Cloud Droplet Growth by Condensation and Aggregation in an EPMS vs AS Cloud

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1 Introduction

Failure to represent cloud feedbacks in global climate models remains one of the greatest impediments to simulation of future climate change scenarios. Thermodynamic and microphysical properties of clouds define their contribution to the global hydrological cycle and energy budget, including those that describe how cloud droplets or crystals form, grow, and dissipate[1]. The rate of cloud droplet growth correlates with properties that determine a clouds albedo and chance of precipitation, including drop size spectra and rate of dissipation. Improvements in model representation of droplet growth could thus alleviate flaws in simulated cloud feedbacks. Furthermore, an improved understanding of droplet growth and aggregation could have particular application in cloud-seeding experimentation. By understanding growth rate sensitivity to initial droplet radius, cloud seeding efficiency would be improved. The improvement of cloud seeding is particularly important for dry regions.

This study examines three droplet growth phenomena in stratocumulus clouds: (1) Droplet growth by condensation (2) Crystal growth by condensation, and (3) Snowflake growth by aggregation. The first is examined through Eastern Pacific Marine (EPMS) stratocumulus clouds, and the latter through Arctic Stratocumulus clouds (AS). EPMS provide an interesting basis for cloud droplet growth studies because they form along upwelling regions along the western boundary of continental land masses, and bring much needed precipitation to the California Coast as well as the Sierra Nevada mountain range via orographic lifting. Ice crystal growth and snowflake aggregation mechanisms are studied through Arctic Stratocumulus because they provide necessary thermodynamic conditions and because of their relevance to global climate models. AS make interesting model subjects because as persistent and pervasive clouds in the region, they contribute significantly to the polar energy budget[4].

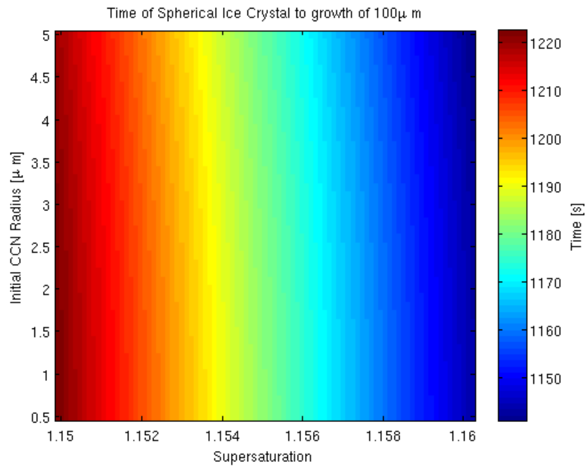

Fig. 1. displays the time of growth of a spherical ice crystal in an AS cloud to a radius of $10\mu m$ with varying supersaturation and intial CCN radius

2 Experimental Design

2.1 General Background

Making a model for the growth of both rain drops and snowflakes involves contributing factors from latent heat, supersaturation, temperature, material densities, and several other factors. A significant assumption to make is that water vapor is the only substance condensing onto the water drop. This can be considered an appropriate assumption due to the relative concentration of saturating materials compared to water.

2.2 Liquid Droplet Growth

For rain drops in EPMS, many of the variables have a strong dependence on temperature. By assuming that the variables stay relatively close to the ensemble average over time, the mean temperature can be assumed as the constant Temperature for the entire environment. This approximation breaks down when looking at large spatial variation of EPMS, however, since the spatial range of the model extends to from microns to centimeters, treating temperature as a constant for each simulation holds. Latent heat varies slowly with temperature, therefore holding it as constant within each simulation is reasonable even at large scale analysis. Though saturation pressure is highly variable with temperature, this study explores droplet growth in relatively small spatial ranges, on the order of 10^-6 to 10^-3 m, and a constant approximation is therefore not unreasonable. However, this approximation may need to be given a small variance in future models. Both thermal conductivity and water vapor diffusivity vary slowly with temperature, and can be easily be approximated as constant. Other variables for modeling rain drops are environmental and material densities, supersaturation, cloud condensing nuclei (CCN) radius, and final rain drop radius. In addition to the previous assumptions, environmental and material densities will be assumed as constant, leaving the only changing variables in each cloud type to be supersaturation, CCN radius, and final rain drop radius. A study by Mason et al. in 1971[3] estimated diffusional rain drop growth to be

$$r\frac{dr}{dt} = \frac{S-1}{K+D} \tag{1}$$

where K is the thermodynamic term, D is the diffusion term, S is supersaturation, and r is the droplet radius. The thermodynamic term, K, relies on latent heat, water density, thermal conductivity and temperature. The diffusion term, D, relies on material density, temperature, saturation pressure, and water vapor diffusivity[2]. By the above assumptions, equation (1) can be used to model rain drop growth and examined when varying supersaturation, CCN radius, and final rain drop radius.

2.3 Ice Crystal Growth

The growth rate of ice balls can be modeled using a lot of the same assumptions as those made for rain drops. This is because diffusional growth of ice crystals can be derived from diffusional rain drop growth[2] as

$$\frac{1}{\rho}\frac{dm}{dt} = \frac{4\pi C(S-1)}{K+D} \tag{2}$$

where K and D are the same definitions as before, m is the mass of the ice drop, ρ is the density of the ice crystal, and C is a factor that accounts for the morphology of the ice crystal. By treating the ensemble average ice crystal as spherical, C can be held as a factor of r. The equation reduces to the same equation as that for diffusional rain drop growth after making the appropriate substitutions for m. The values for K and D vary between the two simulations due to changes in saturation pressure and latent heat.

2.4 Snowflake Growth by Aggregation

Modeling snowflake growth is slightly different because it requires a variety of different dependencies[2].

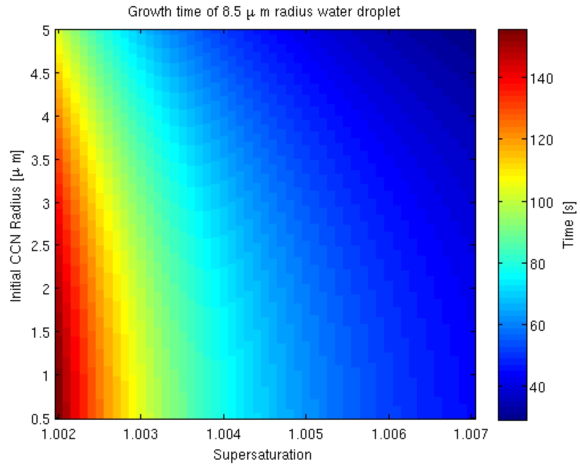

Fig. 2. displays the growth time for a droplet in an EPMS cloud to accumulate a radius of $8.5\mu m$ with varying supersaturation and intial CCN size.

The modeled equations comes out to

$$\frac{dR}{dt} = \frac{\pi}{3}\int_0^R \left(\frac{R+r}{R}\right)^2 [u_T(R) - u_T(r)]n(r)r^3E(R,r)dr. \tag{3}$$

In this equation, R refers to the snowflake size, r to the particle size, u to the terminal velocity, $n(r)$ to the particle size distribution, and E to the collection efficiency. The difference in terminal velocities are assumed to be constant at 1 m/s. This assumption breaks down if the snowflake size gets too big, therefore by keeping the spatial range to the range of centimeters, this assumption holds true. Additionally, collection efficiency can be assumed as constant and equal to 1 under the condition of relatively large interparticle distance to particle size. This is a common attribute of gases, and therefore is accurate enough to be considered valid. Making the assumption that the quotient of particle size and snowflake size does not vary significantly inside the integral from equation (3), the quotient can pulled out of the integral for fixed variables of R. The remaining integral can be related to liquid water mixing ratio by formula

$$w_l = \frac{\rho_l}{\rho_a}\int_0^\infty \frac{4}{3}n(r)r^3dr \tag{4}$$

where the fraction is the ratio of liquid water to air density and w is the liquid water mixing ratio. By assuming $n(r)$ is negligible for $r \gg R$ and taking out the unit sphere volume constant, we can match the integrals and find our resultant equation. This leaves a forward growth model that varies with changing starting radius and liquid water mixing ratio.

3 Results

Model results show that the time needed for droplet growth in EPMS clouds occur about 5 to 10 times faster than aggregation in AS clouds. Figure 1 shows that supersaturation values are the dominant driver of droplet growth instead of initial droplet radius in AS clouds. That is, at any size initial droplet radius within our given range, the crystal is more likely to evaporate (return to liquid phase) at a lower supersaturation value. Figure 3 displays the interdependence of snowflake growth time on initial snowflake size and mixing ratio. As the water vapor content increases, snowflake growth occurs faster for a given initial snowflake size. With typical values of supersaturation and initial/final droplet sizes in EPMS clouds, Figure 2 shows that droplet growth depends more on supersaturation instead of initial droplet size.

Other interesting aspects of our EPMS (warm cloud) results (Figure 2, holding final radius constant) show decreasing variance in growth rate at higher supersaturations, indicative of a higher senstivity to initial droplet radius. This could demonstrate that in drier regions, the initial size of the droplet, and thus of your seeding particle, is more important than in regions with higher environmental supersaturation.

Holding temperature and saturation pressure constant, the results of the simple model confirm the relationships of droplet, crystal and snowflake growth with supersaturation and radius increase.

Though our model falls short of predicting precipitation in either the EPMS and AS clouds, the study aims to contribute to the body of information needed to determine whether these clouds would precipitate. Further study would be needed to determine whether the clouds would precipitate over land. Such as study would require the dependency on other factors, such as, the rate of dissipation of clouds.

The data presented in this study are physically significant for geoengineering practices and a better understanding of precipitation processes. As climate changes, observations show snowpack has declined across much of the western United States over the period 1950-99. As a means to protect Californias water supply, in the face of a growing population and warmer projected climate, geoengineering methods have been proposed (e.g. water seeding).

This study gives insight to microphysical-radiative-dynamical feedbacks due to local aerosol-induced climate change. Variations in aerosol size distribution leads to different effects on cloud growth and precipitation for a given aerosol. Our model demonstrates quicker growth times with larger initial cloud droplet size, which in turn, can lead to more precipitation.

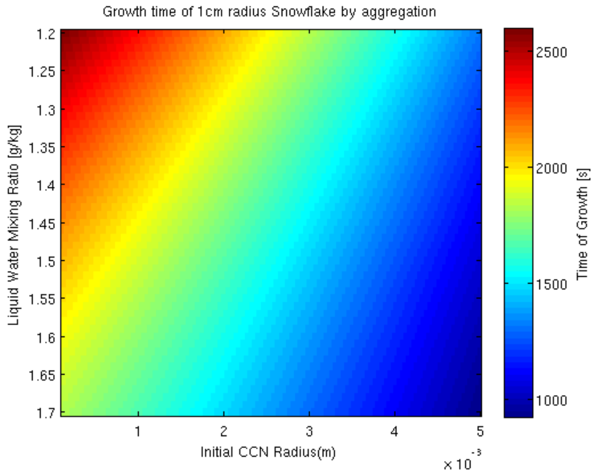

Fig. 3. shows the time of growth for a spherical snowflake in an AS cloud to a radius of 1 *cm* with varying CCN radius and mixing ratio.

References

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