Mid-High Latitude Cirrus Precipitation Processes

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Introduction

In the latter part of the last century, detailed microphysical compositions of cirrus clouds began to arise because of the availability of high flying aircraft equipped with appropriate instrumentation.[1] Prior to the availability of these sophisticated techniques, much of the composition of cirrus clouds and its influence on weather and climate remained ambiguous because of its high altitude in the Earth's atmosphere. It is evident that cirrus clouds play a key role in the atmospheric thermodynamic processes on Earth, as cirrus clouds cover about 20 % of the Earth.[1]

Cirrus clouds are typically found between 100 to 300 mb in the upper troposphere and they are known to be important components contributing to the planetary radiative heating.[2] It has previously been shown that cirrus clouds converge solar and longwave radiation with some perturbations throughout the column.[3] Thus, these clouds yield large amounts of cooling and heating at the top and at the base of the cloud, respectively.[4] Although these radiative processes of cirrus clouds contribute significantly to the Earth's weather and climate, its growth and precipitation processes will be considered here.

Few studies have been concerned with the impact of cirrus cloud precipitation processes on climate change. This is in part due to the low concentrations of nonspherical ice crystals contained in the cirrus.[1] At low pressures near the top portion of the troposphere, ice and water do not nucleate to the same extent as in the lower portion of the troposphere.[5] Thus, the diffusional growth rate of water vapor and ice crystals are small, and the time required for spherical snowflakes to grow is small which contributes to its thin optical thickness. As a result, there is a large uncertainty in the radiative properties which contribute to a net positive feedback. This uncertainty in net warming is a result of the complexity of the microphysics of these cirrus clouds. Cirrus clouds are typically optically thin and nonblack, and its influence on the climate depends on not only its solar and thermal IR radiative properties,[1] but also on its microphysical properties. Understanding how these precipitation processes occur, elucidates the importance of its radiative properties, which includes light scattering. In addition, aerosol nucleation mechanisms in these clouds may terminate these clouds' radiative properties which ultimately can affect the climate. Such sensitivity studies help to elucidate the possibilities for geoengineering the climate by controlling for the necessary variables.

A sensitivity analysis on the diffusional growth rates of water vapor and ice crystals from previous studies[5] on cirrus clouds was performed. The tropical cirrus clouds were of interest to this sensitivity study. Suitable approximations will be discussed along with the models used to describe the precipitative processes of cirrus clouds.

Modeling and Parameters

For each simulation, the *differential* formulae for condensational and aggregation growth were input into Python 2.7. 8. Each program, given the initial conditions (temperature, pressure, etc.), iteratively solved for the radius of the ice droplet/snowflake at incremental time steps until a final radius was reached. The values yielded by each program were written into a file for later analysis.

Growth rate of ice crystals is a complex process that depends on many different properties of the ice crystals, as well as properties of the cloud.[6] For this project two different equations were used to model growth rate, and determine the change in crystal size per time. These models were applied under the assumption that the ice particles are spherical. Spherical particles would have lower surface area, and thus downward settling velocities, than nonspherical particles. This slightly decreases the time it takes for the cloud to precipitate, but this effect will be negligible in cirrus clouds, due to their extremely slow growth rates. The first model used was a simplified, approximate expression first derived by Mason et. al.[7] It is a representation of the condensation growth rate of the ice crystals:

$$r(t) = \sqrt{r_0^2 + \frac{2(S-1)t}{K+D}} \; and \; t = (r(t)^2 - r_0^2)\left(\frac{K+D}{2(S-1)}\right) \quad \text{and} \quad \frac{dr}{dt} = \frac{1}{r}\left(\frac{S-1}{K+D}\right) \tag{1}$$

This is a modeled equation for the deposition of water vapor onto the ice crystals. The parameters K, $\left(\frac{L_{iv}^2 \times \rho_l}{\kappa R_v T^2}\right)$, and D, $\left(\frac{\rho_l R_v T}{e_s(T) \times D_v}\right)$, in equation 1 take into account the pressure and temperature dependence of growth rate. The effect of temperature on saturation vapor pressure and cloud growth is shown by the integrated form of Clausius-Clapeyron equation:

$$e_{si,2} = e_{si,1} \times e^{\left(-\frac{L_{iv}}{R_v}\left(\frac{1}{T_1} - \frac{1}{T_2}\right)\right)} \tag{2}$$

An increase in the temperature leads to an increase in ice saturation vapor pressure, and less deposition will occur. Conversely, increasing the pressure will lead to more deposition of water on the ice crystals. For this model the temperature and pressure were kept constant at 186 K and 100 mb, respectively.[5] The importance of two variables, saturation ratio and initial radius, will be discussed below.

Varying the saturation ratio, S, can have a large effect on clouds, because the saturation ratio of the air parcel determines whether or not a cloud will form. Unless there is a slight supersaturation, or S > 1.005, clouds will not form and sublimation of the ice crystals will occur. Another variable of interest in this study was the initial crystal radius, r_0. This project explores the effect that variation of r_0 has on the condensation growth rate of the crystals. Equation 1 shows that there should be an inversely proportional relationship between radius and growth rate.

Another simplified model was used to calculate aggregation growth rate with different parameters[6]:

$$\frac{dR}{dt} = \frac{\rho_a E}{4\rho_i} \times w_i \times u_T(R) \quad \textbf{(3)}$$

In equation 3 the collection efficiency, E, is assumed to be unity, and a previously measured value for $u_T(R)$, the terminal velocity of the ice crystal, was used .003 m/s.[5] For the model, a previously measured ice crystal number density of .0355 cm^{-3} was used to calculate the ice water mixing ratio 7.71 x 10^{-7} g/kg. Once again there is temperature and pressure dependence of growth rate represented by the density terms for air and ice. This model differs from the first because it takes into account the movement of the ice crystal or snowflake through the cloud. As the ice crystal or snowflake moves through the cloud, it collides with other ice crystals, some of which may aggregate on the particle. The number of collisions, and thus growth rate, is proportional to the number density of ice crystals, and the size of these crystals.[6]

Results and Discussion

Two different models were used to determine the effects of initial radius, terminal velocity, and ice particle density on the growth rate of ice crystals. Measured or typical values for all the variables in equations 1 and 3 were found from the literature for a cirrus cloud.[5] These values were entered into the model used to determine the growth rate. These results were used to explore the possibility of geoengineering precipitation in cirrus clouds.

The first model (equation 1) gave the effect of initial radius on condensation growth rate. An initial radius of 20 μm was tested, which is typical of a cirrus cloud ice crystal.[5] The model was then run for 40 μm and 10 μm of the original initial radius to determine the difference in growth rate. It can be seen from the square root dependence of equation 1 that the growth rate will be parabolic. The graph of Figure 1 shows that the ice crystal with the smallest initial radius has the largest initial growth rate, and the largest initial radius has the smallest initial growth rate. The differential form of equation 1 supports this result because growth rate is inversely proportional to radius. As more time passes the radii of the three sizes grow closer together until they are almost identical around 10^6 s. However, the radius of 10 μm will never become as big as 20 μm, and the radius of 20 μm will never become as big as 40 μm due to the nature of parabolic square root functions. Thus 40 μm will always reach a specified radius before the other two. This is useful information for cloud seeding because it shows that an ice crystal will ultimately grow to a specific size faster if you start with a larger "seeding crystal". The result also shows that over a long period of time, 10^6 seconds, the starting radius does not have much of an effect on the crystal size. If the objective was for cloud seeding and crystal growth to reach a certain size in a few minutes, then a larger initial radius should be used, but if it occurred over a few hours, then the initial radius would not be important.

The second model studied both the effects of initial radius and terminal velocity using equation 3. This can be rewritten in terms of initial radius as:

$$R(t) = R_0 + \left(\frac{\rho_a E}{4\rho_i} \times w_i \times u_T(R) \right) t \quad . \qquad (4)$$

Figure 2 shows that doubling and halving the initial radius does not have any effect on the aggregation growth rate of the snowflake from 1mm to 1 cm. The ice crystal starting at 1 mm is always 0.5 mm larger than the crystal starting at 0.5 mm, and 1 mm smaller than the 2 mm crystal. Because the crystal in the cirrus cloud grows so slowly, this turns out to be a significant size difference. The model shows that it takes 116 years for the crystal of 2 mm to reach 1 cm. It takes the 1 mm and 0.5 mm crystals 130 and 137 years, respectively. This corresponds to 7 more years of growth for each 0.5mm decrease in initial radius. In contrast, the aggregation growth rate has a linear dependence on ice water mixing ratio, and consequently ice particle number density. Figure 3 shows that a particle in a cloud with twice the particle number density will increase in size twice as fast. Initially the particle number density does not have significant impact because it is overtaken by the R_0 term (equation 4), however as time increases the number density term grows larger and dominates the R_0 term. The growth time for a particle with twice the number density will be approximately halved, however Figure 3 shows that it will still take 63 years to grow to 1 cm. Even for a number density of 1 cm^{-3} the particle still takes 5 years to grow, and this is not a reasonable amount of time to produce precipitation.

Figures 4 and 5 show the effect of supersaturation and terminal velocity on growth rate. It can be seen from these graphs that increasing the supersaturation or terminal velocity will increase the growth rate of the particle. The supersaturation increases the condensation growth, while the terminal velocity increases the aggregation growth rate. Comparing these five figures demonstrates that ice particle growth is a complex process that depends on many different parameters. These figures also show that precipitation in cirrus clouds is negligible due to the extremely slow particle growth rates. Thus geoengineering of cirrus clouds by increasing particle number density is not a feasible method for reducing the temperature of Earth. Ice particles and snowflakes would not to have a much larger initial size if they were to precipitate out during the lifetime of the cirrus cloud.

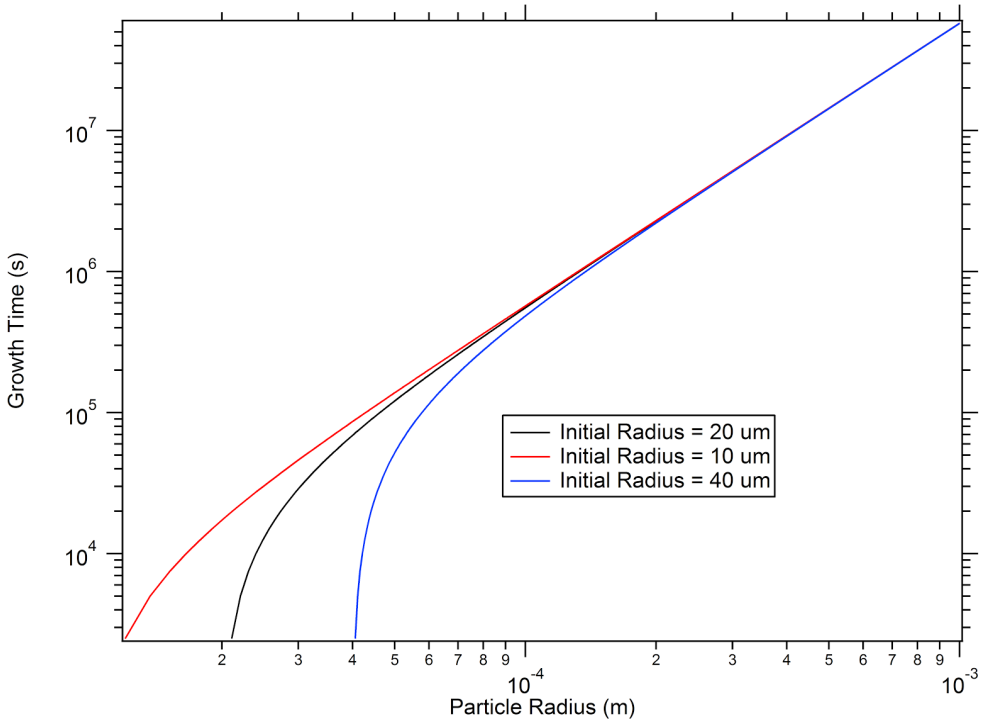

Figure 1: Initial Radius vs. Time for Condensation Growth of Spherical Ice Droplets. **Note red and black curves do not disappear, but go under the blue curve

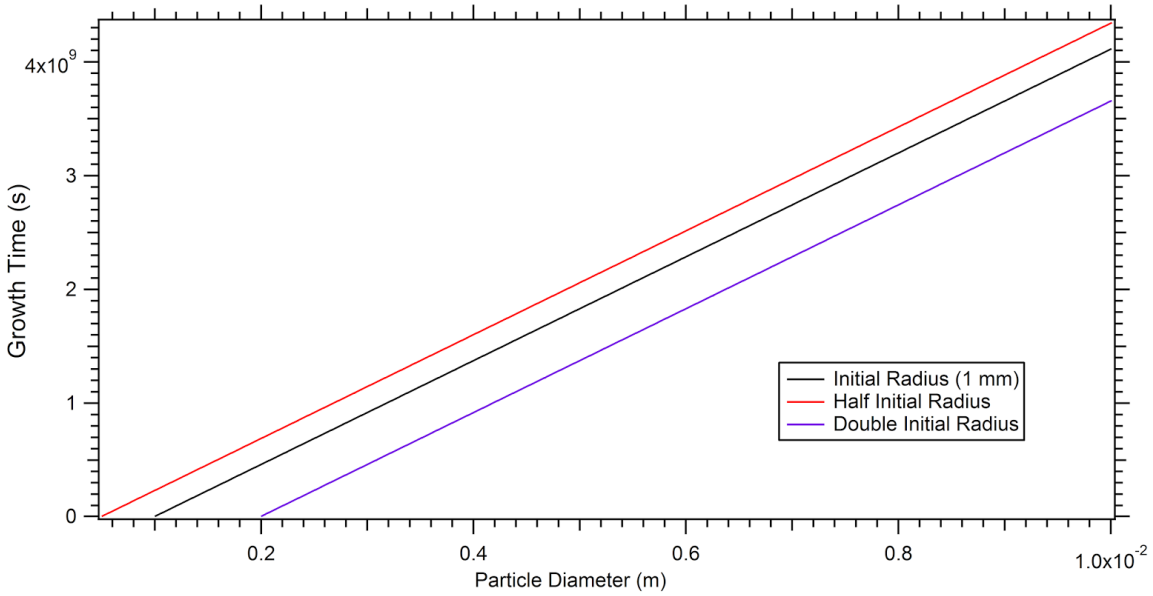

Figure 2: Initial Radius vs. Time for Aggregation Growth of Snowflakes

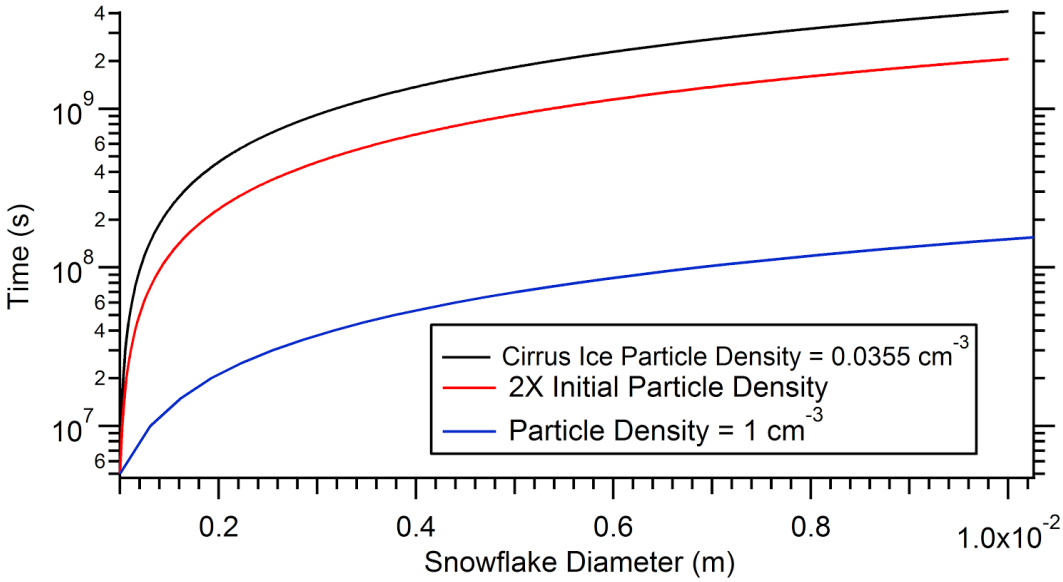

Figure 3: Snowflake Growth Time by Aggregation Growth from 1mm to 1cm with Respect to Different Ice Particle Number Densities

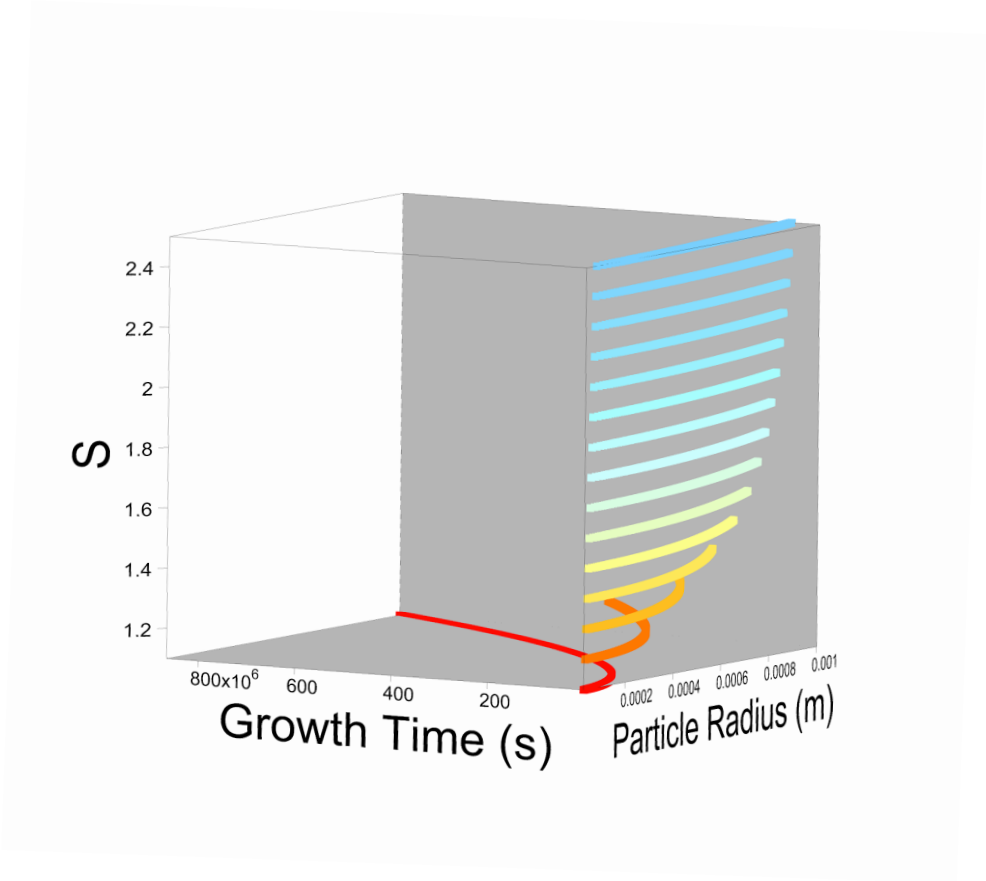

Figure 4: Growth Time from 20um to 1000um for Ice Droplets by Condensation with Respect to Varying Supersaturation

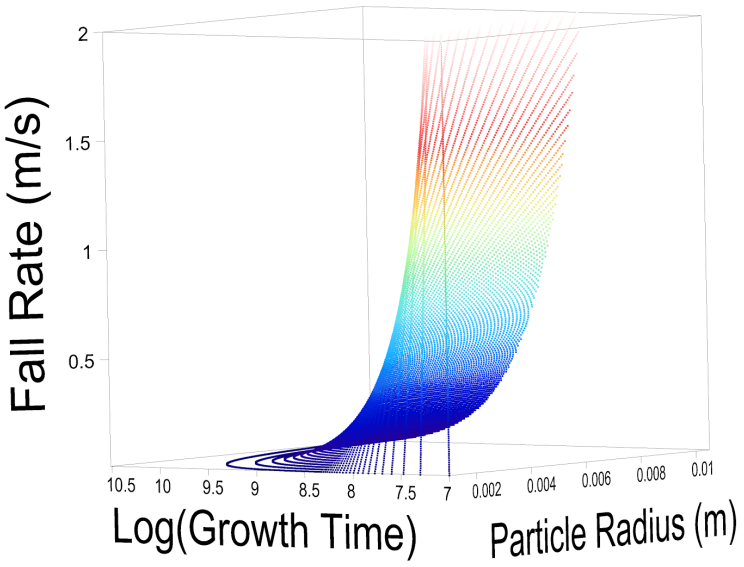

Figure 5: Log Growth time from 1mm to 1cm for Snowflakes by Aggregation with Respect to Varying Fall Rate (Relative Terminal Velocity)

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