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.