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Understanding Wake Capture Effect of the Ice Particle Aggregation Process with the Use of 3D-printed Analogues

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Background

The interactions of ice crystals in a cloud has raised the interest of researchers since the 1950's. With the progress of aviation technology scientists were able to climb high in the troposphere with an airplane and measure the properties of clouds. One of these properties is the habit of ice crystals and how they interact together. With this data in hand, later experiments with ice crystal analogues could be done in a controlled environment of a laboratory, that gave the researchers the chance to compare the behaviour of real ice particles and modelled analogues of them and then form parameterisations that can predict this behaviour. The importance of Reynolds number is its universality, which means that it can describe the flow pattern of an object at different scales. Also, for the purpose of this study, Reynolds number helps to identify the validity of the laboratory ice particle analogue experiments with the ice particles in the atmosphere. Various dimensional and physical parameters for both areas (atmosphere and laboratory) give ratios (Reynolds numbers) of the same order. Consequently, the behaviour of an ice crystal in the atmosphere resembles the behaviour of the modelled analogues in the laboratory. Such behaviour could be fluttering motions of the crystals. Aggregation is the process where two same or different ice crystals are clumping together (Ambaum 2010). The forces that act on ice particles that sediment, which means that they fall only due to the force of gravity (no wind advection or turbulence) are the weight of the particle (w), the buoyant force (B) and the drag force (Fd). Also, terminal velocity (Vt) is very important for the aggregation process as many aggregation models use the parameterisation that all crystals and aggregates fall with their own terminal velocity.

Objectives

The aggregation of ice crystals is an important microphysical process within ice clouds, giving rise to large ice crystals with complex shapes. Aggregation occurs through the collision of ice crystals that sediment within a cloud at different constant velocities which in the literature are called terminal velocities. Current parameterisations in climate models and radar ice content retrievals enable us to estimate the terminal velocity of individual ice crystals. The validity of these parameterisations diminishes as ice crystals approach each other because of the interaction of the trailing particle (upper particle) with aerodynamic forces that are produced in the wake of the leading particle (lower particle) as they sediment through the atmosphere. The impact of the forces that act on each particle during their trajectory is currently little understood, limiting our knowledge of the aggregation process and how efficient actually is. Also, this research aims to expand this knowledge and offer greater understanding of these interactions in order to reduce the uncertainty of ice content and snowfall parameterisations as ice clouds, for example cirrus clouds, cover 1/3 of the atmosphere (Baran 2004) and cirrus clouds affect the solar and infrared energy budget due to their high albedo (reflectivity) and cause heating in the upper troposphere and cooling below (Fu and Liou 1993). It should be made clear that in most climate models, their aggregation processes essentially ignore the interaction of the falling crystals, for example, the wake capture of the trailing crystal and its abrupt acceleration near the aggregation point. In other words, they accept that the two crystals are falling their own constant speeds (terminal velocities).

Methods

To investigate the interaction of two ice particles in a controlled environment and specifically the wake capture of the trailing crystal by the leading crystal laboratory methods are used. The laboratory experiments include a cylindrical tank which is filled with a glycerol and water mixture, a tool for releasing crystals simultaneously and the 3D crystal analogues. Also, for the capturing of the video footage and for the measurement of the terminal velocities and the separation of the crystals a camera and the MATLAB software (mathworks.com) are used respectively. With more details, the cylindrical tank is made by plexiglass and its dimensions are 28cm in diameter and 60cm in height. The height of the tank is adequate for the crystals to reach their terminal velocity, when they are released independently, and aggregation most of the times which is depended by the type, the size and the initial separation of the crystals. Additionally, the width (28cm) of the tank gives the ability to eliminate any drag from the wall of the tank due to high viscosity even for relatively low Reynolds numbers (for example Re=120) (Fidleris and Whitmore 1961). At the bottom of the tank there is a metal mesh which is connected to a wooden handle and helps to retrieve the sedimented particles. The mixture in the tank is consisted by a part of glycerol (in this case it is 40%) and a part of water (60%). This mixture helps to achieve a range of Reynolds numbers which are similar to the ice particles falling in the atmosphere.

Results

In figure 1 and table 1 we see that the increase in velocity of the trailing particle is influenced by its diameter. There is an increase of velocity when diameter of the particle becomes smaller. Also, all types of particles follow this trend (parallel to each other) except type G particle. This is because there is less data (sometimes the crystals were aggregating too early before they enter the field of view of the camera) for the trailing crystal with D=0.74cm and because aggregation only occurred at 1.6cm initial separation (even less data) and this results in higher uncertainty of that particular crystal. Additionally, the trend lines (Figure 1) cannot be defined accurately because of the few measurements and more particle sizes are needed to be tested, for that reason the trends are chosen subjectively. However, the abrupt acceleration in the area of wake capture is experienced in all the particle experiments that have been made and that shows that aggregation possibility is much higher than when the particles fall with steady velocities (terminal velocity) like in most aggregation models parameterisations (Lin et al. 1983; Locatelli and Hobbs 1974; Pruppacher and Klett 2012).

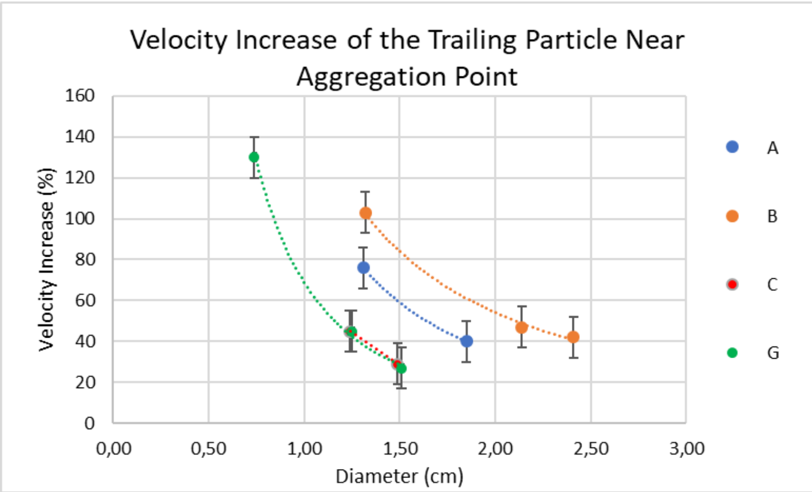

Figure 1. Velocity increase of the trailing particle in relation with its terminal velocity (individually released) near aggregation point. Uncertainty of velocity increase: ± 10%. Uncertainty of diameter is too small to be plotted.

Table 1. Velocity increase in relation to terminal velocity (individually released) at near aggregation point. For B and G particles, two trailing crystals were tested with the larger particle of each type.

Leading Particle		**A (R)** Re=258	**A (r)** Re=140	**B (R)** Re=443	**B (r)** Re=397	**C (R)** Re=255	**C (r)** Re=192	**G (R)** Re=310	**G (r)** Re=234
Trailing Particle	Re	140	258	397	443	192	255	234	310
	r/R	0.71	0.71	0.89	0.89	0.83	0.83	0.83	0.83
	V increase	**76%**	**40%**	**47%**	**42%**	**45%**	**29%**	**45%**	**27%**
	Re			175				89	
	r/R			0.55				0.49	
	V increase			**103%**				**130%**	

Conclusions

The acceleration of the leading particle in the wake capture area is examined and it is found that the acceleration starts after the release of the particles. Although, in the area of reduced pressure the acceleration is steady (on condition that the particles are going to aggregate – initial separation < aggregation threshold), in the area of wake capture the acceleration increases until aggregation. This acceleration in the wake capture is affected by the ratio of diameters of the leading (R) and the trailing (r) particles r/R. The smaller the r/R ratio the higher the increase of the velocity of the trailing crystal. It is observed that the highest increase of velocity of a particle relative to its terminal velocity (when it is released isolated) was measured to be 130% near aggregation point.

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