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Numerical study of sand particles transporting in the atmospheric Ekman boundary layer

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SUMMARY:
The Eulerian-Lagrangian two-phase direct numerical simulation is used to study the dynamics of sand particles transporting in the atmospheric Ekman boundary layer. The results reveal that the velocity of sand particles in the viscous and buffer layers can apparently be influenced by gravity. But nearly no evident difference is discovered in the turbulent region where the inertial force is dominant. Further evidence on the interaction between particle and vortex shows that gravity is not strong enough in our simulation to change their relationship even in the viscous force dominant layers. Sand particles exhibit apparent tendency to accumulate in the low vortex strength regions similar to the particle-laden homogenous isotropic turbulence.

Keywords: Ekman layer, two-phase flow, sand transport, particle-turbulence interaction

1. INTRODUCTION

Sandstorm, which could be seen as a solid-fluid two-phase flow, usually travels thousands of kilometres from its birthplace. Thus, the planetary rotation effect should not be neglected when studying the sand particles transporting with the storm.

With the rotation of the planet, the horizontal velocity direction is twisted along the axis perpendicular to the ground, which is known as the Ekman spiral. The dynamics of turbulent flow within the atmospheric Ekman boundary layer is different from that in the canonical wall boundary layer (Deusebio et al., 2014). Although plenty of research investigations on solid-particle-laden turbulent channel flow have been extensively carried out (Mortimer et al., 2019; Fornari et al., 2018;), it still lacks detailed evidence that how the solid particles transport in the turbulent Ekman boundary layer.

In this study, we briefly investigate the gravity effect on the dynamics of sand particles transporting in the atmospheric Ekman boundary layer.

2. NUMERICAL METHODOLOGY

The Eulerian-Lagrangian two-phase direct numerical method (DNS) is used to simulate the sand particles transporting in the atmospheric Ekman boundary layer.

2.1. Navier-Stokes Equation

The 3D incompressible Navier-Stokes equations of fluid phase in a rotating reference frame are

$$\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u} = -\frac{\nabla p}{\rho_0} - \boldsymbol{f} \times \boldsymbol{u} + \nu \nabla^2 \boldsymbol{u} \tag{1a}$$

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1b}$$

where the velocity vector $\boldsymbol{u} = (u, v, w)$ in the Cartesian coordination system with the horizontal axis x and y, and the vertical axis z, p is the pressure and $\boldsymbol{f}$ is the Coriolis force. The Ekman boundary layer is driven by a constant pressure gradient $\nabla p/\rho_0 = -\boldsymbol{f} \times \boldsymbol{G}$, where $\boldsymbol{G}$ represents the geostrophic wind vector aligned with the x axis.

The governing equation is normalized with the laminar Ekman layer thickness, $\delta_E = \sqrt{2\nu/f}$ and the geostrophic wind speed $G = |\boldsymbol{G}|$. Thus, the Ekman Reynolds number would be $Re = G\delta_E/\nu = 400$, with the corresponding Rossby number $Ro = G/f\delta_E = Re/2$.

2.2. Equation of Motion of a Spheric Particle

The Maxey-Riley (Maxey and Riley, 1983) equation of motion for a spheric particle is adopted here to model the particle phase which can be simplified (see Eq. (2)) considering the assumption that the density ratio $\rho_p/\rho_f = 2500$ is significantly larger than unity.

$$\frac{d\boldsymbol{x}_p}{dt} = \boldsymbol{u}_p(t) \tag{2a}$$

$$\frac{d\boldsymbol{u}_p}{dt} = \frac{C_D(\boldsymbol{u}_{f@p} - \boldsymbol{u}_p)}{\tau_p} + \left(1 - \frac{\rho_f}{\rho_p}\right) g\boldsymbol{e}_z \tag{2b}$$

where $\boldsymbol{x}_p$ and $\boldsymbol{u}_p$ are the particle location and velocity vectors, $\boldsymbol{u}_{f@p}$ is the fluid velocity vector at the particle location, and the drag coefficient $C_D = 1 + 0.15Re_p^{0.687}$ is a function of the particle Reynolds number $Re_p = |\boldsymbol{u}_{f@p} - \boldsymbol{u}_p| d_p/\nu$. The particle response time is $\tau_p = \frac{1}{18}\frac{\rho_p}{\rho_f}\frac{d_p^2}{\nu}$, where d_p is the diameter of the particle.

3. RESULTS

We firstly investigate the effect of gravity on the relationship between fluid and particle velocities (shown in Fig. 1). It is apparent that the gravity facilitates the development of particle velocity in the viscous sublayer and buffer layer, but nearly no effect in the turbulent region. This is mainly contributed to the vertical gravity acceleration, which increases the particle vertical velocities. Since in those two layers, the weak viscous force is dominant, gravity can make more contribution to the particle vertical kinetic energy. However, in the turbulent region, the inertial force is strong enough to counteract the effect from gravity.

Besides, in the buffer layer and viscous sublayer, in the case without gravity, sand particles have higher probability of smaller fluid velocities, indicating that sand particles tend to accumulate in the fluid regions with lower fluid velocity.

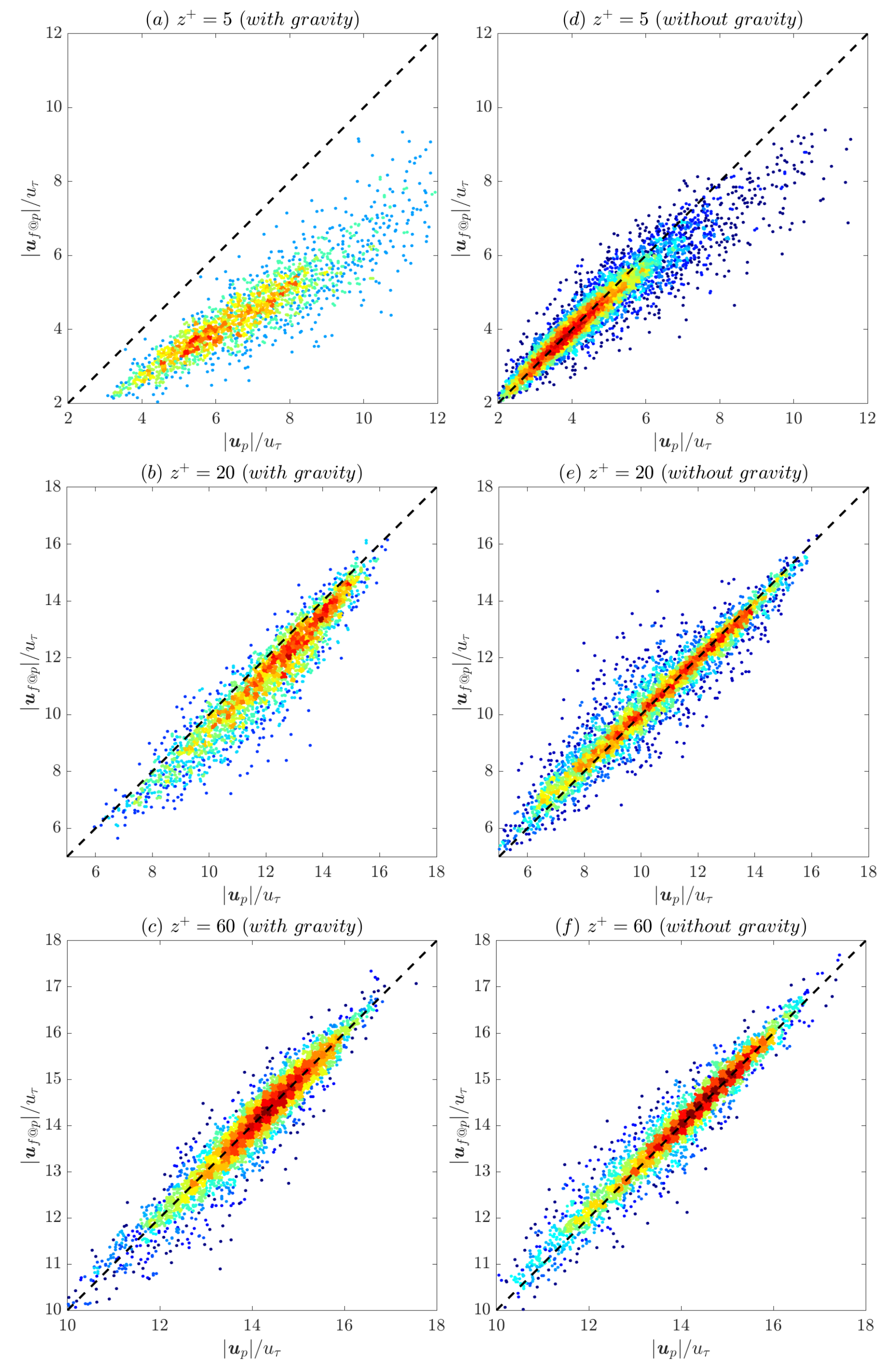

Figure 1. Gravity effect on the relationship between fluid and particle velocities. Dots are coloured by the probability with (a) and (d), (b) and (e), (c) and (f) having the same colorbar interval, respectively.

We further exam the interaction between sand particles and vortex within Ekman layer. The Rortex method (Xu et al., 2019), is used to obtain the vortex strength. The results of vortex strength where sand particles locate are presented in Fig. 2, showing sand particles are prone to accumulate in the low vortex strength regions preferentially. It is evident that in our simulation cases, gravity has no influence on the interaction between particles and vortex.

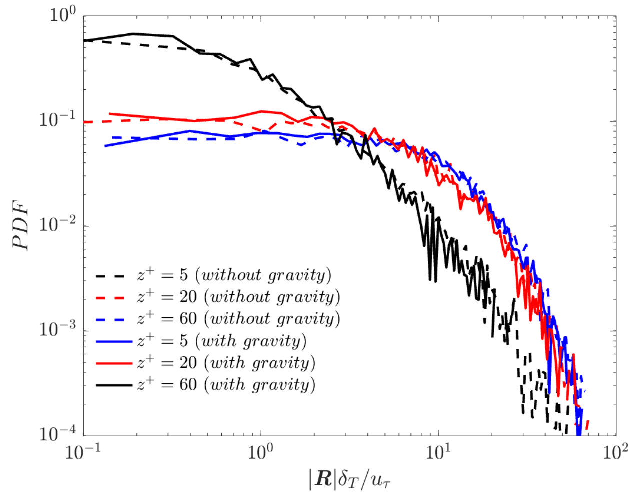

Figure 2. PDF of Rortex magnitude at sand particle locations.

4. CONCLUSION

The dynamics of sand particles with/without gravity effect in the turbulent Ekman layer is studied using Eulerian-Lagrangian two-phase direct numerical simulation. We find that the gravity could increase the particle velocity and impede sand particles accumulating in the low fluid velocity regions significantly in the viscous and buffer layers. However, in the turbulent region, gravity effect is too weak to influence particle velocity, which could attribute to the strong inertial force in the logarithmic turbulent layer. Besides, gravity shows no influence on the interaction between sand particles and vortex in the whole Ekman boundary layer. Sand particles still accumulate in the low vortex strength regions similar to the particle-laden homogeneous isotropic turbulence (Bec et al., 2014). We would further study this interaction between Ekman turbulence and sand particles in the future work to investigate to what extent gravity effect could be neglected.

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