Review of "Quantifying ice crystal growth rates in natural clouds from glaciogenic cloud seeding experiments" by Fuchs et al.

Overview

This paper examines the growth of ice crystals in mixed-phase clouds using data collected during the CLOUDLAB field campaign. CLOUDLAB is a unique experiment designed to observe the evolution of ice crystal sizes and their morphology in natural clouds. Most of the data was collected within a temperature range of -5.1°C to -8.3° C, which is associated with the columnar growth of ice particles. This study specifically investigates the growth rate of ice crystals along their major axis. The assessment of the growth rate of ice crystals was based on measurements of dimensions of single (non-aggregated) ice columns in the assumption of their linear growth. The growth rate of ice columns was calculated for three CLOUDLAB data subsets: (a) "unconstrained" diffusional growth in cloud environments restricted by certain threshold applied to LWC, CDNC, and ICNC, (b) "lucky ice crystals approach", and (c) unfiltered data. The results of this study are summarized in Fig.8, which compares ice growth rates calculated for the CLOUDLAB clouds with those from laboratory studies. The methodology utilized is robust, and the results obtained hold significant value. However, the authors restricted the results by considering the growth rates of ice crystals by their means, medians, and percentiles. It is my opinion that the most crucial aspect of this work pertains to the observation of how introduced ice particles are processed by a liquid cloud. The uniqueness of CLOUDLAB lies in its ability to observe the broadening of initially quasi-monodisperse ice particles (i.e., initial sizes limited by the sizes of frozen cloud droplets) in natural cloud environments due to varying supersaturation histories and, consequently, growth rates experienced by individual ice crystals caused by fluctuations in vertical velocity, entrainment and mixing, and recirculation through the cloud base. This information is essential for calibrating cloud models, and it would be beneficial for the completeness of this study to include this topic in the paper. Otherwise, this subject warrants a separate publication.

Recommendation: This study undoubtedly deserves publication in ACP. In my opinion, the novelty and importance of the presented results have passed the threshold required for acceptance for publication. I leave it to the author's discretion to decide how far they want to go in addressing my comments below.

Comments

1. Section 2.5: One of the assumptions in calculating the growth rate of ice crystals (*dL/dt*) involves steady-state environmental conditions, specifically relative humidity (*RH*) and temperature (*T*), which primarily controls the ice particle growth rate. For most liquid and mixed-phase clouds, *RH* is close to saturation over water (e.g., Korolev and Mazin, JAS, 2003; Korolev and Isaac, JAS, 2006) due to the small phase relaxation time of approximately τ_{ph}~10^{-1} – 10^{0}s seconds. However, *RH* may be temporarily reduced by the entrainment of dry out-of-cloud air through the cloud top and subsequent mixing and result in the decrease of the ice growth rate. Some ice particles may encounter undersaturated environments during circulation through the cloud base which may slow down growth rate of ice particles or even result in sublimation.

Furthermore, *RH* also depends on the vertical velocity (U_Z) of cloud parcels. However, fluctuation ΔRH related to U_Z are expected to be relatively small compared to that related to that generated by entrainment.
Temperature fluctuations (ΔT) play a crucial role as well. Given that ice particles driven by turbulent fluctuations may travel between cloud top and cloud base, temperature fluctuations experienced by ice particles in boundary layer clouds will be largely determined by the cloud depth, i.e., $\Delta T = \gamma_{moist}\Delta H$.
These dynamic processes controlling fluctuations ΔRH and ΔT should be accounted in consideration of ice growth rate dL/dt. Coul you include discussion of the above effect and quantitative assessment of their contributions?

2. Entrainment and mixing are expected to be one of the main drivers of fluctuations of ΔRH and ΔT. The rate of entrainment of the dry air through the cloud top depends on the intensity of turbulent fluctuations (ε) and depth of the cloud top inversion (ΔT_{inv}). Furthermore, the effect of entrainment is most pronounced near the cloud tops of stratiform layers, and it decreases with the increase of the distance from the cloud top. Therefore, it is anticipated that in deeper stratiform clouds *dL/dt* of ice particles will be less affected by entrainment. Summarizing the above, it is anticipated that in addition to LWC, CDNC, and ICNC the growth rate of ice particles *dL/dt* will also depend on ε, ΔH, ΔT_{inv}. For the sake of completeness of the analysis it will be beneficial to the paper to include the analysis of the effect of ε, ΔH, ΔT_{inv} of *dL/dt* similar to those as in Fig.6.

3. Section 3.2. Unfortunately, in the paper LWC, CDNC, and ICNC were introduced as major microphysical parameters affecting the growth rate of ice particles without explanation. The rational of choice of LWC, CDNC, and ICNC should be explained. It makes sense to consider adding the integral radius of cloud droplets (CDNC * mean_radius), which is reversely proportional to the time of phase relaxation τ_{ph}. Such approach would be more physical compared to LWC, CDNC, since in clouds with smaller τ_{ph}, *RH* is expected to be closer to saturation. It might be worth exploring potential explanation of the roll of *dL/dt* for CDNC<100cm-3 and increase of *dL/dt* with increase of LWC through the analysis of the dependence of *dL/dt* vs integral radius.

4. Figure 6a. It is worth noting that boundary layer clouds with higher LWC are expected to have higher cloud depth ΔH, and therefore, ice particles may experience higher temperature fluctuations ΔT. Could you explore if the increase of *dL/dt* with the increase of LWC in Fig.6a is related to the temperature fluctuations ΔT related to the cloud depth?

5. During columns' growth, their hollowness depends on *RH*, i.e., when *RHice* is close to its saturation over ice, then columns grow as solid hexagonal prisms. In contrast, when *RHice* increases and approaches saturation over liquid, the columns develop hollowness. As was shown by Harrington et al. (https://ams.confex.com/ams/105ANNUAL/meetingapp.cgi/Paper/455629, video recording of the presentation is available from the AMS site), the rate of changes of the hollowness is a function of *RH*. In other words, if the images of columns show varying rates of changing of the hollowness along the c-axis, then it is indicative that the ambient *RH(t)* related to this

specific ice crystal was not constant. The analysis (qualitative or quantitative) of the patterns of hollows developed inside columns may shed light on the growth condition of studied "lucky" ice particles. The authors may consider adding this consideration to the paper.

6. Page 10, Line 225 "*The riming efficiency of ice crystals strongly depends on the ice crystal size (Wang and Ji, 2000) and CDNC and is highest for large ice crystals and high CDNC."* The riming rate also depends on the droplet size (Wang and Ji, 2000). The above statement should be modified to include the dependence on the droplet size.

7. Page 17, Line 375 "*The temperature dependence of our growth rates shows reasonable agreement with laboratory studies, although the absolute values tend to be lower for our in situ observations. This discrepancy likely arises from differences in growth conditions: laboratory setups typically provide unlimited water vapor, high LWC, and isolated ice crystal growth, whereas our in situ observations involve limited water vapor availability and high ICNC*" It would be more accurate to rewrite this statement in terms of fluctuations ΔRH and ΔT, rather that "limited" and "unlimited" LWC. Thus, in laboratory studies usually *RH* and *T* are maintained to remain constant with relatively small fluctuations ΔRH and ΔT. Whereas, in natural clouds fluctuations ΔRH and ΔT may be significantly higher compared to those in lab studies due to the effects of ε, ΔH, ΔT_{inv}, U_Z, LWC, CDNC, and ICNC.

8. It is worth adding a discussion that the frequency distribution of *RH* in stratiform mixed-phase clouds is skewed towards smaller values (e.g., Korolev and Isaac, 2006) primarily due to entrainment and the WBF process. Therefore, the net effect of such skewness will be lower ice growth rates *dL/dt* compared to the lab studies.

9. In my opinion, the results in Fig.6 are crucial for parameterizing ice growth rates in stratiform clouds and improving cloud models. Laboratory studies measure *dL/dt* under constant *RH* and *T*, but CLOUDLAB includes effects of turbulence, radiation transfer, riming, and aggregation, which can't be fully replicated in the lab. The obtained dependencies of *dL/dt* vs LWC, CDNC, and ICNC are a very valuable outcome of this study, and I highly recommend expanding consideration and discussion around this question.

10. Figure 7(g,h,i). What are the black solid lines at normalized_growth_rate =1?

Alexei Korolev