SETTLING VELOCITY OF SMALL PARTICLES IN HIGH-RESOLUTION HOMOGENOUS ISOTROPIC TURBULENCE

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Abstract
Turbulence is an important mechanism which influences atmospheric flows and has significant impact on many engineering processes. In particular, turbulence plays a key role in cloud dynamics and intensifies the formation of warm rain. Small-scale turbulent motion augments radial relative velocity between droplets and induces droplet accumulation in the low vorticity region [3]. This leads to enhancement of collision-coalescence and in consequence accelerates the growth of the rain drops. Turbulent collision-coalescence plays an important role for droplets of radius from 10 to 60 μm. For larger droplets gravity dominates the motion but turbulence still affects collision rate through altering settling velocity. Relative differences in settling velocity have a direct effect on the collision rate.
In this study, we examine numerically several mechanisms that may enhance or reduce the settling velocity of small heavy particles. One of those is preferential sweeping (particles show preference to reside in the downward-sweeping sides of eddies), which occurs for strong turbulence and large particle inertia. This was found in experiments by Aliseda et al. (2002) [1] and Hill (2005) [2] and numerical simulations by Wang and Maxey (1993) [3], and model theory by Davila and Hunt (2001) [4]. On the other hand, vortex trapping or loitering (particles spend more time in upflow than in downflow regions of the flow) could lead to reduction of the settling velocity of Stokes particles. This reduction typically occurs for weak turbulence, weak inertia, but strong sedimenting particles (Nielsen, 1993 [5]). In both cases, the distribution of particles relative to vortical structure is mainly controlled by their inertial interactions with the small-scale turbulence. However, the level of increase or decrease in the average settling velocity depends strongly on the large energetic eddies [6, 7].

METHODOLOGY AND NUMERICAL EXPERIMENTS

Recently we developed a new highly scalable implementation of direct numerical simulations of turbulent transport and collision of inertial particles at higher flow Reynolds numbers. The new implementation is used to study the dynamics of inertial particles in isotropic homogenous turbulence, and specifically the conditions for the different mechanisms which affect the settling rate. Our simulations go beyond the cloud droplets, for which particle Stokes number $St = \tau_p/\tau_k$ and velocity ratio $S_v = v_p/v_k$ are interdependently varied. Since $St \sim \epsilon^{1/2}$ and $Sv \sim \epsilon^{-1/4}$ the relative importance of gravity vs inertia will change with the flow dissipation rate. Thus, our first task is to explore the results for several different dissipation rates.
The other problem examined in our study concerns the effects of different ranges of turbulent scales on the settling velocity. This problem for small Reynolds number ~ 65 has been already studied by Yang and Lei (1998) [6]. They concluded that large-scale flow plays a significant role in determining the increase in settling velocity, namely, the increase in settling scales with u', not v_k, but peaks at $\tau_p/\tau_k \sim 1$. They explained this mixed scaling as follows: the preferential concentration is a necessary condition (controlled by τ_p/τ_k), but the level of increase is controlled by drag in the low-vorticity region, which involves the large-scale flow. Our results are more complete and suggest that the maximum level of increase scales with u' for low R_λ numbers (R_λ < 100), then appear to saturate with R_λ for R_λ > 100. The key question here is if the largest scales eventually play no role for a given droplet size. Results using filtered DNS field can clarify this question, or even answer if the loitering effect is relevant.
In addition, for a more complete picture conditional statistics will be provided. The increase in settling velocity on the local flow characteristics such as local dissipation rate / enstrophy, local u' will be examined.

DEPENDENCE ON REYNOLDS NUMBER AND FORCING SCHEME

Here, we present some preliminary results showing the net effect of turbulence on the settling velocity. In a number of simulations we studied the effects of flow Reynolds number and large-scale forcing. Figure 1 presents average particle settling velocity normalized by terminal velocity (settling velocity of isolated particle in the stagnant air). An increase in settling velocity over terminal velocity takes place when particle Froud number is close to unity [4]. This velocity increase is physically attributed to selective downward motion of droplets around Kolmogrov vortices. A few important conclusions can be drawn from the figure 1. The increase in particle preferential sedimentation velocity is observed to saturate with R_λ for droplets sizes of $a = 15\mu m$ and smaller. These saturation trends imply that the range of scales represented in a flow with $R_\lambda \sim 500$ is adequate to study the settling velocity of small cloud droplets. Using the stochastic forcing, the peak value does not show signs of saturation which indicates that further but finite increase in sedimentation is possible for even higher R_λ. For droplets ($a = 20\mu m$ and $a = 30\mu m$), the saturation of the settling velocity depends on the forcing method used (figure 2). More coherent flow structures, generated with deterministic forcing, leads to earlier plateau for increase in sedimentation velocity. Results obtained with deterministic forcing show that even larger

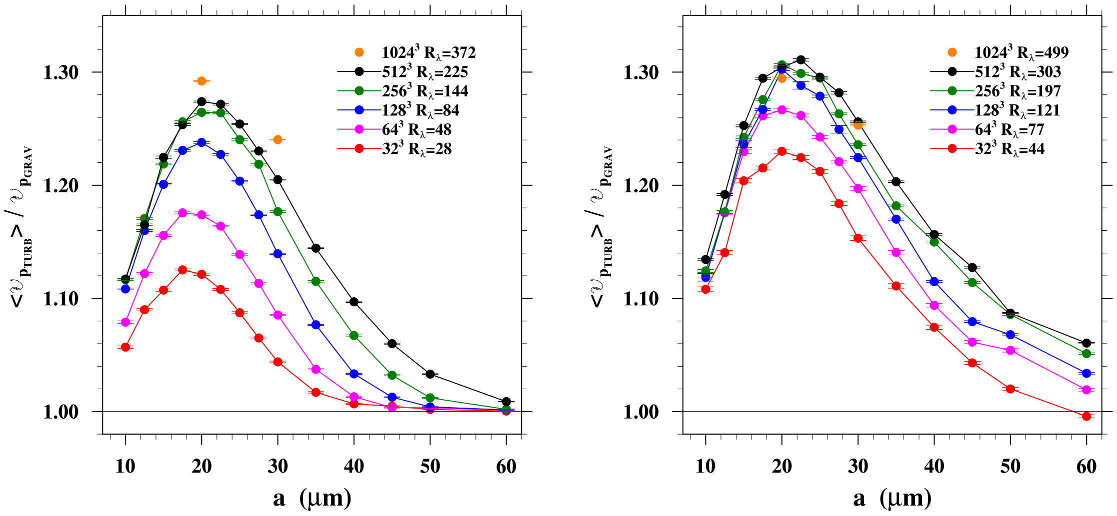

Figure 1. Settling velocity for different Taylor microscale Reynolds number and two different forcing schemes (a) stochastic, (b) deterministic. All simulations have been performed for energy dissipation $\epsilon = 400$ cm^2/s^3

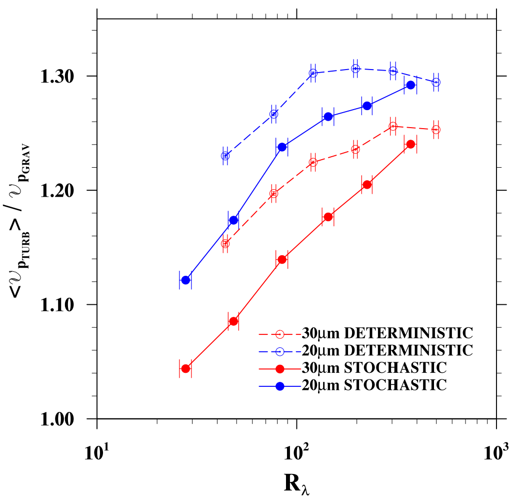

Figure 2. Settling velocity of droplets of two sizes as a function of different Taylor microscale Reynolds number and two different forcing schemes stochastic (solid line) and deterministic (dashed line).

particles ($a \sim 60\mu m$) undergo an increase in sedimentation velocity. From the performed simulations results that the effect of enhancing of the settling velocity is more pronounced for deterministic scheme. The slope of the right side of the maximum is steeper for the stochastic scheme.

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