

Non-monotonic response of net dust deposition kinetics to low wind speeds

Ruochen Jia^{1, 2†}, Chaoqun Ba^{3†}, Chao Zhang⁴, Wennong Kuang⁵, Yuan Liu⁶, Zhigang Wang⁶, Fang Liu⁶,
Zhiming Xin⁶, Yuting Liu⁶, Qun Ma¹, Lu Zong⁷, Wei Liang¹, Jianqiang Qian^{8*}, Zhimin Liu^{1*}

¹ Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China.

² University of Chinese Academy of Sciences, Beijing 100049, China.

³ Hebei Minzu Normal University, Chengde 067000, China.

⁴ Inner Mongolia University of Finance and Economics, Hohhot, 010070, China.

⁵ Beijing Forestry University, Beijing 100083, China.

⁶ Experimental Center of Desert Forestry, Chinese Academy of Forestry, Dengkou 015200, China.

⁷ Wuhan Botanical Garden, Chinese Academy of Sciences, Wuhan 430074, China.

⁸ Henan Agricultural University, Zhengzhou 461101, China.

† These authors contributed equally to this work.

Corresponding author^s:

Jianqiang Qian

Henan Agricultural University

Zhengzhou, Henan, China, 461101

Email: jq.qian@henau.edu.cn

Phone number: 18604019586

Zhimin Liu

Institute of Applied Ecology, Chinese Academy of Sciences

72 Wenhua Road, Shenyang, Liaoning, China, 110016

Email: zmliu@iae.ac.cn

Phone number: 13840580046

Abstract

Dry deposition is a major sink for mineral dust, yet its behavior under weak winds remains poorly constrained and is often parameterized monotonically with wind speed. Here we quantify size-resolved dust ~~net accumulation~~~~deposition~~ kinetics in a ~~large~~ closed-circuit recirculating wind tunnel using a two-stage protocol (brief high-wind loading followed by low-wind deposition at 0, 2, 4, and 6 m s⁻¹). Cumulative ~~retained-mass~~~~deposition~~ time series were measured with an array of collection trays, with the initial suspended dust loading recorded by an online concentration monitor. Particle sizes were characterized by laser diffraction and grouped into six diameter-threshold classes (PM_{2.5}-PM_{6.3}). A first-order kinetic model ~~described the temporal accumulation~~~~dynamic~~~~captured the deposition evolution~~ and yielded an ~~fitted~~ asymptotic ~~retained~~~~masse~~~~umulative deposition~~ (a), ~~effective net-accumulation~~ rate coefficient (k), characteristic time scale ($\tau = 1/k$), and initial ~~net accumulation~~~~deposition~~ flux ($J_0 = ak$). ~~T~~~~A~~~~cross the tested wind speeds, net deposition for fine to medium particles (PM_{2.5}-PM_{4.0}) is highest~~ ~~he observed~~ J_0 was highest at 2 m s⁻¹ for PM_{2.5}-PM_{3.0}, and 4 m s⁻¹ for PM_{4.0} and PM_{6.3}, while J_0 declined markedly at 6 m s⁻¹ for the lower diameter thresholds. ~~becomes suppressed at higher speeds, with the strongest evidence for a peaked response in the 30-μm class.~~ Quadratic fits across the four wind-speed levels suggest a potential maximum near 2–3 m s⁻¹ for PM_{2.5}-PM_{4.0}. These measurements ~~quantify the size-dependent response of effective surface retention to~~~~provide process-based constraints on~~ low-wind speeds and ~~dust deposition and highlight a potential intermediate wind window that can provide benchmark behavior for coupled deposition, retention, and re-entrainment~~ ~~parameterizations~~ ~~inform and evaluate dry-deposition parameterizations.~~

Key-words: ~~net dust accumulation~~~~dry deposition~~; ~~particle re-entrainment~~; low wind speed; ~~recirculating~~ wind tunnel; size-resolved kinetics

1. Introduction

Mineral dust plays a pivotal role in the climate system, terrestrial ecosystems, and human health. It perturbs the atmospheric radiation balance and influences cloud-precipitation processes by scattering and absorbing radiation and acting as cloud condensation nuclei (Kok et al., 2023). Concurrently, it serves as a vital source of long-range nutrient fluxes to both terrestrial and marine ecosystems (Jickells et al., 2005; Mahowald et al., 2010). The atmospheric lifetime and spatial distribution of dust are predominantly governed by dry and wet deposition processes (Tegen & Fung, 1992; Wu et al., 2020). Under large-scale circulation, strong wind episodes produce brief bursts of high dust emission, injecting large amounts of mineral particles into the lower atmosphere over short time scales (Shao, 2008; Kok et al., 2014). As storms subside and near-surface winds transition to a more typical low-speed background state, elevated dust concentrations can persist, making dry deposition the dominant process controlling the final transport distance and atmospheric residence time of particles (Wu et al., 2020; Kok et al., 2021; Mostamandi et al., 2023). Consequently, accurately quantifying deposition efficiency during this post-storm, low-wind phase is crucial for linking source-region emissions to downwind climatic and ecological impacts (Mahowald et al., 2010; Kok et al., 2023).

Over recent decades, most models have simulated dry deposition using a framework that conceptualizes the process as “gravitational settling plus two resistances in series”, in which an

设置了格式: 字体颜色: 自动设置

设置了格式: 下标

设置了格式: 下标

设置了格式: 下标

设置了格式: 下标

设置了格式: 非突出显示

带格式的: 缩进: 首行缩进: 0 字符

aerodynamic resistance and a canopy/surface resistance describe stepwise transfer of particles from the free atmosphere to the underlying surface, allowing for the computation of size-dependent deposition velocities (Slinn, 1982; Wesely ~~et al.~~, 1989; Gallagher et al., 2002; Petroff & Zhang, 2010). Within this framework, particles in the 1–10 μm range are typically considered the least efficiently deposited, associated with the longest transport distances and identified as a critically sensitive size fraction in climate models (Petroff & Zhang, 2010; Zhang & Shao, 2014; Kok et al., 2023). However, a growing body of size-resolved flux observations and model intercomparisons reveals that predicted deposition rates for 0.1–10 μm particles can vary by more than an order of magnitude across dry deposition schemes (Zhang & He, 2014; Bergametti et al., 2018; Emerson et al., 2020), ~~with discrepancies exceeding 200 % even under idealized, homogeneous conditions (Goossens, 2006).~~ These substantial uncertainties propagate directly into estimates of global dust budgets and radiative forcing (Emerson et al., 2020; Kok et al., 2023). Recent systematic evaluations of numerical weather prediction and chemical transport models further demonstrate that differences in dry deposition parameterizations alone can induce systematic biases in simulated dust loads and surface concentrations, even when using identical wind fields and emission sources (Saylor et al., 2019; Zeng et al., 2020; Kong et al., 2025).

Model uncertainties are especially acute under low-wind, weakly turbulent conditions. Both field measurements via eddy-covariance systems and controlled wind-tunnel experiments indicate that for typical background winds (about 2–6 m s^{-1}), dry deposition fluxes do not exhibit a straightforward, monotonic relationship with wind speed. Instead, fluxes appear more sensitive to near-surface turbulence intensity and the particle size distribution (Bergametti et al., 2018; Waza et al., 2019). Furthermore, different samplers and models frequently yield divergent deposition rates at identical wind speeds, and existing schemes often fail to accurately replicate measured deposition fluxes for coarse particles (Petroff & Zhang, 2010; Bergametti et al., 2018; Waza et al., 2019). This evidence ~~highlightse~~ ~~challenges~~ ~~the limitations of using a single monotonic wind-speed dependence to represent net surface fluxes measured under different turbulence, surface, and sampler conditions~~ ~~conventional simplification of dry deposition as a process that increases monotonically with wind speed under weak turbulence. It underscores a lack of process-based understanding of the size-selective near-surface transport and deposition of dust under such conditions~~ (Zhang & He, 2014; Emerson et al., 2020).

In contrast to the extensive research on emission and saltation mechanisms during strong winds, the subsequent deposition phase following dust storms has received comparatively less attention. Conventional models often assume that surface dust fluxes decay rapidly to zero once wind speeds fall below the resuspension threshold. This assumption overlooks the potential for complex interactions among aggregation, resuspension, and gravitational settling in weakly turbulent flows (Shao, 2008; Kok et al., 2012). From an aeolian physics perspective, however, a low-wind environment does not signify dynamical quiescence. The post-dust-storm period, characterized by background winds modulated by large-scale circulation and boundary-layer friction, is a common atmospheric state. During this phase, the near-surface turbulent structure remains a key controller of momentum and scalar vertical exchange. Surface properties, such as roughness, soil moisture, and vegetation structure, collectively set the thresholds for dust emission, rebound, and resuspension (Fécan et al., 1999; Shao, 2008; Kok et al., 2012). As wind speed increases from calm conditions, turbulent fluctuations play a dual role: they help maintain particle suspension, delaying settling, while simultaneously enhancing near-surface transport and particle–surface contacts, which can

promote both deposition and rebound. At higher wind speeds exceeding the resuspension threshold, saltation and splash processes begin to dominate surface fluxes, potentially inhibiting settling or even reversing net deposition (Shao et al., 1993; Shao, 2008; Kok et al., 2012; Zhang & Shao, 2014). This mechanistic reasoning suggests the potential existence of a “low-wind window”, a specific wind speed range in which effective near-surface retention where net deposition efficiency reaches a local maximum, outperforming both calm and stronger wind conditions. Current dry deposition only parameterizations, however, do not explicitly represent such a response when stable retention and subsequent particle loss are considered together capture such a non-monotonic response (Petroff & Zhang, 2010; Zhang & He, 2014).

Insights from two-phase flow and hydrodynamics provide further mechanistic support. In suspensions with weak to moderate shear and relatively high particle concentrations, inter-particle collisions and adhesion can induce aggregation, effectively altering the settling size spectrum (Maggi et al., 2007; Mietta et al., 2009; Zhao et al., 2023; Yu et al., 2022; Penlou et al., 2023). Experiments and numerical simulations consistently show that for fine-particle systems, moderate turbulent shear can significantly enhance bulk settling rates, whereas stronger shear suppresses settling through aggregate breakup and flow dilution (Penlou et al., 2023; Yu et al., 2022). The mean size of particle clusters often exhibits a non-monotonic dependence on shear intensity, peaking at an intermediate level. Recent detailed simulations of cohesive sediment confirm that, within certain parameter ranges, intermediate turbulence intensities can produce the largest flocs, directly illustrating the competition between shear-enhanced aggregation and turbulence-induced breakup (Maggi et al., 2007; Mietta et al., 2009; Zhao et al., 2023). These findings imply that in the post-storm atmosphere, where near-surface dust concentrations remain high and wind speeds are in low-to-moderate, turbulence may assume a dual function: it maintains particle suspension and enhances horizontal transport, while also facilitating dust–dust collisions and aggregation. This interplay could lead to a peaked, nonlinear relationship between net deposition flux and wind speed (Penlou et al., 2023).

To address this critical knowledge gap, we formulated the hypothesis that dust accumulation/deposition kinetics under low-wind conditions exhibits a pronounced, size-resolved non-monotonic dependence on wind speed. This response may reflect enhanced particle delivery and stable retention at moderate shear, followed by reduced retention at higher wind speeds governed by the competition between two opposing turbulent mechanisms enhanced particle aggregation and deposition at moderate shear versus suppressed net deposition from incipient resuspension at higher shear. To test this hypothesis, we conducted a series of controlled experiments in a closed-circuit wind tunnel, quantified size-resolved cumulative retained mass/deposition fluxes and the temporal evolution of particle size distributions (PSDs) from an agricultural soil dust under calm air and precisely regulated low-wind speeds (0, 2, 4, and 6 m s⁻¹). An exponential mass-accumulation model was employed to extract key kinetics parameters (e.g. characteristic time constants and effective net-accumulation rate coefficient/deposition rate), which were then systematically correlated with wind speed, particle size, and shifts in PSDs. Our specific objectives were: (1) to determine if an optimal low-wind speed exists for the net accumulation/deposition of fine and medium particles (e.g., PM_{2.5}–PM₃₀), (2) to identify whether this optimum coincides with temporal changes/observable shifts in the retained PSDs that may be consistent with particle indicative of shear enhanced aggregation, and (3) to quantify the suppression/decline in fine-particle retention/deposition at higher low-end winds within the tested low-wind range, potentially due to enhanced

设置了格式: 非突出显示

设置了格式: 非突出显示

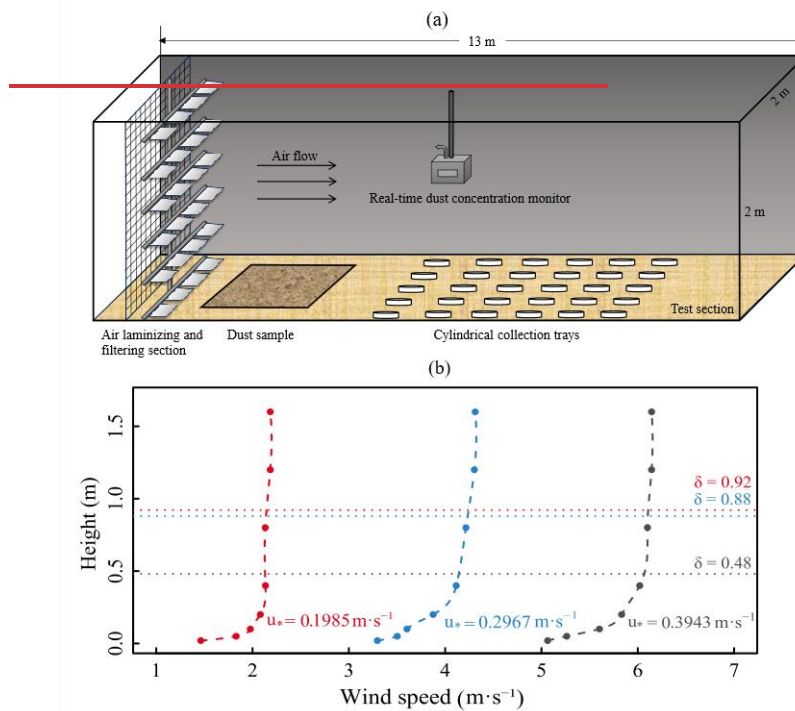
设置了格式: 非突出显示

rebound/resuspension or horizontal export. The findings aim to provide constraints for improving the next generation of dry deposition parameterizations in dust budget and climate models. The findings provide experimental constraints relevant to the representation of effective surface retention in dust transport models.

2. Materials and Methods

2.1 Wind-tunnel facility and dust preparation

Experiments were conducted in a vertical recirculating wind tunnel at the Desert and Forest Research Station of the Chinese Academy of Forestry in Dengkou, Inner Mongolia, China (Fig. 1a). This closed-loop facility, modified from a conventional open-circuit design, enables continuous circulation of air and suspended dust, thereby facilitating long-duration observations of suspended-dust evolution and surface accumulation ~~dust deposition~~. The test section measures 13 m in length, with a cross section of 2 m (width) $\times$ 2 m (height). Flow is driven by four axial fans positioned downstream of the test section, allowing for continuous adjustment of the mean wind speed from 0 to 20 $\text{m} \cdot \text{s}^{-1}$. Upstream of the test section, the flow is conditioned by passing through a diffuser, turning vanes, and a settling chamber equipped with honeycombs and screens, collectively ensuring a uniform approach flow with low turbulence intensity and minimal swirl (Xin et al., 2024). The dust used was sourced from the upper 0–5 cm of local cropland soil, which was air-dried and dry-sieved to obtain particles smaller than 63 μm . Before the wind-tunnel experiments, the sieved dust was further oven-dried at 105 $^{\circ}\text{C}$ for 8 h to standardize its moisture condition among experimental runs.



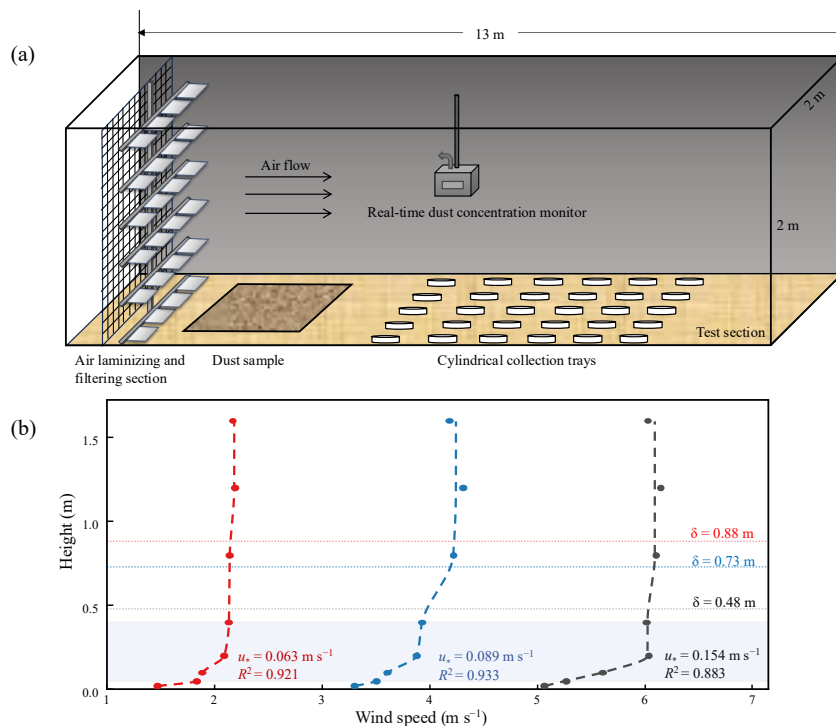


Figure 1. Experimental setup and wind profiles in the closed-circuit wind tunnel.

(a) Schematic layout of the vertical recirculating wind tunnel and sampling section.

(b) Vertical wind-speed profiles measured along the centerline of the test section under nominal approach flows of 2, 4, and 6 m s⁻¹. Symbols show measured values at eight heights, and dashed curves connect the measured values. The shaded band marks the height range (0.05 – 0.40 m) used to estimate friction velocity (u_{*}) from a log-linear regression. The corresponding R^2 values are shown. Boundary-layer thickness (δ) was defined using the 99% upper-profile velocity criterion.

2.2 Experimental Procedure

The experimental protocol comprised two sequential stages. (i) Strong-wind loading phase: the wind speed was initially set to 14 m s⁻¹ for about 5 min to erode the soil source, release dust, and establish a recirculating airborne dust load to achieve a well-mixed, approximately uniform suspension within the closed-circuit tunnel. (ii) Low-wind deposition phase: immediately after the loading phase, the exposed soil source bed was completely covered with steel plates to prevent continued direct emission or re-erosion from the original source. The steel plates remained in place throughout the subsequent low-wind deposition phase. The wind speed was then reduced to a target value of 2, 4 or 6 m s⁻¹. Additional experiments under quiescent conditions (0 m s⁻¹) were performed in the same test section with the fans deactivated, following the same sampling timetable.

At the beginning of each low-wind experiment, subsequently, 25 cylindrical acrylic collection trays (radius: 10 cm, rim height: 3 cm) were placed at predefined positions on the tunnel floor within the test section. Five trays were assigned to each of the five sampling times (30, 60, 90, 120 and 180 min). Each tray was exposed continuously from the beginning of the low-wind phase until its

带格式的: 段落间距段后: 0 磅

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体, 10 磅

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体, 10 磅

设置了格式: 字体: (中文) 宋体

设置了格式: 字体: (中文) 宋体

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体, 10 磅

设置了格式: 字体: (中文) 宋体

设置了格式: 字体: (中文) 宋体

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体, 10 磅

设置了格式: 字体: (中文) 宋体

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体, 10 磅

designated sampling time. Five trays were removed at their designated times to obtain the cumulative deposition sample for a specific wind-speed-time combination, resulting in a progressive reduction in the number of trays remaining in the tunnel. The same initial tray layout, time-specific tray assignments, and retrieval sequence were used for all wind-speed treatments. Thus, the tray configuration at a given sampling time was matched among treatments, although the number of trays decreased progressively within each experimental run.

No water, glass beads, grease, adhesive, or other material was added to suppress particle rebound or re-entrainment from the tray surface. The collected mass therefore represents cumulative tray-retained net accumulation, which integrates particle arrival at the collection surface and subsequent losses through rebound, local re-entrainment, and removal from the tray.

For each wind speed, deposition was sampled at five time intervals (30, 60, 90, 120 and 180 min), with five replicate trays assigned to each interval. Trays were removed at their designated times to obtain the cumulative deposition sample for specific wind speed time combination. Additional experiments under quiescent conditions (0 m s^{-1}) were performed in the same test section with fans deactivated, following the same sampling timetable. A real-time dust concentration monitor (Fig. 1a; TD2000A-CT, Zhonggong Tiandi Technology (Beijing) Co., Ltd., Beijing, China) was operated continuously during both the loading and deposition phases to track the bulk suspended dust mass concentration in the test section. The sampling inlet was located on the longitudinal centreline of the test section, 7.5 m downstream of the test-section entrance and 1 m above the tunnel floor. The instrument has a measurement range of $0\text{--}10\,000 \text{ mg m}^{-3}$ (RS485 output; DC 24 V). During the 14 m s^{-1} loading phase, the monitor was used as a quality-control indicator of mixing and to obtain comparable initial suspended dust loadings among experimental runs ensure that experiments started from comparable initial suspended dust loadings. Immediately after the wind speed was stepped down to the target low-wind value, the monitor reading was recorded as the initial airborne concentration (C_0) for that run, which was used to calibrate the initial condition comparability across wind-speed treatments and to support subsequent interpretation of the fitted kinetic parameters (Sect. 2.5). The concentration recorded at the start of the low-wind phase was defined as the initial airborne dust concentration (C_0). The monitor provided a single-point concentration time series at this fixed sampling location; vertical concentration profiles were not measured. For consistency throughout this study, we define particles of $1\text{--}10 \text{ }\mu\text{m}$, $10\text{--}20 \text{ }\mu\text{m}$, and $20\text{--}63 \text{ }\mu\text{m}$ as “are referred to as fine”, $10\text{--}20 \text{ }\mu\text{m}$ as “medium-sized”, and $20\text{--}63 \text{ }\mu\text{m}$ as “coarse particles, respectively”.

2.3 Flow characterization

Vertical wind speed profiles were measured on the longitudinal centreline of the test section, 9 m downstream of the test-section entrance and immediately downstream of the collection-tray array. The complete initial array of 25 trays was present during the profile measurements. The collection trays were arranged in the same fixed layout as in the deposition experiments, with a spacing of 20 cm between adjacent trays, and the same layout was restored before each run. Wind speed was recorded at eight heights ($z =$ along the tunnel centreline at $z = 0.02, 0.05, 0.10, 0.20, 0.40, 0.80, 1.20$, and 1.60 m) above the floor for under nominal wind approach speeds of 2, 4, and 6 m s^{-1} (Fig. 1b). Friction velocity u_* was estimated from a log-linear regression of the near-surface wind profile, and aerodynamic roughness length z_0 were obtained by fitting the measured profiles to the logarithmic law of the wall,

$$U(z) = A \ln\left(\frac{z}{z_{ref}}\right) + B_z \quad (1)$$

设置了格式: 字体颜色: 自动设置

设置了格式: 上标

设置了格式: 非突出显示

设置了格式: 非突出显示

格式化表格

$$u_* = \kappa A_z \quad (2)$$

where $U(z)$ is wind speed at height z , $z_{ref} = 1 \text{ m}$, A is the fitted slope, B is the intercept, and with $\kappa = 0.4$. To ensure consistency among treatments, the regression was fitted over the common height interval of 0.05–0.40 m, which is above the tray rim height (0.03 m) and below the upper quasi-uniform portion of the profile. Therefore, the measurements at 0.80, 1.20, and 1.60 m were not included in the u_* regression. The resulting profile-derived apparent friction velocities were 0.063, 0.089, and 0.154 m s^{-1} for the 2, 4, and 6 m s^{-1} treatments, respectively, with corresponding R^2 values of 0.921, 0.933, and 0.883.

The displacement height d was set to zero for the nominally planar floor, and the fit was restricted to the well-defined surface-layer portion of each profile (excluding the lowest 1–2 measurement points where near-wall effects and probe interference may occur, and excluding points above the boundary layer thickness). The resulting fits yielded $z_0 \approx 1 \times 10^{-4} \text{ m}$, comparable to values reported for bare sand. The boundary-layer thickness (δ) was defined as the first height at which the shape-preserving interpolated profile reached $0.99U_\infty$, where U_∞ was the mean wind speed at 0.80, 1.20, and 1.60 m. Minor reversals in the measured profiles were first removed using isotonic regression before interpolation.

99 % of freestream velocity (δ) criterion, giving $\delta \approx 0.92, 0.88$, and 0.48 m at 2, 4, and 6 m s^{-1} , respectively (corresponding to δ/z_0 ratios of order 4.8×10^3 – 9.2×10^3). The top upper edge of the collection trays was positioned at $z = 0.03 \text{ m}$ – 0.03 m , corresponding to approximately 3.4%, 4.1%, and 6.3% of δ placing the sampling surface within the surface layer (within 6.3% of δ), respectively. Because the profiles were measured after installation of the complete tray array, they incorporated the collective aerodynamic influence of the trays. The profiles characterize the profile-scale mean flow under the complete initial 25-tray configuration. Local flow separation and wakes around individual tray rims, as well as possible changes associated with progressive tray removal, were not resolved. No inflection point or abrupt velocity change was detected within 0–5 cm above the trays, indicating minimal flow perturbation by the samplers. While the total tunnel height is 2 m (so that the boundary layer does not fill the entire depth and the upper region is partly influenced by recirculation), the roughness and shear structure within the relevant near-surface layer are reasonably analogous to those of the natural atmospheric surface layer.

2.4 Sample analysis

The mass of deposited dust retained in each tray was determined using an analytical balance with a resolution of 0.0001 g. Particle-size distributions (PSDs) of the deposited dust were analyzed using a laser diffraction particle-size analyser-analyzer (Eye Tech, Netherlands). To ensure accuracy and repeatability, the instrument was calibrated before each run using certified reference microspheres (20 μm and 100 nm), requiring agreement between measured and nominal diameters to be within $\pm 1\%$. Ultrapure water blanks were analyzed to confirm background noise levels were below 0.5%. A standard suspension was analysed-analyzed every 4 h during the measurement; if key parameters like the median diameter (D_{50}) deviated by more than $\pm 2\%$, the instrument was recalibrated. All measurements were performed at a circulation speed of 2000 rpm in a temperature-controlled laboratory ($23 \pm 1^\circ\text{C}$). Each tray sample was measured in triplicate, and the average value was used for subsequent analysis. Particle size was reported as a volume-equivalent diameter. Particle morphology, including aspect ratio and sphericity, was not independently characterized, and no shape-dependent correction was applied in the particle-size classification.

2.5 Data processing and kinetic modeling

For each wind speed (U) and sampling-time (t) combination, the total deposited dust mass retained in each tray was measured and the particle-size distribution (PSD) was recorded. Six cumulative diameter-threshold size-classes ($PM_{\leq 2.5}$, $PM_{\leq 10}$, $PM_{\leq 20}$, $PM_{\leq 30}$, $PM_{\leq 40}$, and $PM_{\leq 63}$) were defined by from the laser-diffraction volume-equivalent diameter thresholds (as $D_v D_v < 2.5, \leq 10, \leq 20, \leq 30, \leq 40$, and $\leq 63 \mu m$, respectively). Throughout this study, the PM labels denote cumulative thresholds of laser-diffraction volume-equivalent diameter notation is used for convenience and does not represent aerodynamic PM. The cumulative retained mass below each diameter threshold of each size class was then calculated as the product of the total retained deposited mass and its corresponding cumulative volume fraction, and was then converted to an areal cumulative tray-retained mass deposition $M(t)$ ($mg \text{ cm}^{-2}$) using the known tray area. For each wind-speed-time (U , size)-combination, five replicate trays were processed; results are summarized by the mean across replicates. The standard error of the mean (SEM, $n = 5$) at each time point was used as the measurement uncertainty for model fitting. Before calculating D_{50} , the differential volume fractions of each PSD were normalized to 100%. D_{50} was then determined from the cumulative volume distribution by linear interpolation on the logarithmic diameter scale between the two adjacent diameter channels bracketing 50%.

The temporal evolution of $M(t)$ cumulative deposition was represented by a first-order approach to an asymptote,

$$M(t) = a(1 - e^{-kt}), \quad (3)$$

where a ($mg \text{ cm}^{-2}$) is the fitted asymptotic theoretical maximum retained mass deposition as $t \rightarrow \infty$ representing the system's saturated deposition capacity as $t \rightarrow \infty$. $k(h^{-1})$ (h^{-1}) is the effective net-accumulation deposition rate coefficient, where larger values indicate a faster approach to the fitted asymptote saturation. The characteristic accumulation deposition time-scale was defined as $\tau = 1/k(h) = 1/k(h)$, corresponding to the time required for the fitted curve to reach approximately 63%- a . The initial net accumulation deposition flux is defined as the initial slope of $M(t)$,

$$J_0 = \left. \frac{dM}{dt} \right|_{t=0} = ak \text{ (mg m}^{-2} \text{ h}^{-1}\text{)}, \quad (4)$$

$$= ak \text{ (mg cm}^{-2} \text{ h}^{-1}\text{)}.$$

Because $M(t)$, a , and J_0 were not normalized by the time-varying concentration $C(t)$, they are reported as tray-based net accumulation metrics. To assess whether small differences in initial airborne dust loading affected the wind-speed comparison, a (C_0)-normalized sensitivity check was performed by scaling the retained mass with (C_{ref}/C_0) , where (C_{ref}) was the mean recorded initial concentration across the four wind-speed treatments.

For connection to deposition-velocity formulations used in atmospheric models, dry deposition may be expressed as a downward surface flux $J = V_d C$, where C is the near surface airborne mass concentration and V_d is the deposition velocity. Under a bulk, vertically well-mixed layer of effective height H_{eff} , $\frac{dC}{dt} = -\left(\frac{V_d}{H_{eff}}\right)C$, implies a first-order form consistent with the expression for $M(t)$. An equivalent deposition-velocity was therefore defined by

$$V_{d,eq} = kH_{eff},$$

设置了格式: 字体: 非倾斜

设置了格式: 字体: 非倾斜

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

带格式的: 缩进: 首行缩进: 2 字符

带格式的: 右

格式化表格

带格式的: 缩进: 首行缩进: 0 字符

带格式的: 居中

格式化表格

带格式的: 缩进: 首行缩进: 0 字符

设置了格式: 删除线

noting that $V_{a,eq}$ scales linearly with the assumed H_{eff} . In the present facility, a plausible range for H_{eff} spans the measured near-surface boundary-layer thickness ($\delta \approx 0.48\text{--}0.92\text{ m}$) and the 2-m tunnel height.

Model parameters (a, k) were estimated separately for each wind-speed-size combination by weighted non-linear least squares (NLS), with weights $w_i = 1/SEM_i^2$ applied to the mean at time point t_i . Positive constraints ($a > 0, k > 0$) were enforced. Wald 95% confidence intervals for a and k were obtained from the NLS covariance matrix. Uncertainty in the derived metric $J_0 = a \cdot k$, defined by Eq. (4), was propagated by the delta method to yield 95% CIs (used in Fig. 3b).

To quantify wind-speed dependence for each size class, J_0 was related to U using linear ($J_0 \sim U$) and quadratic ($J_0 \sim U + U^2$) models; likelihood-ratio tests (LRTs) and ΔAIC were used to evaluate evidence for non-monotonicity. The wind-speed corresponding to the maximum fitted J_0 response giving the maximum efficiency was summarized by the quadratic vertex $U_{opt} = -\beta_1/(2\beta_2)$, with bootstrap 95% CIs (10,000 resamples of the four (U, J_0) pairs).

Many dry-deposition parameterizations describe deposition velocity assume that, for a given particle size and surface type as, deposition efficiency (or deposition velocity) increases increasing or remaining unchanged with increasing monotonically with wind speed (or friction velocity), while treating resuspension separately. To quantify the departure of the present net-accumulation response from this simplified deposition-only expectation or at most saturates, a strictly non-decreasing reference curve $J_{0,mono}(U)$ was constructed for each size class by isotonic regression fitted to the four (U, J_0) points. Deviations from the monotonic benchmark were summarized by as

$$R(U) = \frac{J_0(U)}{J_{0,mono}(U)} \quad (5)$$

Here, where $R > 1$ indicates that the observed initial net accumulation flux exceeds the non-decreasing benchmark, whereas indicates underprediction by a strictly monotonic scheme and $R < 1$ indicates that it falls below the benchmark, overprediction at that wind speed.

All analyses were performed in R (R Core Team, 2023) (base stats for NLS, boot for resampling, ggplot2 for graphics).

3. Results

3.1 Exponential kinetics of cumulative tray-retained dust accumulation

The first-order exponential model (Eq. (3)) provided an excellent description of the cumulative tray-retained accumulation kinetics for all wind-speed-size combinations, with coefficients of determination (R^2) exceeding 0.91 and approximately 80% of fits achieving $R^2 > 0.95$ (Fig. 2). This result indicates confirmed that a single effective time-scale adequately characterizes the temporal evolution of dust accumulation under experimental conditions.

设置了格式: 非上标/下标

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: 10 磅

带格式的: 缩进: 首行缩进: 0 字符

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

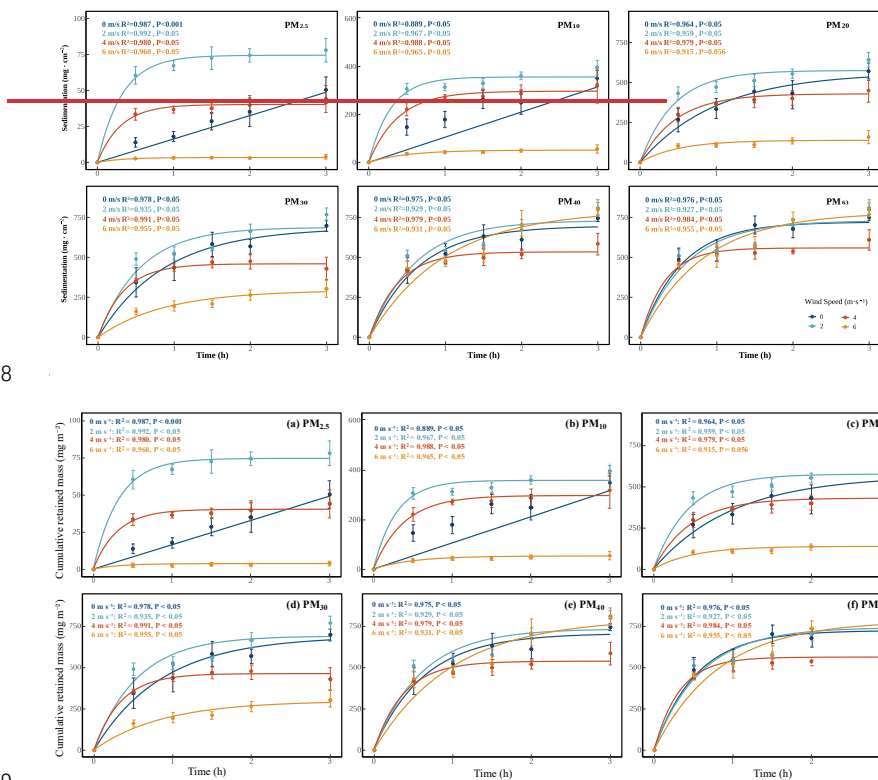


Figure 2. Exponential fits of cumulative retained mass for different particle size classes under varying wind speeds: (a) PM_{2.5}, (b) PM₁₀, (c) PM₂₀, (d) PM₃₀, (e) PM₄₀, and (f) PM₆₃.

Each panel corresponds to one dust size class (PM_{2.5}–PM₆₃). Symbols represent the mean cumulative retained mass $M(t)$ (± 1 SEM, $n = 5$ trays) at four wind speeds (0, 2, 4 and 6 m s⁻¹). Solid curves show non-linear least-squares fits of the first-order exponential model $M(t) = a \cdot (1 - e^{-kt})$. Legends report the coefficient of determination (R^2) and P value for each fit.

Under quiescent conditions (0 m s⁻¹), fine particles (PM_{2.5}–PM₁₀) accumulated slowly, as evidenced by nearly linear cumulative curves, long characteristic times ($\tau \approx 4.2$ h for PM_{2.5}; 1.4 h for PM₁₀), and small rate coefficients ($k = 0.24$ h⁻¹ for PM_{2.5}; 0.71 h⁻¹ for PM₁₀) (Table S1S2). In contrast, coarse particles (PM₃₀–PM₆₃) approached their fitted asymptote saturation within about 1 h ($\tau < 1$ h, $a \approx 600$ –750 mg cm⁻²), exhibiting behavior dominated by gravitational settling.

Increasing wind speed from 0 to 2 m s⁻¹ markedly accelerated early net accumulation across all size classes (Tables S1S2–S2). τ for PM_{2.5} shortened from 4.2 h to 0.3 h (an order-of-magnitude faster approach to the fitted asymptote saturation), while k increased from 0.24 to 3 h⁻¹. Similarly, for PM₁₀, τ decreased from 1.4 h to 0.3 h and k increased to >3 h⁻¹. For medium and coarse particles, τ also decreased and k increased by factors of roughly

设置了格式: 字体: 非加粗

带格式的: 题注, 行距: 单倍行距, 与下段同页

设置了格式: 下标

设置了格式: 字体颜色: 自动设置

2–4, whereas their asymptotic loads remained of the same order as under still air (typically within approximately 20% of the 0 m s⁻¹ values). In contrast, α for PM_{2.5-2.5} was reduced by roughly one quarter. These changes indicate that a wind speed of 2 m s⁻¹ produced rapid early strongly enhances tray-retained accumulation deposition kinetics, particularly for fine particles, while maintaining substantial retained mass for net deposition of medium and coarse particles, representing a low wind regime that effectively balances deposition rate and total deposited mass.

At 4 m s⁻¹, τ remained short for all size classes (often < 0.5 h), and k stayed well above still-air values, indicating a sustained rapid early approach to the fitted asymptotic saturation (Table S1S2). However, the asymptotic retained mass deposition α for all sizes fell below their still-air values, decreasing by roughly 25–60%, especially for fine-to-medium particles. This suppression may reflect increasing competition from particle resuspension and horizontal export at higher shear; because resuspension was not directly measured, we treat this as a plausible interpretation rather than a confirmed mechanism.

At 6 m s⁻¹, the suppression in fine-to-medium tray-retained mass of net deposition became most pronounced. For PM_{2.5-2.5} and PM₄₋₁₀, α was reduced by about one order of magnitude relative to still air, indicating near-complete inhibition of effective accumulation despite still-elevated rate coefficients. Accumulation Deposition of PM₁₀₋₂₀ and PM₂₀₋₃₀ was also substantially suppressed. In contrast, α for the coarsest fractions (PM₄₀₋₆₀, PM₆₀₋₆₃) was similar to or slightly higher than under still air (within 10%), but their kinetics were less favorable than at 2–4 m s⁻¹, with longer τ and lower k compared with the low-wind optimum. Collectively, these results show that high shear maintains large instantaneous settling rates yet strongly suppresses the effective accumulation of fine to medium particles, shifting net deposition toward a coarse dominated regime.

The auxiliary screening test identified an apparent critical wind-speed range of 5.87–6.01 m s⁻¹ for marked dust mobilization from the tray surface, placing the 4 m s⁻¹ treatment below and the 6 m s⁻¹ treatment close to this range (Fig. S1).

Analysis of characteristic times (Table S1S2) further shows that for most wind-speed-size combinations, τ is less than 0.5 h, indicating rapid mass accumulation during the early part of the experiments implying that the majority of total deposition occurs within the first 0.5 h. The PSD comparison in Sect. 3.2 therefore uses the cumulative tray-retained samples collected at 0.5 and 3 h. We therefore define 0–0.5 h as the rapid deposition phase and 0.5–3 h as the slow deposition phase.

The concentration records were used to evaluate the comparability of initial airborne dust loading and the persistence of suspended dust during the low-wind phase. The recorded C_0 ranged from 178.2 to 191.4 mg m⁻³, with a coefficient of variation of 3.1% indicating comparable initial airborne dust loading among treatments. After normalizing by C_0 , the mean airborne concentration during the final 20 min was 5.32%, 0.15%, 9.27%, and 4.24% of C_0 at 0, 2, 4, and 6 m s⁻¹, respectively (Table S1). The C_0 -based rescaling did not change the principal wind-speed ordering of the net-accumulation response. 2 m s⁻¹ treatment showed the lowest late-stage residual concentration, whereas the 4 and 6 m s⁻¹ treatments maintained higher residual airborne concentrations, especially at 4 m s⁻¹ (Fig. S2). This pattern indicates that the lower tray-retained mass at 4–6 m s⁻¹ was accompanied by greater persistence of suspended dust and reduced effective transfer into stable near-surface retention.

设置了格式: 字体颜色: 自动设置

设置了格式: 非删除线

设置了格式: 字体颜色: 自动设置

设置了格式: 非删除线

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman

设置了格式: 非上标/ 下标

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman, 字体颜色: 蓝色

设置了格式: 字体: (默认) Times New Roman

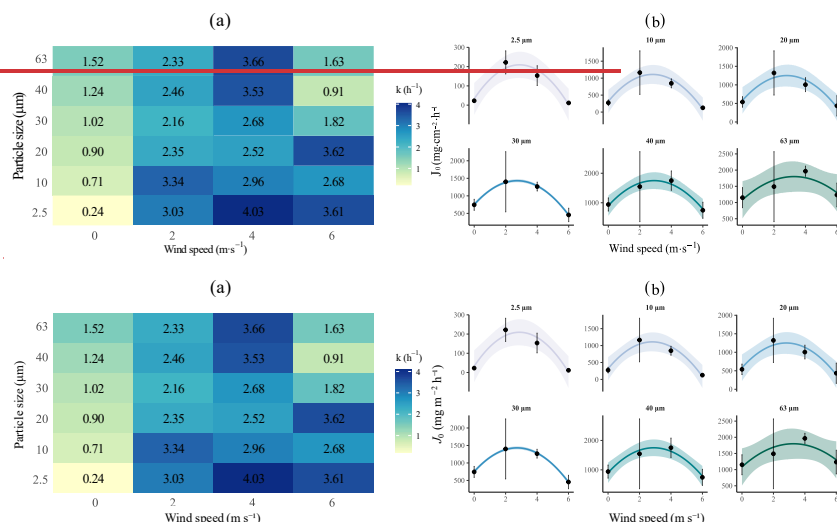


Figure 3. Net accumulation/deposition kinetics and initial early-stage net accumulation flux/deposition as functions of wind speed and particle size.

(a) Effective net-accumulation rate/deposition-rate coefficient k (h⁻¹) for each wind-speed-size combination (cell values show k).

(b) Initial net accumulation/deposition flux $J_0 = a \cdot k$ versus wind speed U . Points are estimates and error bars are 95% Wald confidence intervals propagated from the weighted NLS fit of $M(t) = a \cdot (1 - e^{-kt})$ with $M(0) = 0$, $n = 5$ trays per time point. The curve and shaded band show the quadratic fit $J_0 \sim U + U^2$ and its 95% confidence band.

Fig. 3 compares net accumulation/deposition dynamics across the parameter space and during the initial stage. Fig. 3(a) illustrates the distribution of the effective net-accumulation rate coefficient k . For fine-to-medium particles (PM_{2.5}–PM₂₀), k increased sharply from still air, reached or approached its maximum at 2 m s⁻¹ and generally remained high at 4–6 m s⁻¹, although the wind speed corresponding to the largest k varied among size classes; for these sizes, k decreased slightly. In contrast, the largest k for the coarse fraction (PM₄₀–PM₆₃) occurred at 4 m s⁻¹; the maximum k occurred at 2, 4, 6 m s⁻¹ for PM₁₀, PM_{2.5} and PM₂₀, respectively. For PM₃₀–PM₆₃, the largest k occurred at 4 m s⁻¹. This pattern indicates that weak shear primarily accelerates the deposition of fine-to-medium particles, while moderately higher winds enhance the deposition rate mainly for coarser particles. Fig. 3b shows that J_0 was highest at 2 m s⁻¹ among the tested wind speeds for PM_{2.5}–PM₄₀ and was strongly reduced at 6 m s⁻¹ for the fine size classes. Because $J_0 = a \cdot k$, the maximum initial net accumulation flux did not necessarily coincide with the maximum fitted k . Quadratic fits across the four wind-speed levels yielded a model-implied peak wind speed (U_{opt}) of approximately around 2–3 m s⁻¹ for PM_{2.5}–PM₄₀; several fine-to-medium size classes, with bootstrap 95% confidence intervals typically spanning approximately 2.3–3.3 m s⁻¹ (Table S2). The most pronounced peaked response was found for the PM₃₀–30 μm class, whereas PM₆₃ shows weaker evidence for a peak (Table S2S3).

Synthesizing Fig. 3(a) and Fig. 3(b), a low-wind window centered near 2 m s⁻¹ (model-inferred optimum around 2–3 m s⁻¹) combines relatively high effective net-accumulation rate coefficients simultaneously maximizes the deposition rate (panel a) and with the highest observed J_0 values – the early-stage efficiency – (panel b) for PM_{2.5}–PM₃₀; stronger winds progressively

设置了格式: 字体: 倾斜

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置, 非上标/下标

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置, 非上标/下标

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置, 非上标/下标

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置, 非上标/下标

设置了格式: 字体: 非倾斜, 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置, 下标

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: 非倾斜, 字体颜色: 自动设置, 下标

设置了格式: 字体: 非倾斜, 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: 非倾斜, 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 非上标/下标

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体: (默认) Times New Roman, 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman, 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman, 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman, 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 非突出显示

设置了格式: 字体: 倾斜

设置了格式: 下标

suppress early net accumulation of these sizes and shift the relative contribution net flux toward the coarse fraction.

In summary, dust deposition exhibits a strongly size-selective response to wind speed:

Low wind (2 m s^{-1} , model inferred optimum between $2-3 \text{ m s}^{-1}$): maximizes the initial deposition flux and early cumulative deposition for $\text{PM}_{2.5}$ – PM_{10} .

Moderate wind (4 m s^{-1}): despite relatively high k , both ~~and~~ early cumulative mass for $\text{PM}_{2.5}$ – PM_{10} decline compared with 2 m s^{-1} , consistent with enhanced resuspension; coarse particles PM_{40} – PM_{63} approach their rate maximum.

High wind (6 m s^{-1}): markedly suppresses early deposition of $\text{PM}_{2.5}$ – PM_{10} and shifts net deposition toward coarse particles, yielding a more coarse-dominated yet overall less efficient early flux.

3.2 Temporal evolution of cumulative tray-retained particle-size distributions

Size-selective evolution between rapid and slow deposition stages

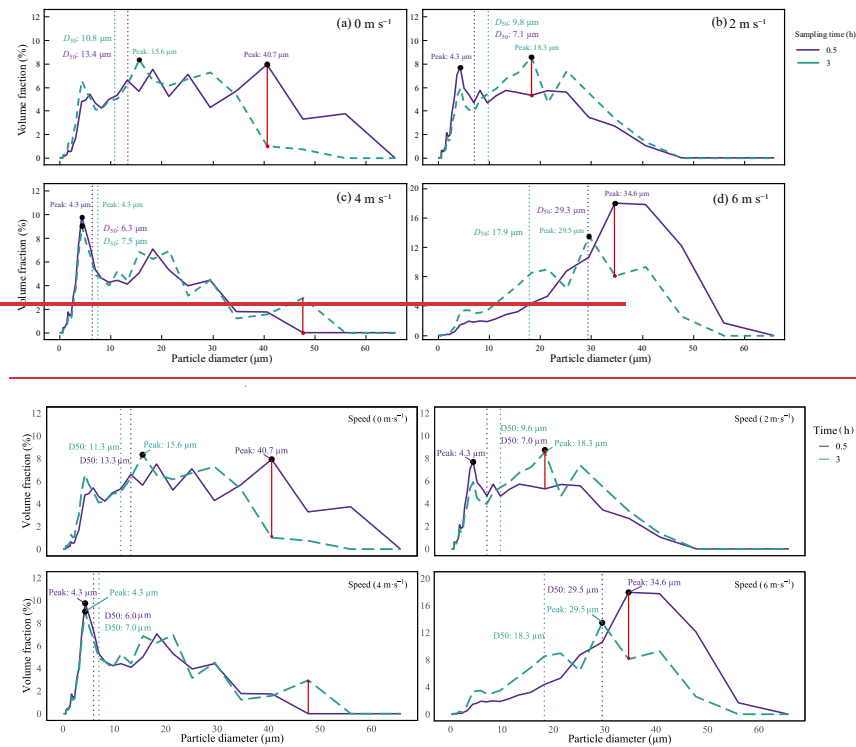


Figure 4. Comparison of the volume-based particle-size distributions (PSDs) of cumulative tray-retained dust collected at 0.5 and 3 h under deposited particle size distributions (PSDs) between rapid (0–0.5 h) and slow (0.5–3 h) deposition phases under different wind speeds. The curves show differential volume fractions at the particle-size channels measured by laser diffraction. Solid purple and dashed teal curves represent samples collected at 0.5 and 3 h, respectively. Filled black circles indicate the modal diameters (“Peak”). Dotted vertical lines mark D_{50} , calculated by log-linear interpolation of the normalized cumulative volume distribution. The red vertical segment marks Δ_{max} , defined as the particle diameter at which the absolute difference in volume fraction between the two

sampling times was greatest. For each wind speed, the PSD for the two phases are compared. The red vertical line (Δ_{max}) connects the size with the maximal volume fraction difference. "Peak" indicates the modal diameter. Dashed lines mark the median diameter (D_{50}) for each phase.

The particle-size distribution (PSD) of deposited net accumulation dust changed evolved distinctly between the rapid (0–0.5 h) and slow (0.5–3 h) deposition phases, reflecting in a wind-speed-dependent and size-selection manner (Fig. 4).

Under quiescent conditions ($0 \text{ m} \cdot \text{s}^{-1}$), the cumulative material collected deposited particles at 0.5 h were showed a prominent coarse mode, concentrated around $40 \text{ } \mu\text{m}$ with ($D_{50} D_{90} = 13.3\text{--}4 \text{ } \mu\text{m}$, peak-modal diameter $\approx 40.7 \text{ } \mu\text{m}$). By 3 h, the relative contribution of particles $> 30 \text{ } \mu\text{m}$ had decreased markedly largely settled, while the PSD contracted into a unimodal distribution dominated by $10\text{--}20 \text{ } \mu\text{m}$ range accounted for a larger fraction of the cumulative retained material particles ($D_{50} D_{90} = 10.8\text{--}3 \text{ } \mu\text{m}$, peak-modal diameter $\approx 15.6 \text{ } \mu\text{m}$). This temporal change is consistent with sequence confirms a gravity-dominated regime where that coarse particles deposit first, followed by medium-sized particles.

Under low wind ($\Delta t 2 \text{ m} \cdot \text{s}^{-1}$), the median diameter $D_{50} D_{90}$ increased from $7.0\text{--}1 \text{ } \mu\text{m}$ at 0.5 h (rapid-phase) to $9.6\text{--}8 \text{ } \mu\text{m}$ at 3 h (slow-phase), representing with a an increase of approximately 37 38% increase. The modal diameter shifted from 4.3 to $18.3 \text{ } \mu\text{m}$, while volume fraction at $18.3 \text{ } \mu\text{m}$ increased from 5.3% to 8.6%. These changes This was accompanied by an increased volume fraction at $18 \text{ } \mu\text{m}$ (from 6 % to 12 %), indicating progressive enrichment of medium-sized particles in the cumulative retained material under weak shear, a clearer enrichment of medium-sized particles compared to still air. Weak shear thus enhances the deposition of fine particles initially and selectively enriches medium-sized particles later.

Under moderate wind ($\Delta t 4 \text{ m} \cdot \text{s}^{-1}$), the PSDs for the rapid and slow phases were nearly identical, both exhibiting a narrow, persistent p modal diameter peak at $4\text{--}5 \text{ } \mu\text{m}$, with $D_{50} D_{90}$ increasing only slightly from $6.0\text{--}3 \text{ } \mu\text{m}$ at 0.5 h to $7.0\text{--}5 \text{ } \mu\text{m}$ at 3 h. The similarity between the two distributions This indicates that a the fine-particle-dominated size spectrum is was established rapidly and remains stable, with subsequent deposition accumulating materials of nearly identical composition early and changed moderately during the remainder of the experiment.

Under strong wind ($\Delta t 6 \text{ m} \cdot \text{s}^{-1}$), the cumulative material collected at early deposition (0–0.5 h) was dominated by $30\text{--}40 \text{ } \mu\text{m}$ particles, with ($D_{50} D_{90} = 29.5\text{--}3 \text{ } \mu\text{m}$, peak-modal diameter $\approx 34.6 \text{ } \mu\text{m}$). By the slow phase (0.5– Δt 3 h), D_{50} decreased to $17.9 \text{ } \mu\text{m}$ and the spectrum shifted towards smaller sizes: the primary peak-modal diameter moved to approximately $\sim 29.5 \text{ } \mu\text{m}$, D_{90} decreased to $18.3 \text{ } \mu\text{m}$, accompanied by a broader contribution from particles a secondary peak emerged in the $10\text{--}20 \text{ } \mu\text{m}$ range. This pattern is consistent with a greater early contribution of coarse particles, followed by an increased relative contribution of finer particles in the cumulative retained material. This demonstrates that under strong shear, coarse particles deposit preferentially early on, with a limited contribution from finer particles later.

In summary, the cumulative evolution of deposited PSDs reveals distinct regimes among wind-speed treatments: gravity-controlled sequential settling in still air; shear-enhanced selective enrichment of fine-medium particles at $2 \text{ m} \cdot \text{s}^{-1}$; rapid establishment of a stable, fine-dominated spectrum at $4 \text{ m} \cdot \text{s}^{-1}$; and a large early relative contribution of coarse particles preferential coarse deposition followed by a modest shift to finer sizes at $6 \text{ m} \cdot \text{s}^{-1}$.

4. Discussion

设置了格式: 字体颜色: 深红

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: 非倾斜

4.1 Non-monotonic response of dust ~~net accumulation~~deposition to low wind speeds

These large-scale closed-circuit wind tunnel experiments suggest a non-monotonic tendency and size-selective response of near-surface dust deposition to low wind speeds ($0\text{--}6\text{ m s}^{-1}$). The first-order exponential model $M(t) = a \cdot (1 - e^{-kt})$ captured the cumulative deposition for all size–wind combinations, indicating that net dust deposition can be approximated as a first-order kinetic process governed by a single effective time scale $\tau = 1/k$. The rate coefficient k and its reciprocal τ therefore provide robust dynamical metrics for comparing tray-retained accumulation responsesdeposition efficiencies across conditions.

Kinetic parameters show a consistent pattern. Deposition in still air is slow and largely controlled by gravitational settling. The introduction of weak turbulence at 2 m s^{-1} significantly accelerates early net accumulationthe deposition of fine-to-medium particles without substantially reducing the asymptotic retained massmaximum deposition of medium-to-coarse particles, creating a distinct low-wind “window” for rapid and efficient dust accumulationdeposition. Quadratic fits of the initial net accumulationdeposition flux $J_0 = ak = a/k$ indicate a low-wind optimum at $\approx 2\text{--}3\text{ m s}^{-1}$, with the strongest response at the experimental level of 2 m s^{-1} . As wind speed increases to $4\text{--}6\text{ m s}^{-1}$, resuspension and horizontal transport may increasingly constrain the mass budget of fine-to-medium particles, strongly suppressing their net deposition and shifting the deposition flux towards a coarse-particle-dominated regime.

Size-resolved PSD evolution further elucidates the size-selective nature of this response. In still air, the cumulative retaineddeposition spectrum evolves sequentially from coarse to finer particles. Under weak shear (2 m s^{-1}), the median diameter (D_{50}) increased from 7.1 to $9.8\text{ }\mu\text{m}$ and the relative contribution near $18.3\text{ }\mu\text{m}$ increased}shifts towards the $10\text{--}20\text{ }\mu\text{m}$ range, suggesting that weak turbulence not only accelerates fine-particle deposition but also facilitates their effective “coarsening” during settling, potentially involvinglikely through aggregation. In contrast, at higher wind speeds ($4\text{--}6\text{ m s}^{-1}$), the deposition spectrum is rapidly stabilized after an initial removal phase, entering a quasi-steady state with limited additional tray-retained accumulationminimal-total deposition and a gradual spectral shift back toward finer sizes, reflecting the strong suppression of net deposition for fine-to-medium particles.

Synthesizing kinetic parameters and PSD evolution, these lines of evidence show that deposition efficiency is lowest in calm air, optimal around 2 m s^{-1} , and reduced at higher speeds. This low-wind window primarily benefits fine-to-medium particles, whereas for coarse particles it mainly maintains, rather than greatly enhances, their deposition capacity.

4.2 Potential mechanisms underlying the observed accumulationdeposition patterns

4.2.1 Roles of turbulent mixing and gravitational settling

For the respirable fine particles ($2\text{--}10\text{ }\mu\text{m}$) central to this study, gravitational settling velocities (w_s) estimated using the Stokes–Cunningham relationship and a representative mineral-particle density of 2650 kg m^{-3} , are approximately $0.35\text{--}8.1$ only on the order of mm s^{-1} . Their ability to penetrate the thin viscous sublayer adjacent to the surface (thickness $z_v \approx 5\nu/u_* \sim 0.2\text{--}0.4\text{ mm}$)} depends critically on the efficiency of turbulent diffusion, expressed by the magnitude of the turbulent diffusive flux $\overline{w'c'}$, expressed by the magnitude of the turbulent diffusive flux $\overline{\omega^2 c^2}$, rather than on gravity alone. The profile-derived apparent friction velocities (u_*) were 0.063 , 0.089 , and 0.154 m s^{-1} at nominal wind speeds of 2 , 4 , and 6 m s^{-1} , respectively. The corresponding nominal near-wall viscous length scales, estimated as $z_v \approx 5\nu/u_*$, where $\nu = 1.5 \times 10^{-5}\text{ m}^2\text{ s}^{-1}$ is the kinematic

设置了格式: 上标

设置了格式: 字体: (默认) Times New Roman

设置了格式: 上标

设置了格式: 上标

设置了格式: 上标

viscosity of air, were approximately 1.20, 0.85, and 0.49 mm.

The relative importance of gravitational settling versus turbulent diffusion can be quantified by the Rouse number, $P = \frac{\omega_s}{\kappa u_*}$. For particle diameters of 2–10 μm and the friction velocities (u_*) measured in our study (0.198, 0.297, and 0.394 m s^{-1} at 2, 4, and 6 m s^{-1} , respectively), P falls in the ranged from approximately 10^{-3} – 10^{-1} 0.006 to 0.32 and decreases-decreased with increasing wind speed for a given particle size. These values below unity support an important role of turbulent mixing relative to gravitational settling, particularly for finer particles and at higher wind speeds. This confirms that turbulent diffusion becomes increasingly dominant over settling for a given particle size as wind speed increases.

This framework explains the observed optimum: at 2 m s^{-1} , turbulence is may have been sufficient to efficiently transport fine particles from the core flow to the top of the viscous sublayer, supporting particle transfer toward the near-surface region maintaining a finite downward flux, yet insufficient to induce substantial resuspension. This creates favorable conditions for deposition. At higher wind speeds (4–6 m s^{-1}), stronger turbulent mixing could prolong particle suspension and enhance horizontal redistribution near the surface, although turbulence transport to the surface remains vigorous, the increased shear stress at the top of the viscous sublayer may promote resuspension and horizontal advection of particles that have reached the near-surface region. This results in high initial deposition rates (large k) but a severely limited ultimate deposition capacity (small a), as observed in this study.

4.2.2 Possible contribution of S shear-induced aggregation and effective particle growth

The PSD of cumulative retained material deposited PSD at 2 m s^{-1} showed the most unique in exhibiting a pronounced temporal enrichment in shift towards the 10–20 μm range. This “effective coarsening” may reflect shear-induced aggregation together with cannot be explained size-selective transport and retention by turbulent transport alone and points to the role of shear-induced aggregation. The increase in the median diameter (D_{50} , D_w) of cumulative deposited material increased from approximately ~7.0–1 μm (0–at 0.5 h) to ~9.6–8 μm (0.5–at 3 h). Under an equivalent-sphere approximation, the characteristic volumes associated with these two diameters differ by a factor of approximately 2.6, of the same order as the combined volume of 2–3 similarly sized primary particles. This geometric comparison is consistent with limited particle clustering, although size-selective deposition and retention could also produce the observed PSD change, corresponds to an effective volume increase by a factor of approximately 2.6, which could be achieved if a fraction of the fine particles deposited as small clusters of only 2–3 primary particles.

This behavior is qualitatively consistent with studies of two-phase turbulent flows and cohesive particles, which often report a non-monotonic relationship between aggregate size and shear intensity, with an optimum intermediate turbulence intensity. Moderate shear can enhance collision frequencies and adhesion, forming transient clusters that increase the ensemble’s settling velocity, while stronger shear leads to cluster breakup and reduced net settling (Tian & Ahmadi, 2007; Mietta et al., 2009; Yu et al., 2022; Penlou et al. 2023; Zhao et al. 2023).

While our experimental setup did not allow for direct observation of aggregate morphology, the concurrent evidence markedly reduced τ , elevated k , and the distinct spectral shift at 2 m s^{-1} strongly suggests that the enhanced deposition of fine particles is at least partially assisted by shear-related aggregation processes. We therefore posit this as a plausible working hypothesis. Future

设置了格式: 上标

studies employing microscopic imaging or in situ cluster statistics are needed to directly quantify this mechanism and its contribution to net deposition.

4.2.3 The possible roles of re-entrainment and horizontal redistribution resuspension

When wind speed increases to 4–6 m s⁻¹, the fitted accumulation-deposition kinetics differed exhibit characteristics clearly distinct from those observed at 2 m s⁻¹. For fine-to-medium particles (1–10 μm), k_a remained relatively high, whereas the asymptotic retained mass a and initial net accumulation flux J_0 declined substantially. This combination represents a rapid approach to a lower retained-mass asymptote. The auxiliary screening test identified an apparent critical wind-speed range of 5.87–6.01 m s⁻¹ for marked dust mobilization from the dust surface (Fig. S1). The cumulative mass curves over the initial 0.5 h remain relatively steep, and the corresponding rate constants k are not small, indicating that particles are still transported rapidly into the vicinity of the trays and that their contact frequency with the sampling surface is not reduced. However, the asymptotic deposition a decreases markedly with increasing wind speed over time. In contrast, for particles in the 10–20 μm range, a at 6 m s⁻¹ treatment lay within this range, making particle rebound and local re-entrainment plausible contributors to the reduced retention. In contrast, the 4 m s⁻¹ treatment remained well below the apparent critical range. Its lower tray-retained mass, together with the higher late-stage airborne concentration, is more consistent with continued suspension, recirculation, horizontal redistribution, and reduced stable retention is slightly higher than under still air, but the characteristic time scale lengthens substantially; these particles can still complete deposition, but over a longer duration. This pattern is consistent with a regime in which enhanced near surface shear and turbulence deliver particles to the surface efficiently (large k) while simultaneously increasing the likelihood of rebound and/or removal from the trays, thereby limiting net retained mass (small a). Because upward resuspension fluxes were not directly measured, the relative contributions of resuspension versus horizontal export cannot be separated here and should be tested in future work.

This wind-speed dependence of feedback on net accumulationdeposition aligns with previous observations of mineral dust dry deposition and resuspension (Goossens and Rajot, 2008; Bergametti et al., 2018; Waza et al., 2019). Field intercomparisons of various passive samplers have demonstrated that dust deposition flux does not always increase monotonically with wind speed; at certain sites and for specific sampler types, apparent net deposition even decreases with increasing wind speed. This inverse relationship is typically attributed to enhanced resuspension fluxes from the surface bed, coupled with increased undercatch of coarse particles by some samplers under high wind conditions (Goossens and Rajot, 2008; Waza et al., 2019). Similarly, wind-tunnel experiments and size-resolved field measurements indicate that near the onset of active wind erosion, particle dry deposition velocities become highly sensitive to friction velocity, surface roughness, and near-surface turbulent structure (Zhang et al., 2014; Bergametti et al., 2018; Waza et al., 2019).

The friction velocities corresponding to 4–6 m s⁻¹ in our experiments fall within ranges typically associated with markedly enhanced wind erosion initiation in loess and agricultural soils (Shao, 2008; Sweeney & Mason, 2013). Within this wind-speed interval, increasing near-surface shear stress and turbulence intensity enhance particle delivery to the surface while simultaneously intensifying rebound and resuspension. As a result, a substantial fraction of fine to medium particles that have just deposited or are nearing deposition are lifted back into the flow and transported away

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置, 非突出显示

设置了格式: 字体颜色: 自动设置, 非突出显示

设置了格式: 字体颜色: 自动设置, 非突出显示

设置了格式: 字体颜色: 自动设置, 非突出显示

设置了格式: 字体颜色: 深红

from the sampling area, leading to a pronounced suppression of net fine particle deposition efficiency (Goossens & Rajot, 2008; Zhang et al., 2014; Waza et al., 2019).

4.3 Implications for dust dry-deposition parameterizations and dust budget assessment

Conventional parameterizations of particle dry deposition commonly calculate assume that for a given particle size and surface type, deposition velocity as a prescribed function of particle size, increases monotonically with wind speed or friction velocity, surface roughness, and land-cover type, or at most saturates, while rebound and resuspension is are either represented using separate treated as an independent flux or represented through simplified empirical coefficients treatments (Zhang et al., 2003; Goossens & Rajot, 2008; Petroff & Zhang, 2010; Kouznetsov & Sofiev, 2012; Zhang & He, 2014; Zhang & Shao, 2014; Khan & Perlinger, 2017; Zeng et al., 2020). Although resistance Classical particle-deposition frameworks account for particle-size-dependent transport and surface collection processes (Slinn, 1982; Wesely, 1989), although the level of process detail differs among parameterizations. Numerical studies of particle-laden turbulent flows further show that predicted deposition rates are sensitive to turbulence closure, boundary conditions, and the treatment of near-wall velocity fluctuations (Tian & Ahmadi, 2007). However, these frameworks provide limited constraints on time-dependent net surface accumulation under low-wind conditions, provide detailed descriptions of size dependence and surface heterogeneity, they typically do not explicitly account for the “flux peak” and “regime shift” phenomena observed in low-wind, weak-turbulence conditions.

Observational studies, parameterization intercomparisons, and model-sensitivity experiments have demonstrated substantial uncertainty in particle dry deposition. Widely used Recent observational and re-parameterization studies (Petroff & Zhang, 2010; Adebisi & Kok, 2020; Emerson et al., 2020; Farmer et al., 2021) have demonstrated that insufficiently detailed treatment of turbulence intensity and near surface processes can cause models to may overestimate dry-deposition rates of accumulation-mode particles, while underestimating coarse particle deposition over terrestrial surfaces (Petroff & Zhang, 2010; Adebisi & Kok, 2020; Adebisi & Kok, 2020; Emerson et al., 2020; Farmer et al., 2021). Such size-dependent biases can affect simulated, resulting in systematic biases in aerosol lifetime, atmospheric burden, and radiative forcing (Emerson et al., 2020). In dust simulations, differences in the representation of surface resistance, impaction collection, and particle rebound can also produce large differences in dry-deposition fluxes and atmospheric dust loading (Zeng et al., 2020).

To quantify the departure from a non-decreasing wind-speed response, make the sign and magnitude of the implied bias explicit under a strictly monotonic wind speed dependence, the observed initial net accumulation deposition flux J_0 was compared against a non-decreasing benchmark $J_{0,mono}$. For the $PM_{2.5}$ – PM_{40} cumulative classes, the observed J_0 values at 2 m s^{-1} exceeded the benchmark by approximately 15–72% ($R = 1.15$ – 1.72). The resulting ratios $R = J_0/J_{0,mono}$ (Table S3) indicate that, for $PM_{2.5}$ – PM_{40} at $U = 2\text{ m s}^{-1}$ exceeds the monotonic benchmark by about 15–72% ($R = 1.15$ – 1.72), implying that strictly monotonic schemes would underpredict early-stage deposition at low wind speeds. In contrast, at $U = 6\text{ m s}^{-1}$, J_0 falls 45–91% below the monotonic benchmark ($R = 0.09$ – 0.55), corresponding to an implying substantial overestimation overprediction of net deposition under stronger low end winds (by factors of approximately 1.8–11 for the affected size classes). Deviations are smaller for PM_{63} ($R \approx 0.77$ at 6 m s^{-1}), suggesting that the non-monotonic response is most pronounced for fine-to-

设置了格式: 字体: (默认) Times New Roman

设置了格式: 字体: (默认) Times New Roman

设置了格式: 非突出显示

设置了格式: 非上标/下标, 非突出显示

设置了格式: 非突出显示

设置了格式: 非突出显示

设置了格式: 非突出显示

设置了格式: 非突出显示

设置了格式: 字体: Times New Roman, 非倾斜, 非突出显示

设置了格式: 非突出显示

设置了格式: 非突出显示

设置了格式: 字体: (默认) Times New Roman

medium particles in the present setup.

This study yields several quantitative insights relevant to dry-deposition parameterizations in the low-wind regime: (i) a distinct peak in the initial ~~net accumulation deposition~~-flux- J_0 occurs at approximately 2 m s^{-1} under ~~the experimental uniform surface~~ conditions, whereas speeds of $4\text{--}6 \text{ m s}^{-1}$ ~~substantially reducesignificantly suppress~~ net deposition of fine-~~to-medium~~ particles; (ii) kinetic time scales vary non-monotonically, with the characteristic time τ for fine particles reaching a minimum at $2\text{--}4 \text{ m s}^{-1}$ while the ~~fitted asymptotic retained massultimate maximum deposition~~ a declines sharply at $4\text{--}6 \text{ m s}^{-1}$, indicating that deposition rate and eventual deposited fraction do not vary synchronously with wind speed; (iii) distinct temporal evolution of the PSD emerges, with rapid progression toward the $10\text{--}20 \text{ }\mu\text{m}$ range at 2 m s^{-1} contrasted against early spectral stabilization at $4\text{--}6 \text{ m s}^{-1}$.

These findings complement multi-sampler comparison studies at the Izaña mountain station and evaluations of deposition schemes over rough surfaces (Bergametti et al., 2018; Waza et al., 2019). While previous studies highlighted flux-closure issues from an observation-parameterization discrepancy standpoint, our controlled experiments provide process-level understanding of wind-speed influences. ~~Collectively, these studies demonstrate that representing dry deposition velocity as a monotonic function of wind speed within the $0\text{--}6 \text{ m s}^{-1}$ range is fundamentally inadequate. Future parameterizations should incorporate size-dependent deposition maxima within weak-turbulence windows and explicitly resolve regime transitions near the resuspension threshold.~~

For numerical simulations, the size-resolved a , k , τ , and J_0 values provide empirical constraints on the temporal response of effective surface retention under matched dust and surface conditions. Existing size-resolved dry-deposition schemes describe particle removal as a function of particle size, friction velocity, surface roughness, and surface collection properties, while model evaluations have demonstrated substantial sensitivity to the treatment of collection efficiency and particle rebound (Petroff and Zhang, 2010; Zhang and Shao, 2014; Khan and Perlinger, 2017; Zeng et al., 2020). In a coupled parameterization, k and τ characterize the adjustment timescale, a describes the fitted asymptotic retained mass under a specified initial dust loading, and J_0 constrains the initial net surface flux. The observed response supports coupling conventional particle deposition with wind and size-dependent stable retention and a surface-specific, threshold-dependent re-entrainment term. The high J_0 near 2 m s^{-1} and its decline toward 6 m s^{-1} provide benchmark behavior for evaluating such coupled parameterizations across the low-wind regime.

From a global dust cycle perspective, this non-monotonicity implies that net dry deposition in source regions under low post-dust wind conditions may be substantially higher than currently modeled, resulting in more rapid atmospheric dust load reduction and shorter effective transport distances. Conversely, under elevated background winds or complex topography, resuspension can extend fine particle residence time and enhance long-range transport fractions. These interpretations align with recent observationally constrained reassessments of dust size distributions and climatic impacts (Kok et al., 2017; Adebisi & Kok, 2020; Emerson et al., 2020; Kok et al., 2021, 2023), which consistently identify model tendencies to underestimate coarse dust and near-source deposition while overestimating long-range transport and remote ocean dust burdens. Systematic underestimation of accumulation-mode and coarse particle deposition under weak-to-moderate turbulence would weaken near-source depositional sinks in models, likely resulting in overestimated dust load and radiative effects in remote oceanic and high-latitude regions.

4.4.4 Uncertainties and future work

Despite controlled experimental conditions with wind speed as the primary variable, several limitations should be acknowledged. First, the use of a single agricultural soil dust ($<63\text{ }\mu\text{m}$), though mineralogically and adhesively representative of specific source regions, limits immediate generalization to dust from other origins, such as desert crusts, loess, or urban construction materials. Differences among dust materials may influence the observed kinetics through variations in airborne particle-size distribution, particle density and morphology, mineral composition, interparticle cohesion, and initial aggregation state. Coarser or denser particles would generally be expected to settle more rapidly, potentially producing a larger initial net accumulation flux J_0 , a shorter characteristic time τ , and a more gravity-dominated response. Finer, lower-density, or more porous particles may remain suspended for longer periods (Richards-Thomas and McKenna Neuman, 2020). Mineralogy, specific surface area, and surface chemistry may further modify particle cohesion and aggregation. A stronger tendency to aggregate under weak shear could increase the effective settling size, whereas aggregate breakup under stronger shear could reduce retained mass (Mietta et al., 2009; Yu et al., 2022; Penlou et al., 2023). Consequently, both the magnitude of the observed low-wind maximum and the wind speed at which it occurs may vary among dust types, which may exhibit substantially different aggregation potential and resuspension thresholds. Future investigations should incorporate diverse dust types to evaluate the universality of the identified “optimal low wind deposition” phenomenon.

Second, tray-retained mass characterizes effective near-surface retention under the present closed-circuit wind-tunnel and collector configuration. Particles outside the tray-retained fraction may have remained in recirculation or deposited on the side walls, ceiling, turning vanes, fan assembly, steel cover plate, and other internal surfaces, which were not quantified. The tray dimensions, 3 cm rim, smooth acrylic surface, and progressive removal of trays may also have affected local flow separation, particle rebound, and re-entrainment. The same initial layout, time-specific tray assignments, and retrieval sequence were used for all treatments, supporting comparisons among wind speeds. Absolute retained masses may vary for natural surfaces or other collector geometries.

Third, soil moisture was not investigated as an independent experimental variable. The sieved dust was oven-dried at 105°C for 8 h before each experiment, and the reported kinetics therefore represent dry dust conditions. Residual gravimetric water content was not measured after oven drying. Soil moisture can modify interparticle cohesion, the threshold wind speed for particle mobilization, aggregation, particle-surface adhesion, and resistance to re-entrainment (Fécan et al., 1999; Shao, 2008; Kok et al., 2012). Because the same dust batch and drying procedure were used for all wind-speed treatments, moisture differences are unlikely to explain the observed differences among treatments. However, the magnitude of the low-wind maximum and the wind speed at which it occurs may differ under moist field conditions.

Finally, particle shape was not independently characterized. Mineral dust particles are commonly non-spherical, and their flatness, elongation, and orientation can alter aerodynamic drag and settling velocity (Ginoux, 2003; Bagheri and Bonadonna, 2016). Consequently, volume-equivalent diameter alone does not fully describe the aerodynamic behavior of particles within each cumulative diameter-threshold class. Particle shape may have influenced aerodynamic transport, settling velocity, and surface retention, thereby affecting the absolute retained mass and fitted kinetic descriptors. Future experiments combining laser diffraction with microscopic measurements of

设置了格式: 字体: 倾斜

设置了格式: 字体: (默认) + 西文正文 (等线), (中文) + 中文正文 (等线), 突出显示

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

带格式的: 缩进: 首行缩进: 2 字符

设置了格式: 非突出显示

aspect ratio and sphericity would allow this effect to be quantified.

5. evidence for shear-induced aggregation remains indirect, derived from deposition kinetics and PSD evolution rather than direct morphological, fractal, or structural characterization of aggregates. Critical parameters including Kolmogorov scales and collision frequencies as functions of wind speed were not explicitly quantified. While observed fine-particle deposition enhancement under weak turbulence is qualitatively consistent with aggregation mechanisms, the quantitative contribution of aggregation to effective settling velocities remains unconstrained. Subsequent research should integrate microscopic imaging, light-scattering spectroscopy, and in situ cluster statistics to characterize deposit structure across wind regimes, enabling direct comparison between experimental cluster size distributions and two-phase turbulence simulations.

5. Conclusions

This study quantified size-resolved net accumulation of mineral dust dry deposition in a closed-circuit recirculating wind tunnel under calm air and low winds ($0\text{--}6\text{ m s}^{-1}$). Across all size-wind combinations, the temporal evolution of cumulative deposited-retained mass was well described by a first-order approach-to-asymptote model ($R^2 > 0.91$), enabling extraction of an asymptotic cumulative retained mass deposition (a), effective net-accumulation rate deposition rate coefficient (k), characteristic time-scale ($\tau = 1/k$), and initial net accumulation deposition flux ($J_0 = ak$). These kinetic descriptors provide size-resolved empirical constraints on the temporal response of effective surface retention provide a compact, process-oriented representation of deposition dynamics that can be compared directly against dry-deposition schemes.

Within the tested wind-speed range, fine-to-medium size classes ($\text{PM}_{2.5}\text{--}\text{PM}_{10}$) show their highest net accumulation deposition at 2 m s^{-1} and lower accumulation reduced net deposition at higher winds, with the strongest evidence for a peaked J_0 response in the $\text{PM}_{30}\text{--}30\text{ }\mu\text{m}$ class. The fitted parameters indicate that increasing wind speed can accelerate the approach to the fitted asymptote enhance the early time delivery of particles to the surface (larger k ; shorter τ), while the ultimate retained mass on the collection surfaces (a) declines at higher winds within the tested range may decrease under higher low-end winds. Quadratic fits across the four wind-speed levels suggest a potential maximum in J_0 net deposition near $2\text{--}3\text{ m s}^{-1}$ for several size classes, but the inferred peak location remains tentative given the limited number of wind-speed treatments.

A conceptual interpretation consistent with these patterns is that an intermediate low-wind regime provides sufficient turbulent transport to promote particle transfer and stable retention deposition while shear-driven particle rebound, re-entrainment, and horizontal redistribution export remain comparatively limited; at higher winds, these competing processes may increasingly constrain the retained deposited mass, effectively decoupling deposition rate from asymptotic loading. Because resuspension fluxes and near-surface particle dynamics were not directly measured in this setup, the relative contributions of rebound/resuspension versus horizontal export cannot be distinguished here and should be evaluated in future experiments with concurrent concentration and flux measurements.

Overall, these measurements offer process-based constraints on low-wind dust accumulation dust deposition in the low wind regime and motivate refinement of dry-deposition parameterizations to represent the possibility of non-monotonic behavior and size-dependent regime shifts. Extending this framework to more realistic boundary-layer turbulence and heterogeneous

带格式的: 缩进: 左侧: 0 厘米, 悬挂缩进: 2 字符, 首行缩进: -2 字符, 段落间距段前: 0.5 行, 段后: 0.5 行

设置了格式: 字体: 倾斜

surfaces ~~heterogeneity~~ will require targeted observations and simulations ~~that explicitly resolve~~ of
near-surface ~~particle exchange~~ transport, retention, and re-entrainment processes.

Supplement

The supplement related to this article is available online and includes [Figs. S1–S2](#) and Tables
~~S1–S3~~ [S4](#).

Data availability

The data and analysis code supporting this study are archived on Zenodo
(<https://doi.org/10.5281/zenodo.2182561618264330>). The files are under embargo until 30
December 2026, after which they will be made publicly available.

Acknowledgements

This study was supported by the Open Project of Inner Mongolia Academy of Forestry Science
(KF2024ZD08), the Natural Science Foundation of Inner Mongolia (2024LHMS03039), the
National Natural Science Foundation of China (32401668, 42377458) and the China Postdoctoral
Science Foundation (2024M753463). We thank the Experimental Center of Desert Forestry, Chinese
Academy of Forestry, for providing the experimental facilities and technical support.

Author contribution

Zhimin Liu, Zhigang Wang, Yuan Liu, and Zhiming Xin conceived the research idea and
contributed to the experimental design. Ruochen Jia led the experimental design and execution,
performed the data analysis, and wrote the first draft of the manuscript. Chaoqun Ba contributed
substantially to the experiments, data processing, and manuscript preparation. Chao Zhang
contributed to data analysis and interpretation. Yuting Liu, Qun Ma, Wei Liang and Lu Zong assisted
with part of the experimental work. Wennong Kuang and Fang Liu provided critical revisions and
constructive comments that improved the manuscript. Jianqiang Qian and Zhimin Liu supervised
the study. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no conflicts of interest.

References

- [1] Adebisi, A. A., & Kok, J. F. (2020). Climate models miss most of the coarse dust in the atmosphere. *Science Advances*, 6(15), eaaz9507. <https://doi.org/10.1126/sciadv.aaz9507>
- [2] Bergametti, G., Marticorena, B., Rajot, J.-L., Forêt, G., Alfaro, S. C., & Laurent, B. (2018). Size-resolved dry deposition velocities of dust particles: In situ measurements and parameterizations testing. *Journal of Geophysical Research: Atmospheres*, 123(19). <https://doi.org/10.1029/2018JD028964>
- [3] Bagheri, G., & Bonadonna, C. (2016). On the drag of freely falling non-spherical particles. *Powder Technology*, 301, 526–544. <https://doi.org/10.1016/j.powtec.2016.06.015>
- [2] ~~Donato, A., & Contini, D. (2014). Correlation of dry deposition velocity and friction velocity over different surfaces for PM2.5 and particle number concentrations. *Advances in Meteorology*, 760393. <https://doi.org/10.1155/2014/760393>~~
- [4] Emerson, E. W., Hodshire, A. L., DeBolt, H. M., Bilsback, K. R., Pierce, J. R., McMeeking, G. R., & Farmer, D. K. (2020). Revisiting particle dry deposition and its role in radiative effect estimates. *Proceedings of the National Academy of Sciences*, 117(42), 26076–26082. <https://doi.org/10.1073/pnas.2014761117>
- [5] Farmer, D. K., Boedicker, E. K., & DeBolt, H. M. (2021). Dry deposition of atmospheric aerosols: Approaches, observations, and mechanisms. *Annual Review of Physical Chemistry*, 72, 375–397. <https://doi.org/10.1146/annurev-physchem-090519-034936>
- [6] Fécan, F., Marticorena, B., & Bergametti, G. (1999). Parametrization of the increase of the aeolian erosion threshold wind friction velocity due to soil moisture for arid and semi-arid areas. *Annales Geophysicae*, 17(1), 149–157. <https://doi.org/10.1007/s00585-999-0149-7>
- [7] Gallagher, M. W., Nemitz, E., Dorsey, J. R., Fowler, D., Sutton, M. A., Flynn, M., & Duyzer, J. H. (2002). Measurements and parameterizations of small aerosol deposition velocities to grassland, arable crops and forest: Influence of surface roughness length on deposition. *Journal of Geophysical Research: Atmospheres*, 107(D12), AAC 8-1-AAC 8-10. <https://doi.org/10.1029/2001JD000817>
- [8] Goossens, D. (2006). Aeolian deposition of dust over hills: The effect of dust grain size on the deposition pattern. *Earth Surface Processes and Landforms*, 31(6), 762–776. <https://doi.org/10.1002/esp.1272>
- [8] Goossens, D., & Rajot, J. L. (2008). Techniques to measure the dry aeolian deposition of dust in arid and semi-arid landscapes: A comparative study in West Niger. *Earth Surface Processes and Landforms*, 33(2), 178–195. <https://doi.org/10.1002/esp.1533>
- [9] Ginoux, P. (2003). Effects of nonsphericity on mineral dust modeling. *Journal of Geophysical Research: Atmospheres*, 108(D2), 4052. <https://doi.org/10.1029/2002JD002516>
- [9][10] Jia, R., & Liu, Z. (2026). Quantification of dust deposition in weak turbulent conditions. *Zenodo [data set]*. <https://doi.org/10.5281/zenodo.21825616>
- [10][11] Jickells, T. D., An, Z. S., Andersen, K. K., Baker, A. R., Bergametti, G., Brooks, N., Cao, J. J., Boyd, P. W., Duce, R. A., Hunter, K. A., Kawahata, H., Kubilay, N., LaRoche, J., Liss, P. S., Mahowald, N., Prospero, J. M., Ridgwell, A. J., Tegen, I., & Torres, R. (2005). Global iron connections between desert dust, ocean biogeochemistry, and climate. *Science*, 308(5718), 67–71. <https://doi.org/10.1126/science.1105959>
- [11][12] Khan, T. R., & Perlinger, J. A. (2017). Evaluation of five dry particle deposition

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体, 字体颜色: 深红

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体: (默认) Times New Roman, (中文) 宋体

- parameterizations for incorporation into atmospheric transport models. *Geoscientific Model Development*, 10, 3861–3888. <https://doi.org/10.5194/gmd-10-3861-2017>
- [12][13] Kok, J. F., Adebisi, A. A., Albani, S., Balkanski, Y., Checa-Garcia, R., Chin, M., Colarco, P. R., Hamilton, D. S., Huang, Y., Ito, A., Klose, M., Li, L., Mahowald, N. M., Miller, R. L., Obiso, V., Pérez García-Pando, C., Rocha-Lima, A., & Wan, J. S. (2021). Contribution of the world's main dust source regions to the global cycle of desert dust. *Atmospheric Chemistry and Physics*, 21, 8169–8193. <https://doi.org/10.5194/acp-21-8169-2021>
- [13][14] Kok, J. F., Albani, S., Mahowald, N. M., & Ward, D. S. (2014). An improved dust emission model – Part 2: Evaluation in the Community Earth System Model, with implications for the use of dust source functions. *Atmospheric Chemistry and Physics*, 14, 13043–13061. <https://doi.org/10.5194/acp-14-13043-2014>
- [14][15] Kok, J. F., Parteli, E. J. R., Michaels, T. I., & Karam, D. B. (2012). The physics of wind-blown sand and dust. *Reports on Progress in Physics*, 75(10), 106901. <https://doi.org/10.1088/0034-4885/75/10/106901>
- [15][16] Kok, J. F., Ridley, D. A., Zhou, Q., Miller, R. L., Zhao, C., Heald, C. L., Ward, D. S., Albani, S., & Haustein, K. (2017). Smaller desert dust cooling effect estimated from analysis of dust size and abundance. *Nature Geoscience*, 10, 274–278. <https://doi.org/10.1038/ngeo2912>
- [16][17] Kok, J. F., Storelvmo, T., Karydis, V. A., Adebisi, A. A., Mahowald, N. M., Evan, A. T., He, C., & Leung, D. M. (2023). Mineral dust aerosol impacts on global climate and climate change. *Nature Reviews Earth & Environment*, 4, 71–86. <https://doi.org/10.1038/s43017-022-00379-5>
- [17][18] Kong, S. S.-K., Fu, J. S., Lin, N.-H., Sheu, G.-R., & Huang, W.-S. (2025). Modeling CMAQ dry deposition treatment over the western Pacific: A distinct characteristic of mineral dust and anthropogenic aerosols. *Atmospheric Chemistry and Physics*, 25, 7245–7268. <https://doi.org/10.5194/acp-25-7245-2025>
- [18] Kouznetsov, R., & Sofiev, M. (2012). A methodology for evaluation of vertical dispersion and dry deposition of atmospheric aerosols. *Journal of Geophysical Research: Atmospheres*, 117, D01202. <https://doi.org/10.1029/2011JD016366>
- [19] Maggi, F., Mietta, F., & Winterwerp, J. C. (2007). Effect of variable fractal dimension on the floc size distribution of suspended cohesive sediment. *Journal of Hydrology*, 343, 43–55. <https://doi.org/10.1016/j.jhydrol.2007.05.035>
- [20] Mahowald, N. M., Kloster, S., Engelstaedter, S., Moore, J. K., Mukhopadhyay, S., McConnell, J. R., Albani, S., Doney, S. C., Bhattacharya, A., Curran, M. A. J., Flanner, M. G., Hoffman, F. M., Lawrence, D. M., Lindsay, K., Mayewski, P. A., Neff, J., Rothenberg, D., Thomas, E., Thornton, P. E., & Zender, C. S. (2010). Observed 20th century desert dust variability: Impact on climate and biogeochemistry. *Atmospheric Chemistry and Physics*, 10(22), 10875–10893. <https://doi.org/10.5194/acp-10-10875-2010>
- [21] Mietta, F., Chassagne, C., Manning, A. J., & Winterwerp, J. C. (2009). Influence of shear rate, organic matter content, pH and salinity on mud flocculation. *Ocean Dynamics*, 59, 751–763. <https://doi.org/10.1007/s10236-009-0231-4>
- [22] Mostamandi, S., Ukhov, A., Engelbrecht, J. P., Shevchenko, I., Osipov, S., & Stenchikov, G. (2023). Fine and coarse dust effects on radiative forcing, mass deposition, and solar devices over the Middle East. *Journal of Geophysical Research: Atmospheres*, 128(22),

- e2023JD039479. <https://doi.org/10.1029/2023JD039479>
- [23] Penlou, B., Roche, O., Manga, M., & van den Wildenberg, S. (2023). Experimental measurement of enhanced and hindered particle settling in turbulent gas–particle suspensions and geophysical implications. *Journal of Geophysical Research: Solid Earth*, 128, e2022JB025809. <https://doi.org/10.1029/2022JB025809>
- [24] Petroff, A., & Zhang, L. (2010). Development and validation of a size-resolved particle dry deposition scheme for application in aerosol transport models. *Geoscientific Model Development*, 3(2), 753–769. <https://doi.org/10.5194/gmd-3-753-2010>
- [25] R Core Team. (2023/2024). *R: A language and environment for statistical computing* (Version 4.4.1). [Computer software]. R Foundation for Statistical Computing. <https://www.R-project.org/>
- [25][26] Richards-Thomas, T., & McKenna-Neuman, C. (2020). Laboratory investigation of particle-scale factors affecting the settling velocity of volcanoclastic dust. *Journal of Geophysical Research: Atmospheres*, 125(17), e2020JD032660. <https://doi.org/10.1029/2020JD032660>
- [26][27] Saylor, R. D., Baker, B. D., Lee, P., Tong, D., Pan, L., & Hicks, B. B. (2019). The particle dry deposition component of total deposition from air quality models: Right, wrong or uncertain? *Tellus B: Chemical and Physical Meteorology*, 71(1), 1–22. <https://doi.org/10.1080/16000889.2018.1550324>
- [27][28] Shao, Y. (2008). *Physics and modelling of wind erosion* (2nd ed.). Springer. <https://doi.org/10.1007/978-1-4020-8895-7>
- [28][29] Shao, Y., Raupach, M. R., & Findlater, P. A. (1993). Effect of saltation bombardment on the entrainment of dust by wind. *Journal of Geophysical Research*, 98, 12719–12726. <https://doi.org/10.1029/93JD00396>
- [29][30] Slinn, W. G. N. (1982). Predictions for particle deposition to vegetative canopies. *Atmospheric Environment*, 16(7), 1785–1794. [https://doi.org/10.1016/0004-6981\(82\)90271-2](https://doi.org/10.1016/0004-6981(82)90271-2)
- [30] Sweeney, M. R., & Mason, J. A. (2013). Mechanisms of dust emission from Pleistocene loess deposits, Nebraska, USA. *Journal of Geophysical Research: Earth Surface*, 118, 1460–1471. <https://doi.org/10.1002/jgrf.20101>
- [31] Tegen, I., & Fung, I. (1994). Modeling of mineral dust in the atmosphere: Sources, transport, and optical thickness. *Journal of Geophysical Research: Atmospheres*, 99(D11), 22897–22914. <https://doi.org/10.1029/94JD01928>
- [32] Tian, L., & Ahmadi, G. (2007). Particle deposition in turbulent duct flows—comparisons of different model predictions. *Journal of Aerosol Science*, 38, 377–397. <https://doi.org/10.1016/j.jaerosci.2006.12.003>
- [33] Waza, A., Schneiders, K., May, J., Rodríguez, S., Epple, B., & Kandler, K. (2019). Field comparison of dry deposition samplers for collection of atmospheric mineral dust: results from single-particle characterization. *Atmospheric Measurement Techniques*, 12, 6647–6665. <https://doi.org/10.5194/amt-12-6647-2019>
- [34] Wesely, M. L. (1989). Parameterization of surface resistances to gaseous dry deposition in regional-scale numerical models. *Atmospheric Environment*, 23(6), 1293–1304. [https://doi.org/10.1016/0004-6981\(89\)90153-4](https://doi.org/10.1016/0004-6981(89)90153-4)
- [35] Wu, C., Lin, Z., & Liu, X. (2020). The global dust cycle and uncertainty in CMIP5 (Coupled Model Intercomparison Project phase 5) models. *Atmospheric Chemistry and Physics*, 20(17),

设置了格式: 字体: 非倾斜

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 字体颜色: 自动设置

设置了格式: 删除线

域代码已更改

- 10401–10425. <https://doi.org/10.5194/acp-20-10401-2020>
- [36] Wu, M., Liu, X., Yu, H., Wang, H., Shi, Y., Yang, K., Darmanov, A., Wu, C., Wang, Z., Luo, T., Feng, Y., & Ke, Z. (2020). Understanding processes that control dust spatial distributions with global climate models and satellite observations. *Atmospheric Chemistry and Physics*, 20(22), 13835–13855. <https://doi.org/10.5194/acp-20-13835-2020>
- [37] Xin, Z., Liu, M., Zhang, J., and Wang, Z. (2024). A vertical expandable comprehensive recirculating wind tunnel for orbital platform (Chinese Patent No. CN117664498A). China National Intellectual Property Administration. Filed December 4, 2023; published March 8, 2024.
- [38] Yu, M., Yu, X., Balachandar, S., & Manning, A. J. (2022). Floc Size Distributions of Cohesive Sediment in Homogeneous Isotropic Turbulence. *Frontiers in Earth Science*, 10, 815652. <https://doi.org/10.3389/feart.2022.815652>
- [39] Zeng, Y., Wang, M., Zhao, C., Chen, S., Liu, Z., Huang, X., & Gao, Y. (2020). WRF-Chem v3.9 simulations of the East Asian dust storm in May 2017: Modeling sensitivities to dust emission and dry deposition schemes. *Geoscientific Model Development*, 13(4), 2125–2147. <https://doi.org/10.5194/gmd-13-2125-2020>
- [40] Zhang, L., & He, Z. (2014). **Technical Note:** An empirical algorithm estimating dry deposition velocity of fine, coarse and giant particles. *Atmospheric Chemistry and Physics*, 14(7), 3729–3737, <https://doi.org/10.5194/acp-14-3729-2014>
- [41] Zhang, J., & Shao, Y. (2014). A new parameterization of particle dry deposition over rough surfaces. *Atmospheric Chemistry and Physics*, 14(22), 12429–12440. <https://doi.org/10.5194/acp-14-12429-2014>
- ~~[42] Zhang, L., Brook, J. R., & Vet, R. (2003). A revised parameterization for gaseous dry deposition in air quality models. *Atmospheric Chemistry and Physics*, 3(6), 2067–2082. <https://doi.org/10.5194/acp-3-2067-2003>~~
- [43][42] Zhang, J., Shao, Y., & Huang, N. (2014). Measurements of dust deposition velocity in a wind-tunnel experiment. *Atmospheric Chemistry and Physics*, 14, 8869–8882. <https://doi.org/10.5194/acp-14-8869-2014>
- [44][43] Zhao, K., Vowinkel, B., Hsu, T.-J., Bai, B., & Meiburg, E. (2023). Cohesive sediment: Intermediate shear produces maximum aggregate size. *Journal of Fluid Mechanics*, 965, A5. <https://doi.org/10.1017/jfm.2023.380>

设置了格式: 字体颜色: 自动设置