MICROPHYSICAL ROOTS OF CIRRIFORM CLOUDS: ROLE OF CRYSTAL-GROWTH KINETICS

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1. INTRODUCTION

Cirriform clouds can be viewed as a visible manifestation of a complex set of physical phenomena interacting over a broad range of spatial scales in the upper troposphere. At some times, synoptic-scale pressure patterns force air to rise slowly over denser airmasses, yielding a uniform shield of cirrostratus cloud (Cs) composed of small ice crystals. At other times, mesoscale waves induce more local, but stronger updrafts that stimulate the formation of cirrus clouds (Ci) with clear evidence of large particles that sediment. The visible distinctions between cirrostratus and cirrus clouds result in part from the different forcing scales, but the microphysical responses (e.g., ice nucleation and crystal-growth kinetics) to the respective external forcings also differ and need to be clarified. Ultimately, our ability to predict the type and evolution of cirriform clouds depends on how well numerical models are able to capture the relevant physics on all scales.

This paper focuses on the microphysics of ice crystal growth under cirriform conditions. We explore the possibility that the observed forms and behavior of cirriform clouds are rooted partly in the detailed, molecular-scale processes responsible for ice crystal growth. After reviewing some of the processes involved, we present early computational results aimed at clarifying the issue.

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2. HYPOTHESIS AND MOTIVATION

The limited efficiency with which ice grows from the vapor phase is hypothesized to control, at least in part, the macrostructure of ice clouds in the upper troposphere. An important visible distinction between the two main genera (Cs and Ci) is the presence or absence of visible fall streaks. The fibrous appearance of *cirrus uncinus*, for instance, is due to the sedimentation of relatively large ice particles. These fall streaks may become distorted by the wind shear, but it is the evidence of large, precipitating crystals that characterizes *Ci uncinus*. By contrast, the uniform appearance and lack of detail of *Cs nebulosus* suggests a uniform population of much smaller crystals. How much of the distinction in crystal size is driven by the macroscopic setting for cloud formation (updraft speed, cloud depth, temperature, etc.) and how much can be ascribed to different growth microphysics?

That a link might exist between ice crystal growth and the morphology of cirriform clouds stems from both theory and laboratory experiments. Theory shows that ice crystals respond to supersaturated environments by building some of the excess vapor molecules into the lattice at steps on individual facets. Each facet advances at a rate that increases monotonically with increased supersaturation, but the dependence on supersaturation is not linear. The involvement of steps in the growth process causes this nonlinearly and ultimately the potential for effects on cloud morphology.

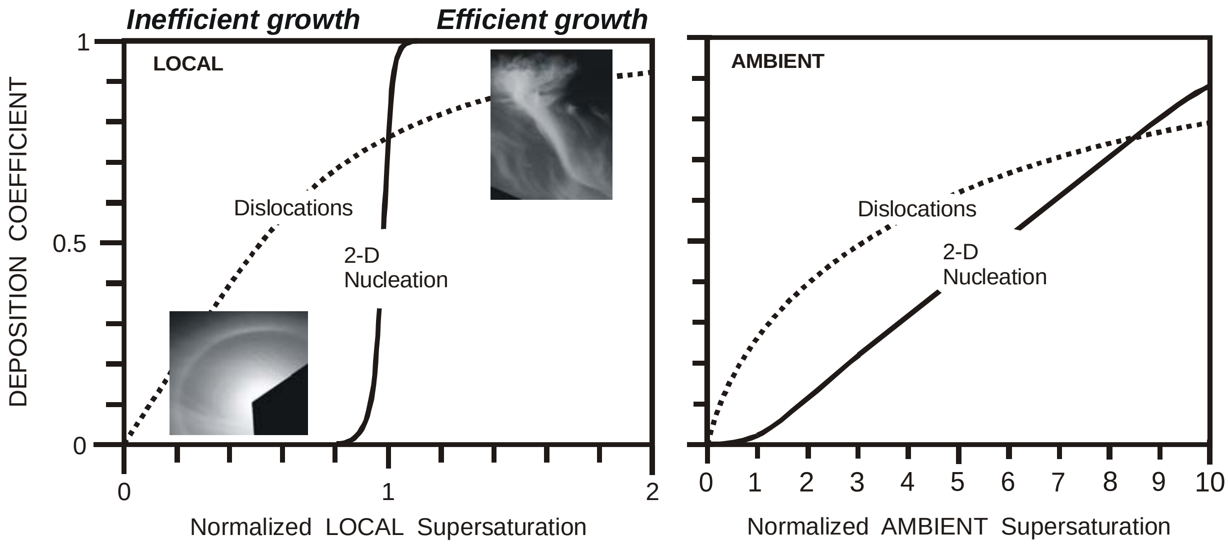

Fig. 1. Dependence of deposition coefficient on supersaturation and its possible link to the morphology of cirriform clouds. Left panel: Dependence on the LOCAL supersaturation immediately over a facet. Photos of Cs (low s_i) and Ci (high). Right panel: Dependence on AMBIENT supersaturation.

A parameter that accounts for the complicated and as yet uncertain surface processes responsible for ice growth is the deposition coefficient, α. Being the ratio of the actual growth rate to the maximum possible, α is a measure of the efficiency with which vapor molecules incorporate into the crystal lattice and contribute to the growth of the ice particle. This coefficient can be both calculated from theory and measured in the laboratory, so it affords a rich physical interpretation, as well as serving as a useful parameter in cloud models.

Recent lab measurements give evidence that ice particles may grow very slowly under cirriform cloud conditions. Libbrecht (2003) found α values of only a few per cent over a range of temperatures and supersaturations. Magee et al. (2006) found particle-average mass deposition coefficients to vary between about 0.004 and 0.008 in the temperature range -60 to -40 °C. Such low values suggest extremely inefficient growth and the likelihood of impacts on the properties of cirriform clouds (Gierens et al. 2003).

Theory gives an expectation that the deposition coefficient depends on conditions in the environment, so these low deposition coefficients may not hold universally. Supersaturation, s_i, in particular, seems to be a variable that plays an important role in the mechanism of growth. Indeed, measurements of individual facets show that α increases significantly with s_i (Sei and Gonda 1989; Libbrecht 2003). The functional form of $\alpha(s_i)$ is contingent on the assumed mechanism of step formation, which is still under debate (Frank 1982; Nelson and Knight 1998; Lamb 2000).

Figure 1 shows the range of possibilities for steps arising at the sites of emerging screw dislocations and for new layers initiated by 2-D nucleation (Nelson and Baker 1996; Lamb 2000). The left panel shows the theoretical dependences of α on the supersaturation immediately over the ice surface, whereas the right panel gives the expected dependence when air is present and ambient supersaturation is used (Lamb and Chen 1995). Because of the need for steps on facets, ice crystals can be expected to grow inefficiently at low supersaturations, but more efficiently once the supersaturation exceeds the critical supersaturation (unity on the abscissa). The inset photos indicate the hypothesized connection between the two genera of cirriform clouds and the kinetic coefficients of crystal growth. Do the crystals of Cs grow in an inefficient growth regime, whereas those of Ci grow efficiently?

3. TESTING AND FINDINGS

The suggestion that ice particles grow from the vapor with different efficiencies in cirrostratus and cirrus clouds was examined using a simplified cloud model (Lebo et al. 2008). The model was used as a tool for sensitivity studies rather than as means for simulating clouds.

Computations were performed with a parcel model using prescribed dynamics (constant updraft speed). The cloud particles were assumed to be spherical and distributed in size by a gamma distribution with initial radii between 1 and 40 μm. No explicit nucleation took place; rather, the concentration of particles (100 L^{-1}) was specified to be ice once ice saturation was reached during uplift. The model was initialized by specifying the temperature (-30 °C) and pressure (350 hPa) at cloud base. Two sets of runs were made by specifying the updraft speed to be 15 cm s^{-1} (to represent Cs) and 75 cm s^{-1} (Ci).

Within each model set, the parameter representing the growth microphysics (α) was varied to test different microphysical options. Several fixed values of α were used between 0.001 and 1. Also, several cases of variable α were tried to represent the supersaturation dependence shown in Fig. 1. The variable α was calculated by iteration for each supersaturation according to

$$\alpha = \left(\frac{x}{1+K\alpha}\right)^m \tanh\left[\left(\frac{1+K\alpha}{x}\right)^m\right],$$

where $x \equiv s_{amb}/s_1$ is the ratio of ambient and critical supersaturations (with respect to ice), and where K ~ 10 is the ratio of transport resistances due to vapor diffusion and surface kinetics (Lamb and Chen, 1995). The parameter m was set to 1 to represent spiral growth ("dislocations") and to 30 to represent 2-D nucleation of new layers, a suggestion offered by Nelson and Baker (1996). Each choice of α was used in the adaptive parameterization of Chen and Lamb (1994).

Examples of output from the model applied over a layer 2 km in depth are shown in Fig. 2 (low updraft speed, Cs) and Fig. 3 (larger updraft, Ci). Each panel presents the indicated variable as a function of height above cloud base. Each curve arises from the selected choice of α, as identified in the legend. Results from using three constant values of α are shown, as are three sets of variable α distinguished by the chosen value of critical supersaturation (s_1). Each set of variable-α curves is further distinguished by the step-origin mechanism. The mean radius of the ice particles is shown in Figs. 2a and 3a, respectively, for Cs and Ci situations. The ambient supersaturations for each case is given in Figs. 2b and 3b, while the computed α values for the variable-α cases are shown in Figs. 2c and 3c, respectively. We are aware of the limitations of this parcel model, in particular the fact that crystals having fallspeeds in excess of the given updraft speed are not able to be lifted, so the estimated cut-off radius is shown.

Noteworthy features of the model output include the grouping of curves for certain ranges of α. To first approximation, it makes little difference what the value of α is for $\alpha >$ 0.01, a result consistent with the fact that the dominant resistance to mass transport is vapor diffusion, not surface kinetics in such cases. Values of $\alpha < 0.01$ severely limit crystal growth and let the supersaturation rise, in some cases, unrealistically. Critical supersaturations of $s_1 = 10$ are unreasonable and so could be eliminated in future work. Large distinctions arise from the assumption of step origin, especially in the case $s_1 = 1$. It seems unlikely that crystals could grow at $s_1 =$ 1 by 2-D nucleation, but spiral growth can not be excluded by these results.

The hypothesis that ice crystals in cirriform clouds grow with variable α was explored with limited success. The variations in α with altitude for the variable-α cases (Figs. 2c and 3c) are large, but they are important only when $\alpha < 0.01$. It appears that the constant-α case, with $\alpha = 0.01$, allows sufficient growth in both Cs and Ci situations.

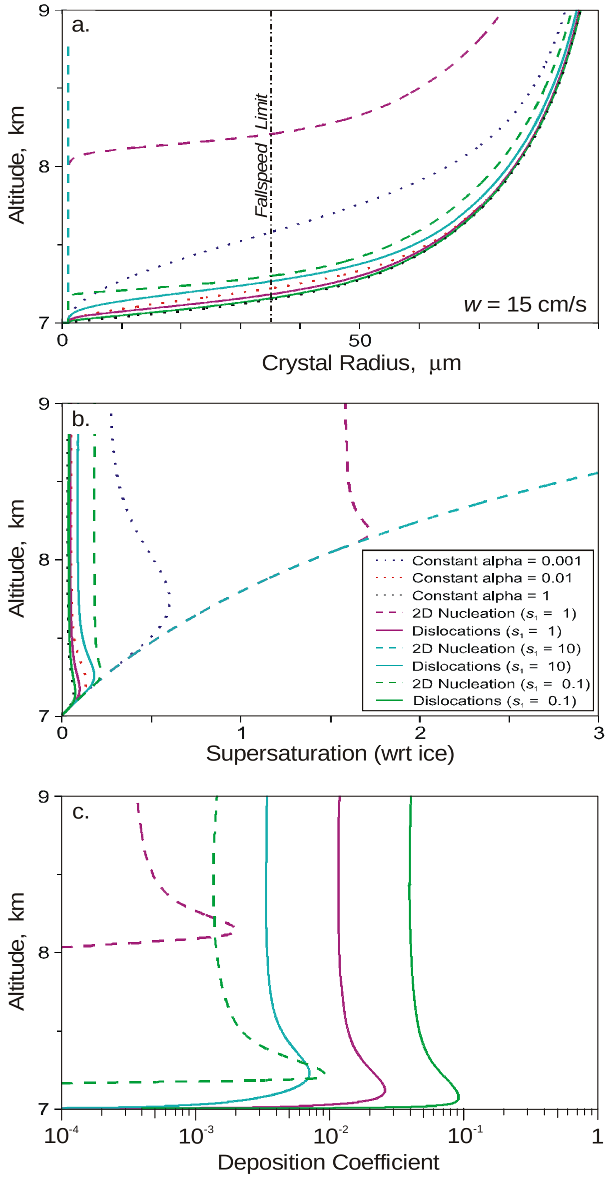

Fig. 2. *Model results representing a Cs cloud with updraft speed w = 15 cm/s. a. Crystal radius. b. Supersaturation. c. Deposition Coefficient.*

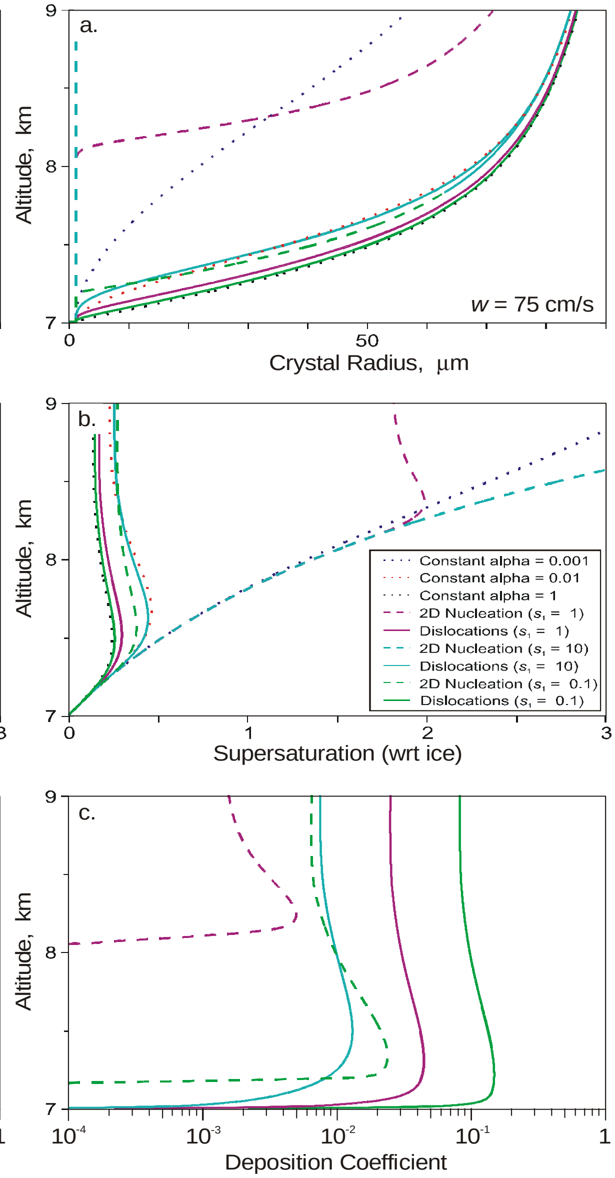

Fig. 3. *Model results representing a Ci cloud with updraft speed w = 75 cm/s. a. Crystal radius. b. Supersaturation. c. Deposition Coefficient.*

4. TENTATIVE CONCLUSIONS

The basic level of modeling used for this study allows a few tentative conclusions to be drawn. We can eliminate certain possibilities as being physically unrealistic, but further study with a more complete model would be needed to refine the conclusions. We cannot yet say with any certainty what, if any, role the growth kinetics play in distinguishing Cs and Ci clouds.

The step origins (dislocations or 2-D nucleation) greatly impact the development of ice particles in these model clouds. The mechanisms of step formation are tied to each other through a common edge energy (Lamb 2000), so one might not have expected to find such large effects. The findings of the model also show that critical supersaturations as large as 10 are not physically realistic; in fact, they are more likely to be in a range about 0.1 (Burton et al. 1951).

This study also highlights the need for new laboratory measurements of ice particle growth under cirriform conditions. In the near term, models may be run with appropriate constant values of α, perhaps, but this representation of surface processes leading to molecular incorporation is almost certain to depend on the supersaturation and on the areas of the facets. We must therefore learn how to identify the likely origins of steps on the low-index facets of complex crystals, and we must learn how to measure the critical super-saturation, which probably varies with temperature and with the crystallographic orientations of the facets.

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