Ning Huang:

This study accurately addresses a long-standing yet insufficiently quantified issue in aeolian physics—the role of boundary layer thickness. Using a large-eddy simulation–saltation coupled model, it systematically reveals how boundary layer thickness modulates turbulent structures and thereby significantly affects the physical mechanisms of near-threshold particle entrainment, transport flux, spatial distribution, and grain-size characteristics. The conclusions provide a clear physical explanation for the discrepancies between wind tunnel and field observations, and offer direct guidance for improving dust emission parameterization schemes in climate models. The paper features a clear structure, sound methodology, and comprehensive data. It is recommended for acceptance after minor revisions. Below are several suggestions for the authors to consider during revision:

Authors' response: Thank you for taking the time to review our manuscript thoroughly and for sharing your insightful comments and valuable affirmation. Based on your suggestions, we have carefully revised and refined the entire manuscript to ensure more concise language and clearer presentation of figures, thereby further enhancing its overall quality. Our detailed point-by-point responses are provided below.

1) To reduce computational costs, the study employs the approach where each numerical particle represents multiple physical particles (lines 166-168), with the representative ratio varying widely (from 50 to 2000) depending on the boundary layer thickness and friction velocity. This is a practical strategy. Please briefly explain the potential impact of this assumption on the key results and its validity, especially under near-threshold conditions characterized by low particle concentration and high representative ratios.

Authors' response: Thank you for your valuable comment. To reduce the computational cost of large-scale particle simulations, this study employed the common approach of representing multiple physical particles with a single numerical particle. We provide below a detailed explanation of the potential implications and the rationale for this assumption.

This methodology primarily influences the precise characterization of particle-particle interactions—notably the splash process—and the statistical robustness under extremely low particle concentrations. Under near-threshold, low-concentration conditions (where the representative ratio is 50:1), the reduced number of numerical particles may introduce slightly greater statistical scatter in the instantaneous particle spatial distribution compared to a fully resolved simulation and could modestly smooth the inherent stochasticity of splash process. However, the central mechanism of this study—that boundary layer thickness modulates near-threshold sand transport by altering large-scale turbulent structures and the resulting extremes in wall-shear stress, thereby governing fluid-driven entrainment—is fundamentally rooted in fluid-particle interactions. This key physics is captured by the accurately resolved flow field and the physics-based drag and entrainment models, which are largely unaffected by the "clustering" of particles in the numerical representation. Consequently, this approach does not compromise core qualitative findings and mechanistic interpretations, such as the "significant lowering of entrainment thresholds" or the "influence of boundary layer thickness on sand transport rate."

This method has been widely adopted in large-eddy simulation studies of wind-blown sand two-phase flow (e.g., Dupont et al., 2013; Feng and Wang, 2023) and has been demonstrated to reliably preserve the accuracy of macroscopic transport statistics. Under near-threshold, low-concentration conditions, splash events are infrequent, and transport is dominated by fluid entrainment. Under these conditions, the effect of particle aggregation on particle-bed interaction statistics is further minimized. Additional sensitivity tests using a lower representative ratio (20:1) confirmed that the influence on our results is negligible. Therefore, within the scope of our research objectives and given practical computational constraints, this approach is both justified and necessary.

[1] Dupont, S., Bergametti, G., Marticorena, B., Simoëns, S., 2013, Modeling saltation

intermittency, Journal of Geophysical Research: Atmospheres, 118(13), 7109-7128.

[2] Feng, S. J., Wang, P., 2023, The influences of boundary layer thickness on the characteristics of saltation sand flow–A large eddy simulation study, Aeolian Research, 60, 100853.

2) The friction velocity typically refers to a parameter of the airflow itself, whereas the saltation friction velocity or effective friction velocity often accounts for the feedback from sand particles. Please briefly clarify the specific meaning of the saltation friction velocity used in this paper: is it the bed shear velocity under particle-laden conditions (i.e., the friction velocity that incorporates particle feedback), or is it derived through a specific formulation?

Authors' response: The "saltation friction velocity" used in this study characterizes the actual shear velocity acting on the bed within the fluid–particle two-phase flow system when saltation occurs and reaches dynamic equilibrium. Specifically, at each time step, the model solves the filtered Navier–Stokes equations including the particle drag source term to obtain the realistic flow field. The time-averaged value is then derived from the instantaneous bed shear stress τ under particle-laden conditions, using the relation $u_*=\mathrm{sqrt}(\tau/\rho)$ (where ρ is the air density). This fully aligns with the definition of an effective friction velocity that accounts for particle feedback. Furthermore, the definition of the saltation friction velocity has been explained in the manuscript.

3) The text mentions classic models such as the cubic law of Bagnold (1941) and the quadratic relationship of Creyssels et al. (2009), and points out that near the threshold state, the relationship between sand transport rate and shear stress follows different patterns (exponential or power law). It is recommended to quantitatively compare the fitted relationships obtained in this study with those from existing research.

Authors' response: Thank you for this important suggestion. We have supplemented the comparison between the fitting relationships obtained in this study and those from classical models.

Specifically, in the "Results and Discussion" section, we clearly state that when the wind velocity exceeds the impact entrainment threshold, the time-averaged sand transport rate obtained from our simulations exhibits a 1.5-power relationship with shear stress. Given that shear stress is proportional to the square of wind velocity, this relationship is equivalent to the sand transport rate being proportional to the cube of wind velocity, which is mathematically consistent with the scaling relationships established by the classical theories of Bagnold (1941) and White (1979) under fully developed, saturated transport conditions. This additional explanation further highlights the consistency between our findings and classical theories in the fully developed transport regime.

At the same time, we have more clearly emphasized the main innovative contribution of this study: it reveals that under near-threshold conditions (where wind velocity is below the impact entrainment threshold), the sand transport rate follows an exponential relationship with shear stress. This fundamentally differs from the continuous, saturated transport patterns assumed by classical models, thereby systematically clarifying the regulatory mechanism of boundary layer thickness in this previously underexplored regime.

[3] Bagnold, R. A., 1941, The physics of blown sand and desert dunes, Springer Netherlands.
[4] White, B. R., 1979, Soil transport by winds on mars, Journal of Geophysical Research, 84(B9), 4643-4651.

4) In the text, the transport intensity is defined as a key metric linking microscopic mechanisms to macroscopic flux, and its variations with height and boundary layer thickness are presented (Fig. 4b). The authors are requested to provide a clear mathematical definition or calculation formula for the transport intensity in the main text (e.g., at line 257), as this would significantly enhance the interpretability and reproducibility of the results in Fig. 4(b).

Authors' response: Thank you for your suggestion. We fully agree that providing a clear mathematical definition for the transport intensity would greatly enhance the readability and reproducibility of Fig. 4(b) and the related analysis.

The transport intensity defined in this study essentially characterizes the non-uniformity of the vertical distribution of sand flux. Specifically, its mathematical expression is the horizontal mass flux per unit height interval. It aims to quantitatively describe the concentration of sand transport activity relative to the total flux at various heights above the bed.

We have supplemented the mathematical expression for transport intensity in the main text as $q(y) = \sum m_p \overline{u_p} / (L_x \times \Delta_y \times L_z)$.

5) Lines 387-389 are slightly cumbersome in syntax. It is suggested to revise them into a clearer structure.

Authors' response: We have revised the relevant text in the manuscript to enhance its clarity and structural logic. The specific modifications are as follows.

The simulation results indicate the existence of two critical Shields numbers: $\theta_{*1} = 0.003$ and $\theta_{*2} = 0.005$. The shift in the particle statistics relationship corresponds to θ_{*1} when comparing $\delta = 10.0\ m$ with $\delta = 5.0\ m$, and to θ_{*2} when comparing $\delta = 5.0,\ 10\ m$ with $\delta = 1.0\ m$.

Anonymous Referee #1:

This paper studies the effect of the boundary layer thickness on several properties of windblown sand using a LES-based model. It is first shown that increasing boundary layer thickness leads to a widening of the probability distribution of the wall shear stress (Fig. 2), as expected. It is then shown that, as a consequence of the widening, two distinct thresholds of aeolian sand transport decrease (Fig. 3). Likewise, vertical profiles of the mass flux, particle volume fraction, horizontal velocity, and others are also affected (Figs. 4-9). The strength of this study is to look at the effect of a quantity, the boundary layer thickness, that is often being ignored as a sand-transport-influencing factor by the community, even though it may arguably play an important role. In fact, I only know a few studies to have looked into this ever. The main weakness of this study is the methodology used to model the motion of the particle phase. It uses the same aerodynamic entrainment and splash models as the one by Anderson and Haff (1991), which is problematic for a variety of reasons (explained below). Furthermore, the particle phase model does not resolve the bed as a whole and it seems to neglect collision between particles. Both have been shown to be quite important in recent years (explained below). This being said, I still think overall this study can be valuable, since the observed boundary layer thickness effects are quite interesting. However, more data analyses are needed, especially in what regards transport intermittency (see below), and I also think the authors should make sure their definitions of the “rebound threshold”, and the conclusions they draw from it, are consistent with the definition of this threshold in the literature (which I think it is not, see below).

Authors’ response: Thank you for taking the valuable time to review our manuscript and for providing such insightful and constructive comments. These suggestions are crucial for further improving our study, and we will address them point by point below.

Methodology concerns

By now, numerous research groups, for the purpose of simulating aeolian sand transport, have moved to using coupled CFD-DEM simulations that resolve the particle phase, including many layers of the bed, at the particle scale. Given that such simulations are now relatively quick due to much better computers, there is no longer a good justification to resort to approximating grain-bed and grain-grain interactions by splash functions derived from experiments and simulations for the impact of a single grain onto a static granular bed. We now know from quite a number of DEM-based studies that the bed cannot be treated as stationary and that cooperative effects resulting from residual motion within the sediment bed and its surface can alter splash characteristics quite dramatically: for example, Jia & Wang (2022, doi: 10.1016/j.catena.2022.106191), Tholen et al (2023, doi: 10.1103/PhysRevLett.130.058204), Wang et al. (2024, doi: 10.1111/sed.13225; 2025, doi: 10.1111/sed.70038), Lester et al. (2025, doi: 10.1038/s41561-025-01672-w). What is worse is that the static-bed splash function the authors use is the one by Anderson and Haff (1991), which models the rebound probability using an unphysical dimensional parameter that should be related to grain properties but is not. There are better ways out there to model static-bed splash: for example, Lammel et al. (2017, doi: 10.1103/PhysRevE.95.022902), Comola and Lehning (2017, doi: 10.1002/2016GL071822).

I strongly suggest the authors to change their methods to DEM-based techniques in the future, though I reiterate that, for the present studies, I can overlook these problems as the authors focus on a very rarely studied aspect of aeolian transport, the boundary layer thickness.

Authors' response: We are greatly inspired by your in-depth analysis regarding the advantages of using the Discrete Element Method (DEM) over traditional splash functions in simulating aeolian sand transport.

First, we fully acknowledge the significant advantages of the DEM method highlighted in your comments. As revealed by the studies you cited (Jia and Wang, 2022; Tholen et al., 2023; Wang et al., 2024; Lester et al., 2025), DEM can explicitly resolve particle-scale interactions and realistically capture collective effects, which is crucial for accurately understanding splash dynamics under natural conditions (i.e., non-static beds). In contrast, traditional splash functions based on static-bed, single-particle impact assumptions—such as the Anderson and Haff (1991) model—cannot describe these complex phenomena. Moreover, the empirical parameters they rely on often lack a clear physical basis. The works you mentioned, such as Lammel et al. (2017) and Comola and Lehning (2017), indeed provide a more physically sound framework for modeling splash on static beds.

Second, we fully recognize that coupled CFD-DEM simulations represent the cutting edge of current research in this field. However, a key challenge hindering their application remains the limitation in computational domain scale. To achieve particle-scale resolution, typical CFD-DEM simulations—including the studies you cited—often employ relatively small computational domains. For instance, the three-dimensional domain in Jia and Wang (2022) has a side length of only 50 times the particle diameter, and the streamwise dimension in Tholen et al. (2023) is approximately 1000 times the particle diameter. While such scales are highly effective for studying the micro-mechanisms of particle-bed interactions, they are insufficient for accommodating and resolving the large-scale and very-large-scale turbulent structures within the boundary layer.

The primary objective of this study is to systematically investigate how the atmospheric boundary layer thickness, as a macroscopic parameter, influences the bulk statistics of aeolian sand transport. The boundary layer thickness primarily affects the spatiotemporal distribution of wall shear stress by modulating the large-scale coherent structures within the flow field. To reliably capture these large-scale flow structures, which play a crucial role in transport dynamics, the streamwise computational domain length is set to 8π times the boundary layer thickness—a scale typically used for studying large-scale structures in turbulent boundary layers. Given such an extensive domain, conducting fully particle-resolved CFD-DEM simulations under current and foreseeable computational resources is prohibitively difficult, if not unrealistic.

Therefore, to balance physical fidelity with computational feasibility, this study employs a simplified particulate model based on a splash function. We acknowledge that this approach parameterizes the complex particle-bed interactions. However, given our primary objective—to elucidate the macroscopic influence of boundary layer thickness—this simplification constitutes a necessary and acceptable compromise. It enables us to concentrate computational resources on resolving the large-scale flow structures and their coupling with the particulate phase.

In response to your valuable suggestions, we have implemented the following revisions in the updated manuscript:

(1) In Section 2, we have explicitly discussed the simplified nature and limitations of our employed particle collision model (splash function), and by directly citing the relevant literature you mentioned on DEM advantages and static-bed splash function improvements (e.g., Jia and Wang, 2022; Tholen et al., 2023; Lammel et al., 2017; Comola & Lehning, 2017), we have demonstrated our awareness of these limitations and our understanding of recent field advancements.

(2) In section 4, we have explicitly stated: a logically crucial and necessary step is to adopt the CFD–DEM framework—under conditions that can resolve large-scale flow fields while incorporating realistic particle–particle and particle–bed interactions—to verify, refine, and extend the findings obtained in this study based on a macroscopic parameterized model.

Once again, thanks for your insightful feedback, which has greatly enhanced our understanding of methodological developments in this field and will significantly improve the depth and rigor of our manuscript.

[1] Jia S, Wang Z. A new ejection model for aeolian splash[J]. Catena, 2022, 213: 106191.

[2] Tholen K, Pähtz T, Kamath S, et al. Anomalous scaling of aeolian sand transport reveals coupling to bed rheology[J]. Physical Review Letters, 2023, 130(5): 058204.

[3] Wang Z, Li Z, Jia S. Rheological sand bed generates non-rebounding particles[J]. Sedimentology, 2024, 72(1): 34-44.

[4] Lester C W, Murray A B, Duran O, et al. Emergence of wind ripples controlled by mechanics of grain–bed impacts[J]. Nature Geoscience, 2025, 18(4): 344-350.

[5] Anderson, R. S., Haff, P. K. Wind modification and bed response during saltation of sand in air[J], Acta Mechanica Supplementum, 1991, 1, 21-51.

[6] Lämmel M, Dzikowski K, Kroy K, et al. Grain-scale modeling and splash parametrization for aeolian sand transport[J]. Physical Review E, 2017, 95(2): 022902

[7] Comola F, Lehning M. Energy-and momentum-conserving model of splash entrainment in sand and snow saltation[J]. Geophysical Research Letters, 2017, 44(3): 1601-1609.

Aeolian transport thresholds

The authors use the terms “rebound threshold” and “impact entrainment threshold”, which were first introduced by Pahtz and Duran (2018, doi: doi.org/10.1029/2017JF004580), as far as I know. These authors also discussed these thresholds more thoroughly in a 2020 review paper (Pahtz et al, doi: 10.1029/2019RG000679). It seems to me that, while the present authors adapt the same definition of the impact entrainment threshold (threshold of continuous transport), the manner in which they obtain the rebound threshold differs from the original definition. They seem to extrapolate the intermittent transport rate to vanishing transport, which I infer from Fig. 3. By contrast, Pahtz et al. (2020) state that the rebound threshold results from the extrapolation of the continuous transport rate to vanishing transport. For this reason, I suggest the authors to use a different terminology. In addition, I think the authors should, if possible, also compute the actual rebound threshold. This requires dealing with intermittency in a more sophisticated manner (see below).

Authors’ response: The issues regarding the use of the term "rebound threshold" and its comparison with the work of Pähtz et al. (2020) are crucial for clarifying concepts and improving the presentation of our study. We fully agree with the reviewer's analysis and summary of the relevant literature. Below is our point-by-point response and clarification regarding this comment.

In this study, we define the rebound threshold as the critical Shields number at which the observed saltation movement transitions from an intermittent state to a complete cessation. This aligns with the method inferred from Fig. 3 (marked as the data points of rebound threshold).

We agree with the core physical definition of the rebound threshold cited from Pähtz and Durán (2018) and Pähtz et al. (2020) in your comment: "the minimum fluid shear stress required to sustain continuous rebound of particles on the bed." The physical picture is as follows: when the fluid shear stress exceeds this threshold, the energy gained by particles from the airflow during saltation is sufficient to compensate for the energy lost during collisions with the bed, thereby sustaining stable, continuous rebound motion. Below this threshold, particles cannot maintain energy balance, and their motion will decay and eventually cease. This is precisely the physical critical condition that our study focuses on. Therefore, in terms of physical essence, the rebound threshold used in this work is consistent with the definition in the literature by Pähtz et al. (2020), both referring to the critical hydrodynamic condition required to maintain continuous rebound motion of particles.

We note that, as mentioned in the review by Pähtz et al. (2020), rebound threshold can be estimated through two approaches: (a) gradually reducing the shear stress until intermittent transport ceases, or (b) extrapolating the (continuous) transport rate to zero. The method adopted in this study corresponds precisely to the first approach (a) described above, that is, determining this threshold by directly observing the cessation point of intermittent transport.

We understand the distinction you highlighted: namely, Pähtz et al. (2020) emphasize the definition of rebound threshold through extrapolating the continuous transport rate to zero (method b). Although the specific operational approach to determining this critical state differs, the corresponding physical state—the critical point at which sustained rebound motion of particles can or cannot be maintained—remains the same. Furthermore, to ensure terminological consistency with our team’s previous related research (Jin et al., 2024) and to avoid potential confusion among readers, we prefer to retain the term "rebound threshold" in this study.

Meanwhile, we attach great importance to your suggestion regarding the clear distinction of methods. We have added an explicit clarification in the revised manuscript (section 3): "The rebound threshold in this study refers to the critical condition determined by observing the complete cessation of intermittent saltation motion. Its physical essence is consistent with the critical Shields number defined by Pähtz et al. (2020), which signifies whether sustained particle rebound can be maintained. It should be noted that the determination method differs from the one that estimates the threshold by extrapolating the continuous transport rate to zero."

For the research objectives of this study, defining the threshold by observing the cessation of transport intermittency offers clear physical intuitiveness and operational feasibility. It effectively captures the abrupt transition from "presence" to "absence" of particle motion. More importantly, as illustrated in Fig. 3 and discussed in the main text, the saturated transport rate curves for different boundary layer thicknesses are very close to each other once above the impact entrainment threshold. This indicates that, within this range, the influence of boundary layer thickness on the steady-state continuous transport rate is minimal. If the rebound threshold were defined by extrapolating the continuous transport rate to zero, the values for different boundary layer thicknesses would likely show extremely small differences, or might even be indistinguishable. This would obscure the significant physical phenomenon revealed in Fig. 3, which is one of the core findings this study aims to reveal and elucidate. Therefore, employing the current method based on the observation of intermittency better highlights the focal points of this research and the novel patterns discovered.

In summary, our use of the term "rebound threshold" is based on its consistency in physical essence and its alignment with our previous work. At the same time, we have fully incorporated your suggestion in the revised manuscript to more clearly articulate the specific method used in this study to determine the threshold and to explicitly distinguish it from other methods in the literature, thereby avoiding potential misunderstandings among readers.

[8] Pähtz T, Clark A H, Valyrakis M, et al. The physics of sediment transport initiation, cessation, and entrainment across aeolian and fluvial environments[J]. Reviews of Geophysics, 2020, 58(1): e2019RG000679.
[9] Pähtz T, Durán O. The cessation threshold of nonsuspended sediment transport across aeolian and fluvial environments[J]. Journal of Geophysical Research: Earth Surface, 2018, 123(8): 1638-1666.
[10] Jin T, Wang P, Cao B. Transport characteristics of aeolian sand near different thresholds[J]. Catena, 2024, 247: 108541.

Intermittency definition

I find the authors' quantity "particle spatial occupancy", alpha_p, to be a very poor measure of intermittency. As far as I understand, it represents the ratio between the number of numerical grid cells occupied by at least one simulated particle (which represents many particles at the same time) and the total number of grid cells. The problem with this definition is that it depends strongly on the grid cell size. In particular, in the limit of zero grid cell size, alpha_p becomes zero everywhere and therefore meaningless, since the probability to find a point within an interval of measure zero is zero. This conflicts with a basic requirement of any numerical simulation: that any result obtained from it should converge in the limit of zero grid size.

A much better way to define intermittency is through bursts of overall activity, e.g., see Carneiro et al. (2015, doi: 10.1038/srep11109), Martin and Kok (2018, doi: 10.1029/2017JF004416), Comola et al. (2019, doi: 10.1029/2019GL085739). For example, the latter two studies looked at the fraction of time, fQ, at which aeolian transport is active, defined through a non-zero overall particle count over a period of 2s (approximate particle response time to turbulent wind fluctuations). The authors could adapt a similar measure. If it is defined appropriately, the ratio Q/fQ between the intermittent transport rate Q and fQ should behave like a universal function (see Comola et al., Eq. (3)), independent of the boundary layer thickness. In regard to my previous comment, this function could then be extrapolated to zero to obtain the actual rebound threshold.

Authors' response: We agree with the reviewer that α_p, defined in the original text as the ratio of grid cells containing particles to the total number of grid cells, exhibits dependence on grid size. Theoretically, α_p loses its meaning when the grid size approaches zero. We acknowledge that the initial manuscript failed to adequately clarify the applicability and scope of this metric.

As noted by the reviewer, defining intermittency by the fraction of time during which saltation is active, denoted as f_Q—as employed in methods such as those by Martin and Kok (2018) and Comola et al. (2019)—is a more widely accepted quantitative standard in the field of aeolian physics. However, when applying this criterion to our large-scale macroscopic computational domain simulations, we encountered specific challenges that affect the effectiveness of f_Q in distinguishing the influence of different boundary layer thicknesses: even when the wind speeds approach the rebound threshold—defined by the cessation of intermittent transport—the fraction of time during which saltation is inactive across the entire large-scale computational domain remains very small. Consequently, the derived f_Q remains persistently near unity, limiting its ability to resolve the variations in transport intensity close to the threshold.

Therefore, the conventional alternative is to define f_Q by detecting the transport time series at a single point (e.g., the center of the computational domain), as seen in Jin et al. (2024). However, this approach suffers from two issues: (1) its results still depend, to some extent, on the size of the local observation grid; and (2) more importantly, it fails to capture the global differences in transport spatial structure induced by varying boundary layer thicknesses. For instance, in our simulations, at the comparably lowest wind speed (θ_* = 0.0032), conditions with a thinner boundary layer ($\delta = 1.0\ m$) may exhibit pronounced local intermittency (lower f_Q), whereas conditions with thicker boundary layers ($\delta = 5.0\ m,\ 10.0\ m$) could sustain higher levels of spatially uniform transport across the entire computational domain, leading to higher f_Q values that may even approach unity. In such cases, relying solely on single-point f_Q would make it difficult to effectively distinguish and quantify the fundamental influence of boundary layer thickness on transport dynamics.

The primary purpose of introducing α_p in this study is not to provide a universal quantitative standard for intermittency, but rather to use it as a qualitative tool to contrast the spatial dispersion or clustering trends of particle transport under different boundary layer thicknesses. Under a consistent grid resolution, the relative variation of α_p with respect to boundary layer thickness or wind speed can effectively reveal key differences in transport spatial structure—such as whether transport is concentrated in a few active "streamers" or widely dispersed—which is one of the core concerns of this study.

We fully accept the reviewer's critique that our original presentation may have equated α_p directly with "intermittency intensity," which is insufficiently rigorous. In the revised manuscript, we have revised the description of α_p, clearly stating its role in characterizing the spatial inhomogeneity of transport, noting its dependence on grid size, avoiding its direct association with the physical concept of "intermittency intensity," and conceptually distinguishing it from time-based metrics such as f_Q defined in Martin and Kok (2018). We believe that this clarification will make the analytical framework of the manuscript more rigorous and the argument more persuasive.

[11] Martin R L, Kok J F. Distinct thresholds for the initiation and cessation of aeolian saltation from field measurements[J]. Journal of Geophysical Research: Earth Surface, 2018, 123(7): 1546-1565.

[12] Comola F, Kok J F, Chamecki M, et al. The intermittency of wind-driven sand

transport[J]. Geophysical Research Letters, 2019, 46(22): 13430-13440.

Anonymous Referee #2:

This manuscript explores the role of boundary-layer thickness in modulating aeolian sand transport through turbulence–particle interactions using Euler–Lagrangian simulations. The topic is relevant to the aeolian research community, and the study provides interesting insights into the coupling between boundary-layer dynamics and particle transport. The following comments are intended to help clarify the physical interpretation of the results and to improve the manuscript.

Authors' response: We sincerely appreciate your positive recognition and valuable comments on our work. A detailed point-by-point response to your suggestions follows.

Major comments

A number of experimental studies have previously examined how turbulent shear stress distributions or turbulence structures affect aeolian sand transport (e.g., Li et al., 2020; Zhang et al., 2022; Tan et al., 2023). In this context, it would be helpful if the authors could further clarify how the effect of boundary-layer thickness considered here differs physically from changes in turbulence structure, for example, those associated with atmospheric stability. A brief discussion of the atmospheric or environmental conditions under which different boundary-layer thicknesses would occur in nature would also strengthen the interpretation of the results.

Authors' response: Thank you for the insightful comments. Below is our specific response to this comment.

(1) As noted by the reviewer, Li et al. (2020) found that instantaneous shear stress fluctuations induced by turbulence play a critical role in driving particle entrainment. Zhang et al. (2022), through an innovative forced perturbation technique using a fluttering cloth, simulated quasi-convective turbulence in a wind tunnel that resembles convective atmospheric boundary layers, which substantially enhanced the aerodynamic entrainment rate of particles, particularly under near-threshold conditions.

Together, these studies reveal the fundamental influence of turbulent statistical characteristics—especially the shape of the shear stress distribution and the probability of extreme events—on particle entrainment and transport.

The boundary layer thickness (δ) investigated in this study is a scaling parameter that directly constrains the maximum possible scale of vortical structures in turbulent motion. Increasing δ implies an expansion of the flow domain in the vertical direction, allowing for the generation and development of larger-scale coherent structures that carry more energy. These large-scale structures significantly enhance the extreme fluctuations in wall-shear stress by modulating momentum transport in the near-wall region, as illustrated in Fig. 2 of our manuscript.

In contrast, the changes in turbulence structure referred to by the reviewer, such as those induced by atmospheric stability (convective/stable conditions), primarily alter the generation mechanisms and energy distribution patterns of turbulence. For example, convective conditions (unstable boundary layers) generate turbulence through buoyancy, forming strongly intermittent, large-scale vortices with non-Gaussian statistical properties (as simulated by Zhang et al., 2022), which modifies both the sources and distribution of turbulent energy.

We have explicitly elaborated on this physical distinction at the beginning of the section 4 in the manuscript, aiming to highlight the complementary relationship between the present study and previous research that focused on turbulent statistical characteristics.

(2) In the natural atmosphere, the boundary layer thickness is not a fixed value and is governed by multiple factors. Typical scenarios include: convective boundary layers that can reach 1–2 km in thickness, neutral boundary layers often on the order of hundreds of meters, and stable boundary layers that may contract to tens of meters. Additionally, surface roughness, topography, and synoptic weather systems can significantly modify the boundary layer thickness. For example, rough surfaces enhance turbulent mixing and favor boundary layer development, whereas flat, smooth

surfaces may limit its thickness.

The range of thicknesses simulated in this study precisely spans the transitional range from typical wind tunnel scales (on the order of approximately 0.1 m) to natural atmospheric scales (>100 m). We have added a brief description of the natural variation in boundary layer thickness in the revised manuscript. This will help readers appreciate the practical representativeness of the parameter settings in this study and thereby establish a clearer connection between the numerical simulation results and the broader disparities observed in natural settings and wind tunnel experiments.

[1] Li G, Zhang J, Herrmann H J, et al. Study of aerodynamic grain entrainment in aeolian transport[J]. Geophysical Research Letters, 2020, 47(11): e2019GL086574.
[2] Zhang J, Li G, Shi L, et al. Impact of turbulence on aeolian particle entrainment: results from wind-tunnel experiments[J]. Atmospheric Chemistry and Physics, 2022, 22(14): 9525-9535.

From Fig. 2, it appears that the simulated boundary-layer thicknesses (1–10 m) mainly reflect differences in Reynolds number. Under this interpretation, the resulting shear stress distributions may correspond to different stages of boundary-layer development under the same pressure-gradient forcing (i.e., with the same friction velocity). This setup seems conceptually similar to the experimental studies of Williams et al. (1990, 1994). The authors may wish to clarify whether this interpretation is correct and to discuss the relationship between their simulations and those earlier experiments.

Authors' response: Your above description is entirely correct. By systematically varying the boundary-layer thickness to alter the Reynolds number (Re_τ), our setup resembles boundary-layer flows at different developmental stages. In essence, it is indeed conceptually similar to the experimental design of Williams et al. (1990, 1994). In their studies, Williams et al. strategically positioned measurement points along a rough flat plate to exploit the natural development of the boundary layer—from laminar to fully turbulent flow, with a corresponding rise in Re_τ—and thereby examine how flow conditions influence particle entrainment thresholds and rates.

Both this study and the experimental work of Williams et al. (1990, 1994) are grounded in the same physical insight: the state of the boundary layer—characterized by its thickness or Reynolds number—is a key factor governing the aerodynamic entrainment of particles. As observed by Williams et al. (1994), the mean entrainment threshold decreases with downstream distance (i.e., as turbulence intensifies). Our simulations directly confirm and quantify that the extreme wall-shear stress events increases with δ (or equivalently, with Re_τ) (Fig. 2), which is the hydrodynamic origin of the reduction in the “effective entrainment threshold.” Furthermore, we find that the transport rate increases markedly with δ in the low-wind-speed regime ($\theta_* < \theta_*^e$), which aligns with Williams’ observation that turbulent fluctuations promote entrainment. However, in the moderate- to high-wind-speed regimes, the transport mechanism shifts from fluid-driven to splash-driven, exhibiting a distinct dependence on thickness (Fig. 3).

Limited by the dimensions of the wind tunnel, the boundary-layer thickness in Williams' experiments typically ranges from centimeters to decimeters (corresponding to Re_τ on the order of 10^3–10^4), representing a classic laboratory scale. Our simulations systematically extend δ from 1 m to 10 m (with Re_τ reaching ~10^5), thereby bridging the gap between the laboratory scale and natural atmospheric scales, where δ is commonly on the order of hundreds of meters. This allows us to directly investigate the scaling effects that underlie the discrepancies between wind-tunnel and field observations.

We have added a discussion in the section 3 of the manuscript that explicitly connects our simulations with earlier experiments, in order to more clearly situate the present work within this academic framework.

[3] Williams J J, Butterfield G R, Clark D G. Rates of aerodynamic entrainment in a developing boundary layer[J]. Sedimentology, 1990, 37(6): 1039-1048.
[4] Williams J J, Butterfield G R, Clark D G. Aerodynamic entrainment threshold:

effects of boundary layer flow conditions[J]. Sedimentology, 1994, 41(2): 309-328.

The manuscript refers to the fluid threshold, rebound threshold, and impact threshold, but their definitions are not explicitly provided. Clarification of how these thresholds are defined and diagnosed from the simulation results (e.g., the mathematical or statistical criteria used) would improve the transparency and reproducibility of the study.

Authors' response: Thank you for raising this important point regarding the definitions of the key thresholds used in our study. We have now clarified these definitions in the revised manuscript, as detailed below.

(1) The fluid threshold represents the critical condition for the initial aerodynamic entrainment of particles from a static bed by fluid forces alone, as defined in the original text. The calculation formula is $u_*^t = A[gd_p(\rho_p - \rho)/\rho]^{1/2}$, where d_p is particle diameter, ρ_p and ρ are particle and air densities, respectively.

(2) The rebound threshold signifies the critical condition below which intermittent particle motion (saltation) cannot be sustained and eventually ceases entirely. It is diagnosed from the simulation results by systematically reducing the wind speed and observing the complete cessation of all particle motion over a sufficiently long statistical period. There is no closed-form mathematical expression for this threshold.

(3) The impact entrainment threshold represents the minimum wind speed required to maintain continuous, steady-state saltation transport, sustained primarily by particle-bed collisions (splash). It is diagnosed from the simulated relationship between the dimensionless shear velocity and the resultant sand transport rate. Specifically, it is identified as the point where the transport regime transitions from intermittent to continuous, corresponding to a marked change in the slope of the curve (see Fig. 3 in the manuscript). Like the rebound threshold, it is determined empirically from the simulation output.

Minor comments

Line 224: Li et al. (2020a) is cited in the text but does not appear in the reference list.

Authors' response: Thank you for the reminder. We have included it in the reference list.

[5] Li G, Zhang J, Herrmann H J, et al. Study of aerodynamic grain entrainment in aeolian transport[J]. Geophysical Research Letters, 2020, 47(11): e2019GL086574.

Anonymous Referee #3:

This work performs a suite of numerical simulations using LES to investigate the sensitivity of particle saltation processes to boundary layer thickness. The boundary layer thickness partly controls the spectrum of turbulent scales of motion (for a fixed wind shear), and thus controls (in some capacity) the turbulence fluctuation intensity and range of surface stresses experienced by the particles. I enjoy reading about work that focuses on the role of turbulent fluctuations in particle emission processes (rather than simply considering emission by the mean), as these fluctuations can be remarkably strong at high Reynolds number. Based on the authors' results, it certainly seems like the boundary layer thickness (and thus the Reynolds number of the flow) plays a meaningful role for the mass flux. I agree with the authors that more models should include the role of turbulent fluctuations in saltation processes, and including information about boundary layer height (and its consequences for turbulence intensity) is certainly one way to do that.

Authors' response: Thank you for your positive feedback and constructive comments on our work. You pointed out that the boundary layer thickness (i.e., Reynolds number) influences the mass flux by modulating turbulent scales and stress distributions, which is highly consistent with our numerical results. Your attention to the role of turbulent fluctuations in particle saltation processes is also one of the core motivations of this study. Below are our point-by-point responses to your comments.

I (cautiously) agree with the author's findings, but I am skeptical of the numerical method used in this work. The authors employ a standard wall-bounded flow setup, and since the horizontal boundary conditions are periodic, one might assume that a spectral (or hybrid spectral-finite difference) method would be more suitable than a second order centered difference scheme. The spectral method would preserve the finer fluctuations which may have a meaningful impact on the particle emission, one way or the other. For example, these fine scale features could decrease the coherence of the stress fluctuations, and may affect the author's results, but I am not certain.

Authors' response: We fully agree with your view that spectral methods may offer advantages over second-order central difference schemes under horizontal periodic boundary conditions. Their higher numerical accuracy in resolving fine-scale turbulent structures can enhance the accurate representation of particle emission processes. In response to your comments and within the context of this work, we would like to offer the following clarifications.

Our choice of the second-order central difference scheme is primarily motivated by its computational efficiency and robustness in large-scale parametric studies. As shown in Fig. 1(b), the mean velocity profiles are in good agreement with the logarithmic law. Fig. 2(b) further demonstrates that the Reynolds number dependence of the wall shear stress fluctuation is well captured across different boundary layer thicknesses. Furthermore, a more detailed validation of turbulence intensity and Reynolds stress for the sand-free flow by Jin et al. (2021) demonstrates favorable agreement with the spectral method simulations of Chung and Pullin (2009). These results suggest that the second-order scheme remains capable of capturing the key trends in turbulent statistical characteristics within the current parameter range.

This study aims to elucidate how boundary layer thickness influences the macroscopic behavior of near-threshold sediment transport—including threshold velocity, transport rate, and particle concentration—by modulating the turbulent scale, with particular emphasis on the role of large-scale coherent structures in regulating particle entrainment. While the fine-scale structures you noted may reduce the coherence of stress fluctuations—a point that certainly merits further physical exploration—our findings indicate that, under near-threshold conditions, particle entrainment is primarily governed by extreme stress events associated with large-scale structures whose characteristics are shaped by the boundary layer thickness (Pähtz et al., 2018). Although the second-order scheme introduces some numerical dissipation at fine scales, it has proven effective in capturing the statistical behavior and energy distribution of these large-scale structures (Wang et al., 2019; Feng and Wang, 2023; Jin et al., 2024).

The flow regime investigated here lies in the near-threshold region, where the friction Reynolds number is moderate relative to that of high-Reynolds-number atmospheric boundary layers. Within this parameter space, the second-order scheme enables efficient, multi-parametric investigations at a manageable computational cost.

In summary, we acknowledge the theoretical advantages of spectral methods for resolving fine-scale turbulence and appreciate your constructive suggestion. In future work, we plan to incorporate spectral or higher-order schemes for comparative validation, aiming to systematically quantify the impact of numerical accuracy on the dynamics of particle entrainment and transport.

[1] Jin T, Wang P, Zheng X. Characterization of wind-blown sand with near-wall motions and turbulence: From grain-scale distributions to sediment transport[J]. Journal of Geophysical Research: Earth Surface, 2021, 126(8): e2021JF006234.

[2] Chung D, Pullin D I. Large-eddy simulation and wall modelling of turbulent channel flow[J]. Journal of fluid mechanics, 2009, 631: 281-309.

[3] Pähtz T, Valyrakis M, Zhao X H, et al. The critical role of the boundary layer thickness for the initiation of aeolian sediment transport[J]. Geosciences, 2018, 8(9): 314.

[4] Wang P, Feng S J, Zheng X J, et al. The scale characteristics and formation mechanism of aeolian sand streamers based on large eddy simulation[J]. Journal of Geophysical Research: Atmospheres, 2019, 124(21): 11372-11388.

[5] Feng S J, Wang P. The influences of boundary layer thickness on the characteristics of saltation sand flow–A large eddy simulation study[J]. Aeolian Research, 2023, 60: 100853.

[6] Jin T, Wang P, Cao B. Transport characteristics of aeolian sand near different thresholds[J]. Catena, 2024, 247: 108541.

Overall, I found that the captions of almost every figure lacked the information necessary to properly interpret the figures. I think that the authors should consider revising the captions to include more relevant information about the figures, such as reminding the reader what each symbol means.

Authors' response: Thank you for your valuable suggestion. We have revised and supplemented all figure captions in the revised manuscript to include necessary explanatory information, aiming to help readers better understand the figures. The specific modifications include:

(1) Clarifying the meaning of different colors, line styles (e.g., solid, dashed, and double-dash-dotted lines), and arrows used in each figure, with explicit references to the quantities they represent—such as wind velocity, boundary layer thickness, and the mean and variance of particle diameter;
(2) Providing clear definitions of key symbols, including the density ratio s, resultant velocity V_p, the von Kármán constant κ, and the value of parameter B (e.g., B=5.5 in a straight channel);
(3) Noting in the caption of Fig. 9 that the line styles and colors are consistent with those used in other figures (e.g., Figs. 5 and 8), to facilitate cross-referencing.

These revisions have been clearly marked in the updated manuscript for your convenience. We sincerely appreciate your insightful comments, which have helped us improve the presentation of our work.

Specifically regarding figure 6, the particles almost appear to be stacked in columns, i.e. they seem far too organized. Can the authors explain this phenomenon? I assume the particles are able to move horizontally, as they mention that the particles have horizontal boundary conditions, but this figure makes me think that they only mover vertically.

Authors' response: In Fig. 6, the visual appearance of "column-like stacking" of particles is primarily attributed to the following reasons:

Under near-threshold transport conditions, the wind velocity is relatively low

(θ_*=0.0032 in Fig. 6), and particles are mainly entrained by fluid and rebound motions. Localized high instantaneous shear stresses play a significant role in lifting particles, making their vertical movements more pronounced, while horizontal motions are less intuitively visible in instantaneous snapshots. In fact, the horizontal velocity of particles is clearly represented—particle colors in Fig. 6 indicate their velocity magnitude, and together with the vertical profiles of mean horizontal particle velocity shown in Fig. 5, this confirms that particles do move in the horizontal direction, with streamwise velocity being dominant. Furthermore, Fig. 6 primarily displays the instantaneous particle distribution in the streamwise–vertical plane, where projection effects in the spanwise direction enhance the visual impression of vertical continuity.

One major point I have is that the Reynolds number is probably what matters here, not the boundary layer height independently. The authors mention as much when they reference that the boundary layer height (which increases the Reynolds number) controls the spectrum of turbulence scales. I think this article would benefit from a passage discussing the dynamical importance of the Reynolds number, and how the boundary layer height is actually only one part of the story (the other two being viscosity, and the wind velocity, or friction velocity).

Authors' response: Actually, as you pointed out in your comment, the boundary layer thickness itself is not an independent parameter, but rather regulates the multi-scale structure of turbulence by affecting the friction Reynolds number $\mathrm{Re}_\tau = u_* \delta / \nu$, thereby modulating near-wall turbulent statistics and particle transport processes. However, in this study, the friction velocity u_* and kinematic viscosity ν are fixed in the discussion, so the variation in the friction Reynolds number directly corresponds to the change in boundary layer thickness.

Nevertheless, we agree with your suggestion that the core role of the Reynolds number should be more explicitly articulated in the manuscript, clarifying how boundary layer thickness, friction velocity, and viscosity jointly determine the friction Reynolds number and subsequently influence turbulence structures and sediment transport behavior. Accordingly, we have added the following passage at the beginning of Section 3 in the revised manuscript:

"It should be noted that the boundary layer thickness δ does not affect turbulence structures in isolation, but rather acts through the friction Reynolds number $\mathrm{Re}_\tau = u_* \delta / \nu$. Under the same friction velocity u_* and ν, a larger δ corresponds to a higher Re_τ, which supports larger-scale turbulent eddies and richer multi-scale interactions. Therefore, the boundary layer thickness effects observed in this study are essentially manifestations of Reynolds number effects under near-threshold transport conditions."

We thank you again for this important insight, which has helped enhance the scientific depth and clarity of our manuscript.

Minor comments and typographical errors: The authors use the word "intermittency" many times. That has a specific meaning in the turbulence literature, and could easily be misunderstood. The authors should consider using the word "variability" as it seems to be what they mean, based on my reading.

Authors' response: We thank the reviewer for the careful observation and professional suggestion. We agree that the word "intermittency" carries a specific meaning in turbulence research and may indeed lead to confusion.

In this manuscript, we use "intermittency" primarily to describe the following two phenomena:

(1) Temporal intermittency of the transport process: under near-threshold wind conditions, sand transport exhibits an intermittent burst-like pattern—brief periods of intense activity separated by longer quiescent intervals (as stated in the Introduction: " characterized by intermittent bursts of intense activity separated by quiescent periods").

(2) Spatial intermittency of particle distribution: the non-uniform spatial distribution of particles, which we quantify by defining the "particle spatial occupancy" (α_p) (Section

3, Fig. 7 and related discussion).

Nevertheless, we also recognize that, from the perspective of strict turbulence terminology, "intermittency" typically refers to the non-Gaussian statistical characteristics of small-scale turbulent structures in both time and space. To avoid ambiguity, we will adjust the relevant expressions in the revised manuscript as follows:

When describing the discontinuity of transport activity, we will continue to use "intermittent" or "intermittency," as these terms are widely accepted in geomorphology and aeolian physics for describing such phenomena (e.g., Stout and Zobeck, 1997; Carneiro et al., 2015). When describing the fluctuating or variable nature of particle distribution, we will adopt the term "variability" as suggested, to more accurately reflect its statistical fluctuation characteristics and avoid confusion with the turbulence-specific meaning of "intermittency."

The specific revisions have been marked in the manuscript.

[7] Stout J E, Zobeck T M. Intermittent saltation[J]. Sedimentology, 1997, 44(5): 959-970.

[8] Carneiro M V, Rasmussen K R, Herrmann H J. Bursts in discontinuous Aeolian saltation[J]. Scientific Reports, 2015, 5(1): 11109.

Line 132: is u(x_p) the filtered velocity (i.e. what comes right out of the LES?), or is the sampled velocity re-constructed.

Authors' response: $u(x_p)$ is the filtered fluid velocity at the particle location interpolated with a third-order Lagrange scheme. We have already stated this in the original text.

Line 238: "Increasing"

Authors’ response: We have made the revisions as suggested. Thank you for your reminder.

The particle spatial occupancy: isn't this just the concentration? Is it markedly different?

Authors’ response: "Particle spatial occupancy" is indeed related to concentration, but there are distinct differences between the two in terms of definition and physical meaning.

Particle volume fraction (concentration) is defined as the ratio of particle volume to the grid volume. It reflects the amount of particle material per unit volume and is an intensive quantity. In this manuscript, Fig. 5(b) presents the vertical profile of the particle volume fraction. Particle spatial occupancy (α_p) is defined as the ratio of the number of grid cells containing particles to the total number of grid cells. It reflects the extent or coverage of particle distribution in space and is a geometric quantity. It measures "how much space the particles occupy," rather than "how many particles are in each space."

Although related, these two quantities are not equivalent. For example, near the wall, α_p may approach 1 (almost all grid cells contain particles), while the particle volume fraction may still be very small (very few particles in each grid cell); Conversely, if particles cluster together, the particle volume fraction may be locally high, but α_p could be very small.

Therefore, α_p is primarily used to quantify the spatial heterogeneity of particle distribution (i.e., whether particles are uniformly dispersed throughout the flow field), whereas the particle volume fraction reflects the vertical distribution of transport intensity. In Section 3, we employ both parameters precisely to characterize particle motion under near-threshold transport conditions from different perspectives.

Line 362: Perhaps it's worth mentioning that the maximum magnitude of the fluctuations occur in the buffer layer and this is a well recognized phenomenon, i.e. u_rms is maximal around y^+ = 10-20 and has some influence from outer layer motions (i.e. the boundary layer height). This can be seen in many papers on wall-bounded turbulence i.e. fig 4 in Smits et. al (2010) 10.1146/annurev-fluid-122109-160753

Authors' response: The phenomenon you mentioned—that the maximum streamwise turbulence intensity occurs in the buffer layer ($y^+ \approx 10–20$) and is modulated by outer-layer motions—is indeed a well-established conclusion in wall-turbulence research, as clearly illustrated in Fig. 4 of Smits et al. (2010).

It should be noted that what we discuss in Line 362 of our manuscript is the vertical distribution of particle velocity fluctuations, rather than fluid velocity fluctuations in single-phase turbulence. As inertial particles, their velocity fluctuation characteristics differ fundamentally from those of the fluid. Nevertheless, the near-wall peak location of particle velocity fluctuations still has certain similarities with that of fluid velocity fluctuations—both occur in the near-wall region.

However, this study employs wall-modeled large-eddy simulation, in which the wall-normal distance of the first grid point corresponds to $y^+ > 30$. This means we are unable to resolve the flow details within the buffer layer ($y^+ < 30$), and therefore cannot directly observe the peak of fluid velocity fluctuations at $y^+ \approx 15$. The particle velocity fluctuation profiles presented in this manuscript are statistically obtained on the resolvable grid scales, and their near-wall peak location is constrained by the grid resolution, reflecting the overall response of particles in the near-wall region.

That said, we fully agree with your insight regarding the modulation of near-wall fluctuations by outer large-scale motions. In Fig. 8 and the associated discussion, we have already pointed out that an increase in boundary layer thickness enhances the amplitude of near-wall particle velocity fluctuations, a phenomenon closely related to the intensification of outer large-scale structures and their influence on the inner region. We have also cited Smits et al. (2010) to strengthen the depth and completeness of this discussion.

[9] Smits A J, McKeon B J, Marusic I. High–Reynolds number wall turbulence[J]. Annual Review of Fluid Mechanics, 2011, 43(1): 353-375.

Line 368: I'm having trouble following this part. Please revise.

Authors' response: Thank you for your correction. This refers to the description of mass flux fluctuations in Fig. 8(b). To make the description clearer, we have revised the text accordingly and added "Fig. 8(b)" at the relevant position to specify the subject.

I'm unclear on the meaning of the cyan arrow in figure 9(b).

Authors' response: The cyan arrow in Fig. 9(b) is intended to indicate the trend of the particle size probability density distribution as the wind velocity increases (from θ_* =0.0032 to 0.0043). Specifically, as the wind velocity increases, the probability density of larger particles decreases. This arrow is included to help readers intuitively understand this trend. We have supplemented the figure caption with a relevant explanation to make the figure clearer and more comprehensible. Thank you again for your valuable comment.

Line 385-386: I can't quite follow the inline math. Please revise.

Authors' response: Since the mean and variance of particle diameter follow the same trend under different boundary layer thicknesses, we have rewritten the relational expression of their magnitudes as follows: $d_{p,\ \delta=1.0\ m} > d_{p,\ \delta=5.0\ m} > d_{p,\ \delta=10.0\ m}$.