Response to Reviewer 2

Manuscript: *Non-monotonic response of net dust deposition kinetics to low wind speeds*
Manuscript No.: egusphere-2026-261

Dear Reviewer,

We sincerely thank you for your careful reading of the manuscript, your positive assessment of the experimental framework, and your constructive comments. Your questions led us to clarify the distinction between gross dry deposition and the cumulative net mass retained by the trays; document the steel-plate isolation of the original dust source; use the available concentration records to test initial-condition comparability and describe suspended-dust persistence; expand the treatment of tunnel-wall losses, recirculation, dust type, moisture, and particle shape; fully revise the wind-profile analysis; correct the median-diameter calculation and the temporal interpretation of Fig. 4; and add a detailed discussion of how the kinetic descriptors can inform numerical parameterizations. The line numbers below refer to the current clean revised manuscript supplied with this response. For clarity, we have numbered the previously unnumbered soil-type comment as Comment 4 and renumbered the subsequent comments consecutively.

General assessment

Reviewer comment:

The present study investigates the quantification of size-resolved dust deposition kinetics in a large closed-circuit wind tunnel. Overall, the manuscript is well written, well organized, and strongly motivated, addressing a genuine and insufficiently constrained problem: the behavior of dry dust deposition under weak, post-storm background wind conditions, where existing parameterizations show large discrepancies and typically assume a monotonic response. The experimental facility is impressive, the kinetic framework provides a sensible and concise approach for summarizing the experimental runs, and the size-resolved analysis represents a notable strength of the study. The finding that deposition rates at 2 m s^{-1} exceed those observed at 0, 4, and 6 m s^{-1} for fine- to medium-sized particles is particularly interesting and may prove valuable for the development and improvement of deposition parameterizations. I have only a few minor comments that should be addressed by the authors before the manuscript is considered for publication.

Response:

We appreciate the reviewer's encouraging assessment. In response to the detailed comments, we retained the central empirical finding but tightened its definition and scope. The experiment measures cumulative mass remaining in untreated floor trays after particle arrival, rebound, local re-entrainment, and removal have all acted; it does not isolate gross downward deposition or directly determine a deposition velocity. Accordingly, the revised title and manuscript describe the experimental quantity as cumulative tray-retained net accumulation. The fitted parameters are now defined as the asymptotic retained mass a, effective net-accumulation rate coefficient k, characteristic time $\tau = 1/k$, and initial net accumulation flux $J_0 = ak$. We removed the old manuscript's equivalent deposition velocity calculation, added the concentration-based sensitivity analysis and the missing experimental details, and reframed the modelling implication as a need to couple conventional deposition with stable retention and re-entrainment.

Specific Comments

Comment 1: Isolation of the source bed and interpretation of reduced retention at 4–6 m s^{-1}

Reviewer comment:

Dust is generated through erosion of the soil source at a wind speed of 14 m s^{-1}, while the source bed remains present on the tunnel floor during the subsequent deposition phases conducted at 2, 4, and 6 m s^{-1}. Under the higher deposition wind speeds, the source bed may continue to emit particles or undergo re-erosion. Consequently, the observed suppression of net deposition at 4–6 m s^{-1} may partly reflect ongoing source emissions rather than the re-entrainment of previously deposited particles. The manuscript attributes this behavior to "resuspension and horizontal export"; however, it does not clearly distinguish between continued emissions from the source bed and the re-entrainment of deposited material. Could the authors please comment on the relative importance of these two processes and discuss how they may affect the interpretation of the results?

Response:

We thank the reviewer for identifying an important procedural detail that was omitted from the manuscript. Immediately after the approximately 5 min loading phase at 14 m s^{-1} and before the target low-wind condition was established, the exposed soil source bed was completely covered with steel plates. The plates remained in place throughout the 0, 2, 4, or 6 m s^{-1} accumulation period. Therefore, continued direct emission or re-erosion from the original source bed was deliberately prevented and should have been negligible during the low-wind measurements. We have added this sequence explicitly to Sect. 2.2.

This source isolation does not eliminate all particle-removal or redistribution processes. The collection trays contained no water, beads, grease, adhesive, or other retention medium. Consequently, particles already suspended in the tunnel could arrive at a tray and subsequently rebound or be locally re-entrained, while other particles could remain suspended, recirculate through the closed loop, move horizontally past the collection area, or deposit on unmeasured internal surfaces. We therefore define the measured quantity as cumulative tray-retained net accumulation, not total deposition.

We also revised the process interpretation to separate the 4 and 6 m s^{-1} cases. An auxiliary tray-scale screening test identified an apparent critical wind-speed range of 5.87–6.01 m s^{-1} for marked particle mobilization. The 6 m s^{-1} treatment lies close to this range, so rebound and local re-entrainment from deposited material are physically plausible contributors to its reduced retention. In contrast, 4 m s^{-1} is well below the apparent mobilization range. At 4 m s^{-1}, the combination of lower tray-retained mass and the highest late-stage residual airborne concentration is more consistent with continued suspension, recirculation, horizontal redistribution, and reduced transfer into stable retention than with new emission from the covered source or threshold-driven re-entrainment alone. Because the experiment did not measure vertical fluxes or separately quantify every internal surface reservoir, we cannot assign numerical fractions to these pathways; the revision now states this limitation rather than attributing the response to a single process.

Photograph of the test section after the original soil source bed was covered with steel plates. The plates remained in place throughout the low-wind accumulation phase.

Location in the revised manuscript: Lines 143–165, 303–305, and 444–454; Supplement, Fig. S1.

Comment 2: Concentration normalization and interpretation of the kinetic quantities

Reviewer comment:

A deposition velocity is defined as $V_d = J/C$. However, the quantities $M(t)$, a, and J_0 appear to be reported as absolute values without dividing by the suspended concentration $C(t)$, which both decays during a run and may differ between runs. The manuscript states that C_0 was recorded "to calibrate the initial-condition comparability across wind-speed treatments" (Lines 155–157) but does not state whether the fitted quantities are normalized by C_0. Could the authors please clarify this point and discuss its implications for the interpretation and comparison of the reported deposition kinetics?

Response:

We thank the reviewer for this kind reminder. We agree that the tray-derived quantities must not be confused with a deposition velocity strictly defined by $V_d = J/C$. The revised manuscript now states explicitly that $M(t)$ is the measured areal cumulative tray-retained mass; a is the fitted asymptotic retained mass; k is the effective rate coefficient governing the approach to that fitted asymptote; $\tau = 1/k$ is the characteristic adjustment time; and $J_0 = ak$ is the initial slope of the fitted retained-mass curve. The units are mg m^{-2} for M and a, h^{-1} for k, h for τ, and mg m^{-2} h^{-1} for J_0.

None of these primary fitted quantities was divided by the time-varying airborne concentration $C(t)$. In particular, J_0 is an initial net accumulation flux into stable tray retention, not a concentration-normalized dry-deposition velocity. A defensible deposition velocity would require concentration at the relevant flux-reference height and an independently resolved downward surface flux or vertical concentration/flux structure. The experiment had only one fixed-point concentration monitor and did not measure a vertical concentration profile. For this reason, we removed the equivalent-deposition-velocity derivation and the associated Vd-based interpretation in the revised manuscript.

The concentration data serve two more limited but useful purposes. First, they establish that the low-wind runs began with comparable suspended dust loading: C_0 was 191.35, 178.20, 186.36, and 189.44 mg m^{-3} at 0, 2, 4, and 6 m s^{-1}, respectively. The range was 178.2–191.4 mg m^{-3} and the coefficient of variation was only 3.1%. Second, we performed an initial-loading sensitivity check by multiplying each retained-mass series by C_{ref}/C_0, where C_{ref} = 186.3 mg m^{-3} is the mean C_0 across treatments. This rescaling did not change the principal wind-speed ordering of the net-accumulation response. It therefore shows that the observed non-monotonic ranking is not an artefact of the small initial-loading differences. The complete 180 min normalized concentration curves and the concentration summary have been added as Fig. S2 and Table S1.

Location in the revised manuscript: Lines 166–175, 218–248, and 310–320; Supplement, Table S1 and Fig. S2.

Comment 3: Wall losses, internal deposition, and recirculation

Reviewer comment:

In the wind tunnel, a wind-speed-dependent fraction of dust may be lost to the walls, ceiling, turning vanes, and fan assembly through inertial impaction, while recirculated air may continue to resupply dust to the test section. At higher wind speeds, deposition may plausibly shift toward vertical or internal tunnel surfaces, meaning that the observed reduction in floor deposition could partly reflect a redistribution of deposited material rather than a reduction in total deposition. The authors are therefore encouraged to address, at least qualitatively, the potential influence of wall losses and recirculation on the reported deposition patterns and their interpretation.

Response:

We agree. The floor-tray measurements are not a closed whole-tunnel deposition budget. The facility is a closed-circuit wind tunnel, so particles that are not retained by the trays may continue to circulate and repeatedly pass through the test section. At the same time, particles may be lost to the side walls, ceiling, turning vanes, fan assembly, steel cover plates, or other internal surfaces. None of those surface reservoirs was measured, and their relative contributions may vary with wind speed and particle size. We have therefore revised the terminology and limitations to make clear that the measured quantity is effective near-surface retention by the floor trays under the present tunnel and collector configuration, rather than total deposition to all tunnel surfaces.

The concentration record helps constrain the interpretation. Initial C_0 values were comparable among treatments (178.2–191.4 mg m^{-3}; coefficient of variation 3.1%), so the relatively high retained mass at 2 m s^{-1} cannot be explained by a higher initial dust loading. During the final 20 min of the 180 min experiment, mean $C(t)/C_0$ was 5.32%, 0.15%, 9.27%, and 4.24% at 0, 2, 4, and 6 m s^{-1}, respectively. Thus, 2 m s^{-1} had the lowest late-stage residual concentration, whereas 4 and 6 m s^{-1} retained more airborne dust, especially at 4 m s^{-1}. In combination with the tray data, this pattern is consistent with greater suspended-dust persistence and reduced effective transfer into stable floor retention at 4–6 m s^{-1}.

We have also moderated the conclusion drawn from this pattern. Lower tray-retained mass at 4–6 m s^{-1} does not demonstrate a proportional reduction in whole-tunnel total deposition. It may reflect a combination of continued suspension, recirculation, horizontal redistribution, local re-entrainment, and deposition onto unmeasured internal surfaces. The single-point concentration series cannot distinguish those pathways or provide a spatial mass balance. The revised manuscript now states both what the concentration data support and what they cannot resolve.

Location in the revised manuscript: Lines 121–130, 166–175, 310–320, 444–454, and 545–553; Supplement, Table S1 and Fig. S2.

Comment 4: Dependence on dust or soil type

Reviewer comment:

The experiments were performed using a cropland/agricultural soil. How different might the results be if other dust soil types had been used? The authors acknowledge this limitation in Section 4.4; however, it would be useful to include some further discussion, or at least qualitative estimates, of how soil type, mineralogy, texture, particle-size distribution, and aggregation state may influence the reported deposition kinetics.

Response:

We thank the reviewer for this helpful suggestion. We have expanded Sect. 4.4 from a brief general limitation into a process-based discussion of how dust properties could affect each aspect of the observed response. The tested material was a single local cropland soil, sampled from 0–5 cm depth and sieved to <63 μm. Therefore, the measured values should not be assumed to apply quantitatively to desert crust, loess, construction dust, or other mineral aerosol sources.

The revised manuscript now gives the following directional expectations. A coarser or denser airborne population would generally have larger gravitational settling velocities and could produce 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 would tend to remain suspended longer. Mineral composition, specific surface area, surface chemistry, and texture can indirectly affect the kinetics through cohesion, particle morphology, and the initial aggregation state. A material with a stronger tendency to aggregate under weak shear could acquire a larger effective settling size and show enhanced retention at an intermediate wind speed. Conversely, breakup of weak aggregates under stronger shear could reduce the retained mass and alter the high-wind response. These material differences could therefore change not only the magnitude of a, k, τ, and J_0, but also the height and wind-speed location of the observed low-wind maximum.

Because only one material was tested, a numerical correction factor would be speculative and is not supported by the present data. We therefore provide physically based qualitative expectations and explicitly call for comparative experiments using dusts with contrasting particle-size distributions, mineralogy, density, morphology, cohesion, and aggregation states.

Location in the revised manuscript: Lines 120–133 and 531–544.

Comment 5: Treatment and implications of soil moisture

Reviewer comment:

I was not able to fully understand whether, and to what extent, the role of soil moisture was considered in the experimental design and analysis. Since soil moisture can influence particle cohesion, threshold friction velocity, dust emission rates, and potentially deposition behavior, its treatment may have important implications for the interpretation of the results. Could the authors please clarify whether soil moisture was measured or controlled during the experiments and discuss its potential impact on the reported deposition kinetics?

Response:

Thank you for this helpful suggestion. Soil moisture was not varied as an independent experimental factor, but the material was subjected to a common dry pretreatment. After air drying and dry sieving to obtain the <63 μm fraction, the dust was oven-dried at 105 °C for 8 h. The same soil material and drying procedure were used for all wind-speed treatments. This procedural control was intended to minimize run-to-run differences in moisture-related cohesion and emission threshold.

Residual gravimetric water content was not measured after oven drying. We therefore describe moisture as operationally standardized by drying, rather than quantitatively measured or set to a specified water content. Within the experiment, the common treatment makes moisture differences unlikely to explain the contrasts among 0, 2, 4, and 6 m s^{-1}. The reported kinetics should nevertheless be interpreted as applying to dry dust conditions.

We have expanded the limitations to explain why moist field conditions could behave differently. Water can strengthen capillary and cohesive forces, alter the threshold for initial particle release, change the airborne size distribution and aggregation state, increase particle-surface adhesion, and increase resistance to rebound or re-entrainment. These effects act in competing directions: moisture may suppress source emission but enhance aggregation and stable surface retention. Consequently, moisture could alter the fitted retained mass a, response rate k, characteristic time τ, initial net flux J_0, and potentially the magnitude or location of the low-wind maximum. The direction and size of the net change cannot be inferred from this dry dust experiment, so we now limit the conclusion accordingly and identify controlled-moisture experiments as necessary future work.

Location in the revised manuscript: Lines 120–133 and 554–562.

Comment 6: Revision and clarification of the wind-profile methodology

Reviewer comment:

Lines 166–178: I suggest rephrasing this section and providing a more detailed explanation to help the reader better understand the methodology and interpretation of the results.

Response:

We agree and have completely rewritten Sect. 2.3. During re-examination of the source data, we found an error in the manuscript: profiles measured at speeds of 4, 6, and 8 m s^{-1} had inadvertently been associated with the 2, 4, and 6 m s^{-1} deposition treatments. We corrected the assignment, replaced Fig. 1b with the correct 2, 4, and 6 m s^{-1} profiles, and recalculated every profile-derived quantity. The deposited masses, particle-size distributions, kinetic fits, and wind-speed rankings were obtained independently from the tray measurements and are therefore unaffected by this correction.

The revised section now specifies the measurement geometry and array state. Profiles were measured on the longitudinal centreline, 9 m downstream of the test-section entrance and immediately downstream of the collection-tray array. All 25 trays were present in their complete initial layout, with 20 cm spacing between adjacent trays; this layout was restored before each run. Wind speed was measured at z = 0.02, 0.05, 0.10, 0.20, 0.40, 0.80, 1.20, and 1.60 m.

We also replaced the poorly constrained roughness-length formulation used in the old manuscript with a transparent two-parameter log-linear regression over the same height interval for all three treatments:

$$U(z) = A \ln(z/z_{ref}) + B, \text{ and } u_* = \kappa A,$$

where κ = 0.4 and z_{ref} = 1 m. The common fitting range was 0.05–0.40 m, which supplies four points above the 0.03 m tray rims and below the upper quasi-uniform part of the profile. The corrected profile-derived apparent friction velocities are 0.063, 0.089, and 0.154 m s^{-1} at nominal speeds of 2, 4, and 6 m s^{-1}, respectively, with R^2 = 0.921, 0.933, and 0.883.

Boundary-layer thickness δ was estimated independently. We first removed minor local reversals using isotonic regression, applied shape-preserving interpolation, and then identified the first height reaching $0.99U_\infty$, where U_∞ is the mean measured velocity at 0.80, 1.20, and 1.60 m. The resulting operational δ values are approximately 0.88, 0.73, and 0.48 m. The 0.03 m tray rim therefore corresponds to about 3.4%, 4.1%, and 6.3% of δ. The text now states that these profiles include the collective influence of the complete tray array on the downstream mean profile but do not resolve individual-rim wakes or changes caused by progressive tray removal.

Finally, the corrected u_* values were propagated into the mechanistic discussion. The corresponding nominal near-wall viscous length scales are approximately 1.20, 0.85, and 0.49 mm, and the Rouse numbers for 2–10 μm particles span approximately 0.006–0.32. These values support an important role for turbulent mixing relative to gravitational settling, especially for the finer particles.

Location in the revised manuscript: Lines 136–142, 178–203, and 409–428.

Comment 7: Particle shape and definition of the PM classes

Reviewer comment:

Figure 2: How important is the shape of mineral particles for the sedimentation process? Was particle shape considered in the analysis? Since particle shape can influence aerodynamic properties and settling velocities, a brief discussion of its potential impact on the results would be helpful. Lines 193–197: Are the PM classes cumulative or differential?

Response:

We thank the reviewer for raising these two related points.

First, particle shape was not independently characterized and no shape-dependent correction was applied. Laser diffraction reports a volume-equivalent diameter; it does not provide particle-level aspect ratio, sphericity, flatness, elongation, or orientation. Non-spherical mineral particles can experience drag and settling velocities that differ from those of equivalent spheres, with the magnitude depending on shape, orientation, density, and Reynolds number. Shape can also influence interception, rebound, and stable retention at the tray surface. Accordingly, the Stokes–Cunningham settling-velocity calculation in the mechanistic discussion is a nominal spherical-equivalent estimate based on a representative mineral density, not a particle-specific aerodynamic calibration.

The kinetic curves in Fig. 2 were fitted directly to measured tray-retained mass and therefore did not require an assumed shape to calculate $M(t)$, a, k, τ, or J_0. Nevertheless, the unmeasured shape distribution may affect the absolute transport and retention within each size class. Use of the same soil batch and preparation procedure limits systematic differences in the initial shape distribution among wind-speed treatments, but wind-dependent shape-selective transport or retention cannot be excluded. We added this methodological clarification and a dedicated limitation, including the need for future microscopic measurements of aspect ratio and sphericity.

Second, all PM classes in Fig. 2 are cumulative, nested diameter-threshold classes, not mutually exclusive differential bins. They are defined from laser-diffraction volume-equivalent diameter as $PM_{2.5}$: $D_v < 2.5$ µm; PM_{10}: $D_v < 10$ µm; PM_{20}: $D_v < 20$ µm; PM_{30}: $D_v < 30$ µm; PM_{40}: $D_v < 40$ µm; and PM_{63}: $D_v < 63$ µm. Thus, $PM_{2.5}$ is included in PM_{10}, PM_{10} is included in PM_{20}, and so forth. For each threshold, the total retained tray mass was multiplied by the cumulative laser-diffraction volume fraction below that diameter and divided by tray area. The definition is now stated both in Sect. 2.5 and in the Fig. 2 caption so the nested structure is visible at the point of interpretation.

Location in the revised manuscript: Lines 204–232, 272–278, 409–423, and 563–570.

Comment 8: Recalculation and interpretation of the median particle diameter in Figure 4

Reviewer comment:

Figure 4: I may have misunderstood the calculation, but it appears that there could be an issue with the reported median value. Could the authors please check the calculation and clarify this point?

Response:

Thank you for drawing our attention to this issue. We returned to the normalized source particle-size distributions and recalculated every D_{50} value. In the old manuscript, D_{50} had been assigned to the discrete measurement channel whose cumulative volume fraction was closest to 50%. The revised calculation first normalizes the differential volume fractions to 100%, constructs the cumulative volume distribution, and then uses linear interpolation on the logarithmic diameter scale between the two adjacent channels that bracket 50%. This procedure avoids the channel-selection bias in the original annotations.

The corrected D_{50} values at 0.5 and 3 h are, respectively: 13.4 and 10.8 µm at 0 m s^{-1}; 7.1 and 9.8 µm at 2 m s^{-1}; 6.3 and 7.5 µm at 4 m s^{-1}; and 29.3 and 17.9 µm at 6 m s^{-1}. The vertical D_{50} lines and annotations in Fig. 4 have been updated. The differential PSD curves and modal-diameter channels were not altered by the recalculation.

The revised text reports the observed temporal changes without over-interpreting them. At 2 m s^{-1}, D_{50} increases from 7.1 to 9.8 µm (approximately 38%), the modal channel moves from 4.3 to 18.3 µm, and the volume fraction at 18.3 µm increases from 5.3% to 8.6%. We describe this as progressive enrichment of medium-sized effective diameters. Aggregation is discussed only as one plausible contributor, because size-selective transport and retention could produce a similar change.

Location in the revised manuscript: Lines 152–161, 229–232, 306–309, 347–382, 399–407, and 429–437.

Comment 9: Use of the results in numerical simulations and deposition parameterizations

Reviewer comment:

The authors should briefly discuss how the results of this study could be exploited in numerical simulations, particularly with respect to the development or improvement of dust deposition parameterizations.

Response:

We agree and have substantially expanded Sect. 4.3. The revision first separates the standard model quantity from our experimental quantity. Existing size-resolved schemes generally calculate a dry-deposition velocity from particle size, friction velocity, surface roughness, land-cover type, and surface collection processes, while particle rebound or resuspension is often represented separately. Our experiment does not provide a universal replacement deposition velocity. Instead, it supplies empirical constraints on the transient net surface-retention response after a matched initial airborne dust loading.

The four fitted quantities provide complementary constraints that can be used in model development or evaluation. The asymptotic mass a characterizes the fitted stable retained-mass level for a specified initial loading and collector surface. The effective coefficient k and its reciprocal τ specify how rapidly the surface reservoir approaches that level. The initial slope $J_0 = ak$ constrains the early net surface flux. Thus, a model can be tested not only against the amount retained after a fixed time, but also against the adjustment timescale and the initial response for each size threshold. The empirical kernel $M(t) = a\,[1 - \exp(-kt)]$ can be used as a compact benchmark for a surface-reservoir component, provided that its configuration-specific nature is retained and that concentration normalization is handled separately in the atmospheric model.

To make the non-monotonicity quantitatively useful, we compared the observed J_0 values with a non-decreasing wind-speed benchmark representing a simplified deposition-only expectation. For $PM_{2.5}$–PM_{40}, observed J_0 at 2 m s^{-1} exceeds that benchmark by approximately 15–72%. At 6 m s^{-1}, it is approximately 45–91% below the benchmark, equivalent to benchmark-to-observation factors of about 1.8–11 for the affected size classes. The deviation is smaller for PM_{63}. These values provide a direct low-wind test case for determining whether a model that treats deposition alone produces too much stable surface retention when particle rebound, persistence, and re-entrainment become important.

On this basis, we recommend a coupled parameterization rather than applying a single monotonic multiplier to deposition velocity. Conventional particle delivery to the surface should be coupled to (i) wind- and size-dependent stable retention or rebound and (ii) 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 behaviour for the coupled response. Extension to field or global simulations will require calibration for natural roughness, vegetation, soil moisture, dust composition, and vertically resolved concentration/flux conditions; the present values are process-level constraints, not universally transferable coefficients. The conclusion now explicitly identifies targeted observations and simulations of near-surface particle exchange as the next step for transferring this framework to realistic boundary layers.

Location in the revised manuscript: Lines 466–518 and 590–594; Supplement, Tables S2–S4.

We again thank the reviewer for these constructive comments. They helped us clarify the definition and scope of the measured quantity, strengthen the methodological description and limitations, and better articulate how the experimental results may inform numerical parameterizations.