On the Fall velocity of a Hydrometeor in a Turbulent flow

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Abstract

Understanding the falling velocity of cloud droplets and ice crystals in a nonuniform flow is fundamental to cloud physics and precipitation. In this study, the mean settling velocity of a hydrometeor falling into a non-stationary fluid is examined. To investigate the possible particle-fluid interaction, a homogeneous and isotropic turbulent flow fields is considered. The study covers a wide range of flow velocities and hydrometeor density and size. The results show initially reduction of hydrometeor settling velocity and then enhancement in strong turbulence. The mean settling velocity depends on a) mean flow and turbulent intensity i.e., standard deviation of flow and b) particle terminal velocity i.e., the shape and size of hydrometeor, its density, the dynamic viscosity and the density of the fluid, and the gravitational acceleration. The non-dimensional parameters that are important in characterization of hydrometeor settling velocities are estimated using dimensional analysis. These non-dimensional parameters are then used to formulate the mean settling velocity.

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I. Motivation

- Our work is motivated by observations of fall velocity distributions of hydrometeors measured by the Multi-Angle Snowflake Camera (MASC) located at Oliktok Pt. Alaska.
- Without a wind shield, the MASC measures hydrometeor mean settling velocity. With a wind shield the fall velocity is closer to the terminal velocity.
- The distinction between mean settling velocity and terminal velocity is not included in atmospheric sciences numerical modeling efforts.
- The existing fall velocity parameterizations that have been derived from measurements of hydrometeors in still air are appropriate representations of the average settling velocity in turbulent air and no current model treats the hydrometeors otherwise.

II. Introduction

Improved understanding of the effect of particle-turbulence interactions on fall-out is fundamental to many scientific and engineering problems.

In the atmospheric sciences, it affects the residence time of aerosol contaminants in the atmosphere, the evolution of cold-weather storms, precipitation extremes, and climate sensitivity.

The purpose of this study is to examine the mean settling velocity of a hydrometeor falling in a homogeneous, isotropic turbulent flow with a diameter d_p ranging from 0.2 to 10 mm and a specific density s from 20 to 500.

Similarity theory based on organization of variables into dimensionless groups is used to developed non-dimensional parameters that are important in characterization of settling velocities. These non-dimensional parameters are then used to formulate the mean settling velocity in a turbulent flows.

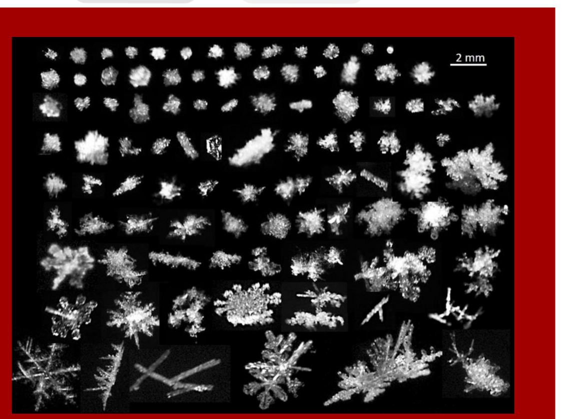
III. Methods

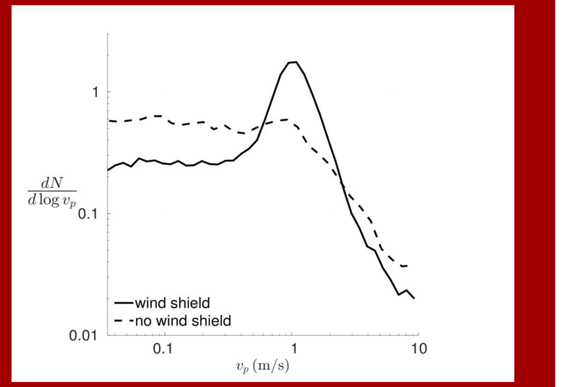
The time-dependent motion of a particle falling under the influence of gravity force in a non-uniform flow is often determined by following modified Maxey-Riley force equation:

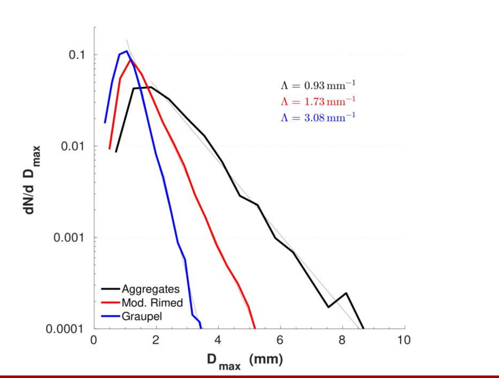
$$
\begin{aligned}
m_p \frac{d\vec{u}_p(t)}{dt}
&= (m_p - m_f)\vec{g} + m_f \frac{d\vec{u}_f(t)}{dt} - k m_f \frac{d}{dt}\left(\vec{u}_p(t) - \vec{u}_f(t)\right) \\
&- \frac{1}{2} C_D(Re) A_p \rho_f \left|\vec{u}_p(t) - \vec{u}_f(t)\right| \left(\left(\vec{u}_p(t) - \vec{u}_f(t)\right) + d_p \int_{t_0}^{t} \frac{\frac{d}{d\tau}\left(\vec{u}_p(\tau) - \vec{u}_f(\tau)\right)}{\sqrt{4\pi\nu(t-\tau)}} d\tau \right)
\end{aligned}
$$

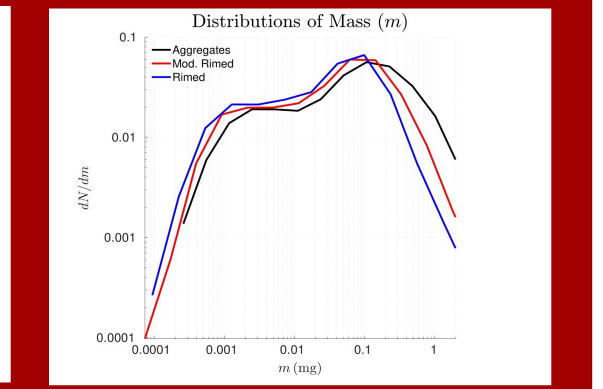
The settling velocity in a Gaussian turbulent flow could be a function of turbulent intensity v_{rms}, mean wind v_m and the size of the particle d_p, its density ρ_p ,the fluid dynamic viscosity μ, the fluid density ρ_f, and the gravitational acceleration g that is $v_p = f\left(v_{rms}, v_m, d_p, \rho_p, \mu, \rho_f, g\right)$. Using the combined scaling variables, the velocity ratio is related to two dimensionless groups as:

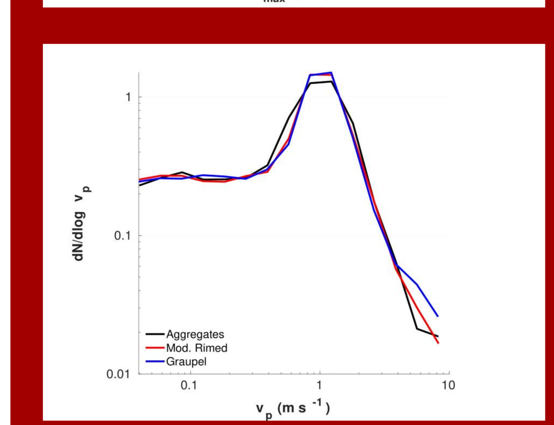
$$\frac{v_p}{v_T} = f\left(\frac{v_{rms}}{v_T}, \frac{v_m}{v_T}\right)$$

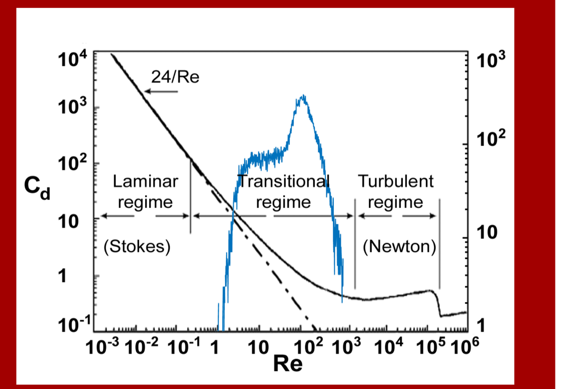












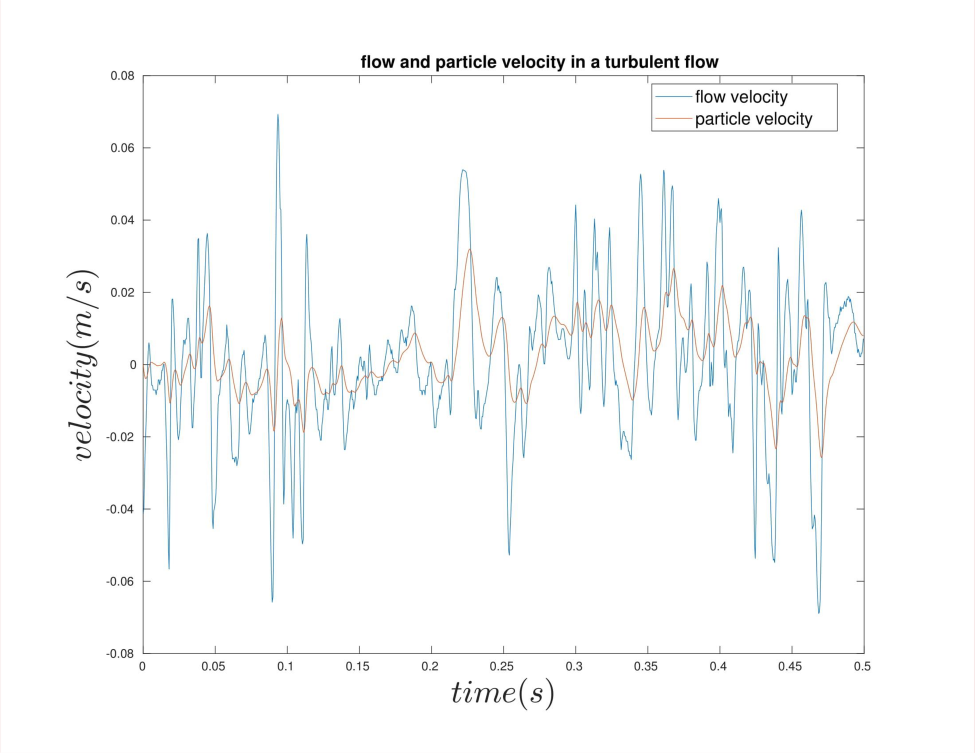
IV. Conclusions

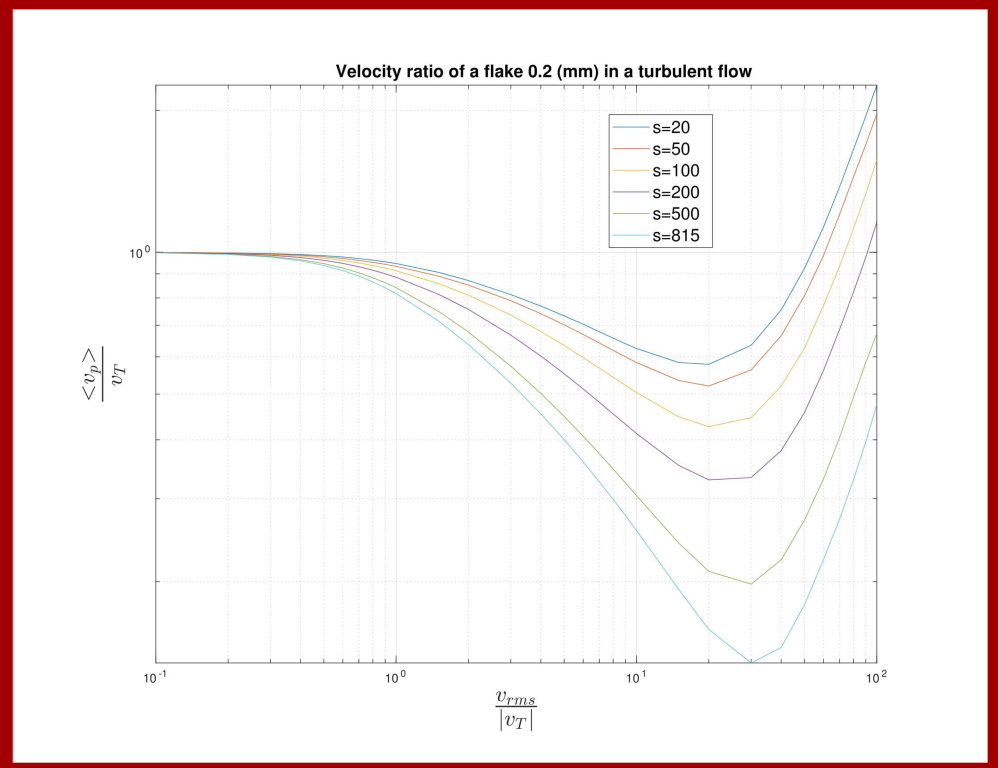
- The difference between hydrometeor terminal velocity and the settling velocity in a turbulent flow depends on the turbulence intensity v_{rms}, the mean wind v_m, and v_T.
- Parameterized $< v_p > / v_T$ shows an exponential decrease with v_{rms} for low turbulence and a linear increase with v_{rms} for high turbulence. We developed a new parametrization as:

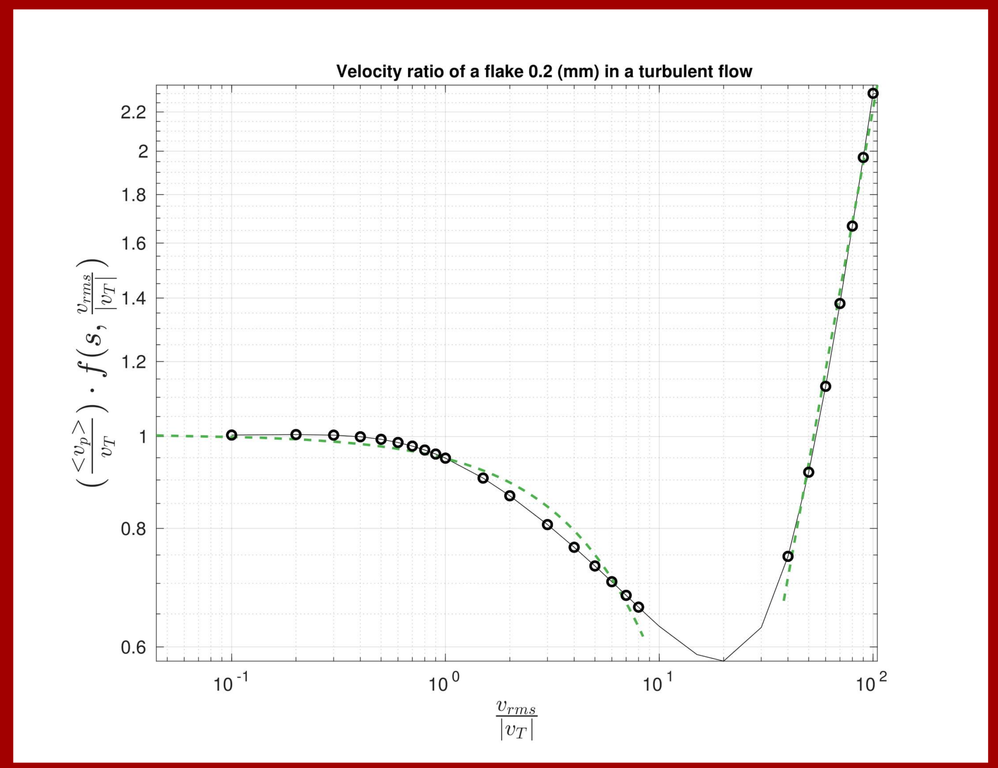
$$
\frac{\langle v_p \rangle}{v_T} = \frac{1}{f\left(s, \frac{v_{rms}}{|v_T|}\right)} \cdot
\begin{cases}
\exp\left(-\alpha \cdot \frac{v_{rms}}{|v_T|}\right) & \frac{v_{rms}}{|v_T|} < 10 \\
\beta \cdot \left(\frac{v_{rms}}{|v_T|}\right)^{\gamma} & \frac{v_{rms}}{|v_T|} > 50
\end{cases}
$$

Where $\alpha = 0.42 \cdot d_p$, $\beta = 0.006$, $\gamma = 1.5$ and

$$f\left(s, \frac{v_{rms}}{|v_T|}\right) = 1 + [0.005 \cdot s - 0.06]\left[1 - \exp\left(-\frac{1}{15}\frac{v_{rms}}{|v_T|}\right)\right]$$







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