stochastic vertical fluxes. These processes repeatedly redistributed particles into fields of downward motion, effectively shortening settling time. As a result, deposition consistently involved a mixture of particle sizes rather than a simple “largest-first” sequence as would be expected from Stokes law. This indicates that, under the combined downward motions generated by forced and free convection, the effective downward transport of MP can substantially exceed the settling velocities predicted by Stokes' law. Consequently, no “chromatographic” separation of particle sizes occurs during settling, as turbulence-driven transport overrides purely gravitational sorting. This indicates that MP deposition in shallow systems is governed by hydrodynamically driven transport pathways rather than intrinsic particle settling properties alone.

4.4 Environmental Implications

Our results show that hydrodynamically driven microplastic transport leads shallow lakes to function as active exposure zones rather than sedimentary sinks. About 10% of added MP accumulated in surface layers, increasing contact with surface zooplankton, insect larvae, and filter feeders. Also, the diurnal changes in hydrodynamics and vertical mixing are likely to keep MP suspended and distributed throughout the water

column, exposing a wide range of mid-water and sediment communities to MP. Once ingested, MP particles can accumulate within organisms and transfer through the food chain (e.g., through predation), potentially causing a range of effects such as reduced growth and alterations in migration and reproductive patterns (Canniff & Hoang, 2018; Coppock et al., 2019). Thus, exposure time and uptake probability are affected by hydrodynamics as well as by particle properties, concentration, and interactions with natural organic matter and suspended particulates in the lake.

4.5 Limitations of the Mesocosm Setup and CFD Simulations

While mesocosm experiments captured MP transport dynamics in a shallow water column during summer when wind and temperature fluctuations induce mixing, the simplified setup cannot fully represent the complexity of natural systems. The relatively small mesocosm volume (112 m^3) amplifies wall effects and constrains larger-scale processes such as internal waves, seiches, and horizontal currents that strongly influence MP transport in real lakes (but less in ponds). Also, the rectangular prism shape of the mesocosm serves as a compromise between real lake and laboratory studies but does not accurately represent natural lakes, lacking features such as littoral zones and gently sloping banks. In addition, both MP concentrations, water temperatures and water velocities were measured only at the center of the mesocosm, limiting insights into their spatial variability across other regions of the system.

Although the CFD model incorporated fluid-particle interactions, it still relied on turbulence closure schemes that cannot fully resolve fine-scale convective plumes and short-lived turbulent events. Consequently, simulated MP concentration fluctuations were lower than observed. Improving turbulence closure models or adopting higher-resolution approaches such as large eddy simulations will be critical for capturing the intermittent mixing processes that strongly influence MPs' dynamics. Another limitation of this study arises from the simplified representation of particle drag in the Lagrangian framework. The implemented drag formulation assumes spherical particles, consistent with the microspheres used in the experiments, and does not explicitly account for shape irregularity, surface roughness, or biofouling effects commonly observed in environmental MP. These

factors can alter the drag force and, consequently, the settling velocity of particles.

Future work should extend to more complex geometries, particle heterogeneity, and biological interactions to better capture real-world fate of MP in shallow lakes. Such interactions include biofouling, aggregation, and ingestion-excretion cycles by planktonic organisms, all of which can alter particle density, size distribution, and settling dynamics. Incorporating these processes will be essential to bridge the gap between controlled mesocosm studies and the highly dynamic conditions of natural aquatic systems.

5 Summary and Conclusion

This study employed a combined aquatic mesocosm experiment and equivalent CFD modeling to investigate how wind and changes in water temperature forcing influence MP transport dynamics in a shallow water column during summer. By disentangling the relative roles of free and forced convection and gravitational settling, we identified depth-dependent mechanisms that control MP transport.

Our results show that MP was retained near the surface (0–0.25 m) primarily by forced convection generated by wind and by local particle–water interactions, both of which prolonged their residence time in the shallow region close to the water surface. Within this layer, upward and lateral motions associated with wind-driven turbulence continually redistributed the MP, preventing its rapid descent. However, because the influence of forced convection depends on both the local wind intensity and the instantaneous position of particles within the turbulent field, its effect is spatially variable. Particles located in upward shear zones remain suspended near the surface, while those encountering downward motions experience enhanced settling and are transported out of the turbulent layer. Once below this zone, particle transport becomes increasingly influenced by free convection acting over longer timescales, where vertical exchange results from diurnal heating and cooling rather than direct wind forcing. This transition from short-lived, high-frequency shear to slower, thermally driven convection explains the depth-dependent distribution of MP and the increase in Péclet numbers with depth, which, while remaining well below one, indicates a growing contribution of settling.

Furthermore, the combined downward motions of forced and free convection, together with gravitational settling, markedly shortened particle settling times compared to Stokes' predictions. Depending on particle location and the timing of convective events, the vertical components of these water movements accelerated MP transport toward the bed. As a result, deposition involved a mixture of particle sizes rather than a size-segregated sequence, indicating that turbulence-driven transport dominated over purely gravitational settling.

The ecological implications depend strongly on the position of MP within the water column and their interaction with turbulent structures. When MP particles coincide spatially with eddies and mixing zones, turbulence can either suspend them for longer periods in the water column and accelerate their downward transport, depending on the local flow direction. Particles outside these turbulent regions are more strongly governed by settling, which becomes increasingly dominant with depth as free convection acts on longer timescales than wind-driven turbulence. Consequently, MP near the surface remain trapped within short-lived eddies, while deeper particles experience slower, periodic redistribution driven by convective mixing. This dynamic determines whether MP remains bioavailable near the surface, enhancing exposure for planktonic organisms, or are transported rapidly to sediments, increasing the risk of benthic accumulation and sediment–water exchange.

Future work should extend these insights to natural systems, incorporating more realistic particle diversity, larger-scale hydrodynamic processes, and biological interactions to better constrain the fate and ecological risks of MP under seasonally varying lake conditions.

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Author Contribution **HE** performed all MP release experiments, worked on data analysis and interpretation, and wrote the manuscript. **PA** conceived the modeling strategy, extended the numerical framework, performed all CFD simulations (including pre- and post-processing, data analysis, and interpretation), and wrote the manuscript. **JF** assisted in data interpretation and contributed to reviewing and editing the manuscript. **CT** and **WB** contributed to the experiments by planning, building, operating and analyzing the observations from the fiber optic column and the wind anemometer. Both revised the manuscript. **ML** and **SF** helped with planning and conducting the experiments.

and revising the final manuscript. **BSG** conceived the experimental part of the project, helped with conducting the experiments, assisted in data interpretation, and contributed to reviewing and editing the manuscript. Both HE and PA have equal contributions to this research.

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Data Availability All data supporting the findings of this study will be made available upon request.

Declarations

Ethical Approval Not Applicable.

Consent to Participate Not Applicable.

Consent to Publish Not Applicable.

Competing interests The authors declare no competing interests.

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