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Technical note

Effects of long-range particle–particle hydrodynamic interaction on the settling of aerosol particle clouds

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ABSTRACT

The cloud settling effect for aerosol particles is examined based on approximation of long-range particle–particle hydrodynamic interactions. It is indicated that the normalized cloud settling velocity (CSV) exhibits a linear relationship with the product of particle number and particle size ratio. A particle-level analysis, combined with the Stokes/Oseen dynamics simulation, is applied to study the effects of fluid inertia and cloud shape on the CSV. Prediction functions for both spherical and columnar clouds, considering the effect of fluid inertia, are obtained through both simulation regression and analytical derivation.

1. Introduction

Dynamics of airborne fine particles has been extensively studied both experimentally and theoretically, due to harmful effects on environment, climate change, and public health (Lighty, Veranth, & Sarofim, 2000). While single particle analysis is commonly used to evaluate mobility of aerosol particles, hydrodynamic interactions between particles may cause a many-particle system to behave differently when moving as a whole.

A typical particle system is the aerosol cloud, defined as a high concentration region which has a distinct boundary with the ambient clean air or low-concentration aerosol. Aerosol clouds tend to move significantly faster than individual particles under external forces due to the complex particle–particle hydrodynamic interactions inside (Robinson & Yu, 2001). As one area of application, a series of investigations explained that the cloud settling effect significantly enhances penetration of aerosol particles into the lung (Hofmann, Morawska, & Bergmann, 2001; Robinson & Yu, 2001; Zhang, Kleinstreuer, & Hyun, 2012).

Systematical studies on cloud setting effect are mostly concentrated on colloidal systems. For instance, settling of a spherical cloud of colloidal particles was investigated using Stokeslet simulations (Metzger, Nicolas, & Guazzelli, 2007; Nitsche & Batchelor, 1997). However, application of Stokeslet simulations is restricted to low particle Reynolds number due to neglect of fluid inertia. While this restriction is satisfied for colloidal flows, it is frequently not satisfied for aerosol clouds. For example, a settling particle with radius of 2.5 μm and density of 2000 kg/m^3 has a particle Reynolds number of

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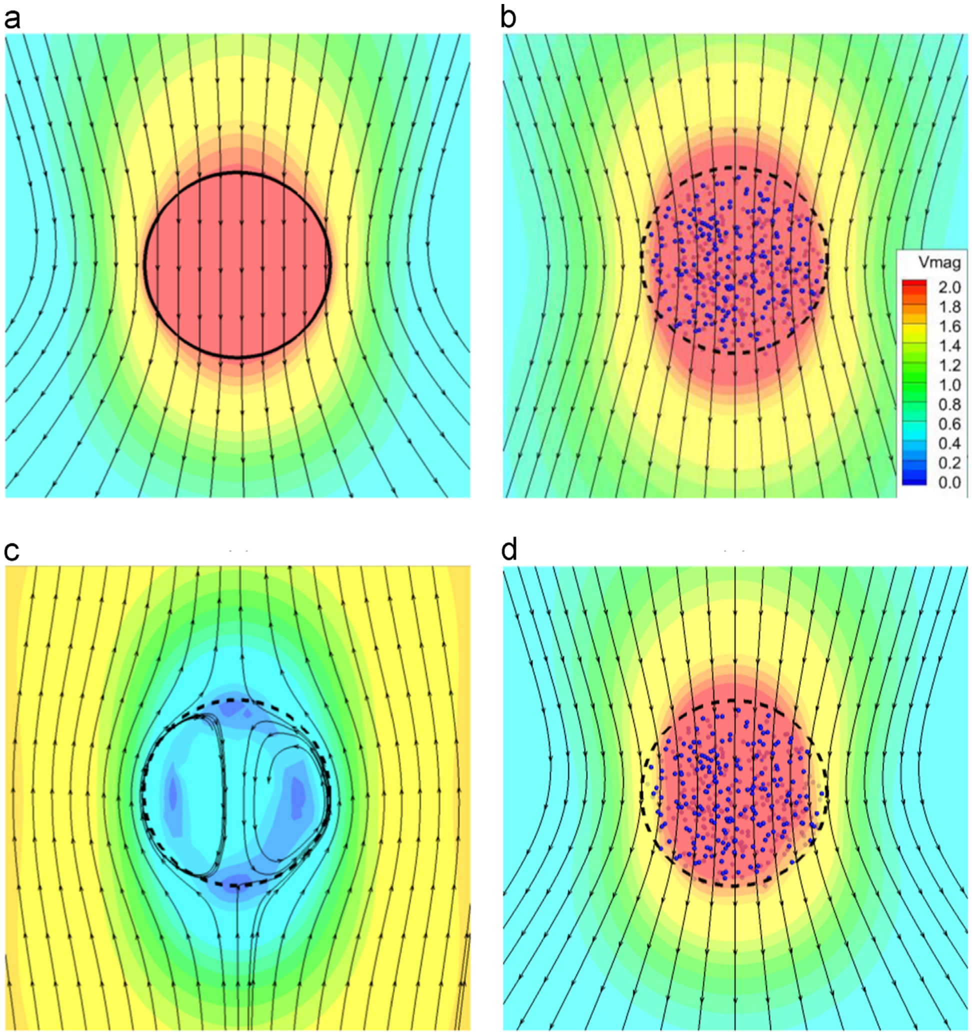

Fig. 1. Flow field around a settling cloud of 400 particles: (a) flow field around the equivalent solid sphere; (b) prediction by Stokes dynamics; (c) relative field inside the cloud (relative to the mean flow inside the cloud); and (d) prediction by Oseen dynamics. Contours indicate the magnitude of flow velocity.

4.2×10^{-6} in water or 3.3×10^{-5} in air. Pignatel, Nicolas, and Guazzelli (2011) and Chraïbi and Amarouchene (2013) conducted Oseenlet simulations for settling of spherical and columnar clouds, indicating that the fluid inertia suppresses the cloud settling velocity. We and co-workers also applied Oseenlet simulations to analyze particle segregation in the settling clouds (Faletra, Marshall, Yang, & Li, 2015). Nevertheless, expressions for correction of fluid inertia effect have not yet been reported, due to the complexity of hydrodynamic interactions which is also increased by the difference of the cloud shape.

The objective of current work is to examine the cloud settling effect of aerosol clouds with consideration of fluid inertia and cloud shape effects. An analytical expression integrating effects of fluid inertia and cloud shape is derived to predict the cloud settling velocity. Dynamics of cloud settling is presented in Section 2. In Section 3, we examine the fluid inertia effect and propose a correction coefficient. The shape effect on cloud settling velocity is analyzed in Section 4. Conclusions are given in Section 5.

2. Mechanisms and dynamics of cloud settling

Settling velocity of a particle in a cloud can be expressed as summation of the bulk flow velocity $\mathbf{U}_0(\mathbf{x}_i)$, the overall disturbance $\mathbf{u}_{dis}(\mathbf{x}_i)$ and the terminal velocity $\mathbf{v}_{0,i}$ of this particle, where $\mathbf{x}_i$ is position of the particle's centroid. Settling velocity of the cloud is thus determined by averaging over all the particles, as $V=U_0+\overline{u}_{dis}+\overline{v}_0$. The bulk velocity and terminal velocity of individual particles are known. So the key question is how to obtain the overall disturbance flow. In this section, several methods to calculate the overall disturbance flow are introduced and discussed, including the equivalent solid body (ESB) approach, equivalent liquid drop (ELD) approach, Stokes/Oseen dynamics simulation, and analytical method. The overall disturbance fields obtained by the above