Mechanistic limitations to the release of latent heat during the natural and artificial glaciation of deep convective clouds

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SUMMARY

The latent heat thermodynamically available in the supercooled water of deep convective clouds is released at rates governed by the glaciation mechanism, presumed here to involve primary nucleation, capture nucleation of rain by small ice particles and secondary ice production (rime-splintering hypothesis). A simple microphysical model of the glaciation shows the importance of regenerative feed-back on the evolution of ice when the primary nucleation and regenerative processes proceed simultaneously, leading to insensitivity to the primary ice nucleus concentration. This allows rapid glaciation and heat release to occur naturally in clouds exhibiting a broad supercooled drop size spectrum.

New observational data and model results of artificially induced glaciation are consistent with the idea that the primary microphysical role of seeding is the creation of many small ice particles which substitute for the secondary ice splinters of naturally induced glaciation. The aerodynamic capture of the splinters by the supercooled rain leads to the formation of new graupel particles and the rapid release of fusional heat, shown by calculation to dominate the heat release mechanisms. With a seeding agent acting in the contact mode the small (cloud drop) end of the spectrum is required, since Brownian scavenging of the nuclei by the few large rain drops is inefficient. The quantitative analysis of these glaciation concepts also demonstrates that realistic seeding under conditions conducive to ice multiplication could increase materially the rate of heat release and offer opportunities for artificially invigorating the dynamic structure of a cloud if glaciation is induced to occur within a relatively narrow 'time window' for seeding.

1. INTRODUCTION

The energy required to sustain the buoyancy of a convective cloud in an otherwise stable environment comes from the latent heat released during phase transformations of the individual cloud particles. It is this heating which enables the cloud to maintain an excess temperature over its surroundings at each pressure level and compensate for entrainment, that mixing process which dilutes the cloudy air with the drier and colder environmental air and serves as the primary brake against cumulus growth (Malkus and Simpson 1964). The delicate balance that generally exists between these forces of buoyancy production and destruction means that small cumulus clouds growing in isolation are more vulnerable than large, multicellular clouds that have their vital updraught regions somewhat protected by a buffer mantle of inactive cloudy air (Simpson et al. 1965). Entrainment may be less effective in destroying the larger clouds, which may readily continue their mesoscale organization, conceivably allowing them to grow still larger and become more efficient in processing the available moisture into precipitation.

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Although the initial gain in temperature excess comes from the condensation of vapour to the liquid phase, an additional source of warming arises from the conversion of the supercooled liquid to the solid (ice) phase in clouds which are able to grow to temperatures colder than 0°C. Even though smaller in magnitude than the condensational heat release, heating from glaciation can nevertheless be very important in providing enough additional buoyancy to enable a cloud to penetrate weak, stable layers or survive shallow, dry zones which often exist in the atmosphere.

The evolution of the in-cloud water and ice budgets and the resulting rates of heat production depend upon a number of microphysical and dynamical processes continuously operating within the cloud. We are now understanding how some of these processes are intertwined and dependent upon each other and how their interrelationships differ in clouds growing under various air mass conditions. Such an understanding is a prerequisite to a clear appreciation of how the microphysics might be manipulated, as with intentional ice-phase seeding to produce a dynamical stimulation of the cloud and, perhaps, additional rainfall. The forced invigoration of cumulus clouds, through the timely release of seeding agent (e.g. silver iodide) and the production of additional buoyancy, does indeed seem to be the basis for enhancing cloud growth from populations of summertime convective clouds in Florida (Simpson 1967) and Arizona (Weinstein and MacCready 1969; Weinstein and Takeuchi 1970) and may have been the underlying cause of the ‘explosive’ cloud growth observed by Kraus and Squires (1947).

Whether naturally or artificially induced, the glaciation of convective clouds is complicated by the large range of scales involved. Whereas the transforming of individual liquid cloud and precipitation drops into ice particles is by its very nature microscopic, the propagation of the ice phase throughout the cloud body and any stimulation granted the cloud-scale circulations by the latent heat released range into the mesoscale.

Although a complete ‘solution’ to this highly interactive phenomenon is distant, especially since many of the intermediate steps are themselves little understood, an important aspect of the problem is the link between the specific mechanisms of cloud glaciation and the rate with which the latent heat can be released. Beyond the earliest observations by Kraus and Squires (1947) and by Simpson et al. (1965) that the dynamic structure of cumuliform clouds is responsive to imposed alterations in the glaciation rate, the relationship between glaciation microphysics and cloud-scale warming has been treated theoretically by a number of workers. Some (e.g. MacCready and Skutt 1967; Orville and Hubbard 1973; Fukuta 1973; and Chappell and Smith 1975) have considered the thermodynamics of the glaciation process and have shown that sizeable enhancements of the cloud buoyancy are to be expected following glaciation. A simple thermodynamic argument (Appendix) shows that over half of any heat produced by glaciation should be available for net warming and buoyancy enhancement. Nevertheless, information about rate limitations cannot come from thermodynamic arguments, but rather from consideration of specific microphysical mechanisms.

Cotton (1972) detailed much of the pertinent glaciation microphysics and incorporated them into a numerical cloud model to assess the dynamic response of the simulated clouds to AgI seeding. Although he showed that clouds rich in supercooled rainwater were dynamically sensitive to the presence of small ice crystals, by being captured hydrodynamically by the rain drops and forcing the rapid release of their fusional heat, only parametrized treatments of ‘ice multiplication’ were then available, precluding any type of regenerative glaciation from being considered. Chisnell and Latham (1976), on the other hand, did consider the possibility of secondary ice initiating the generation of its own source, but not the liberation of any latent heat. Koenig (1977) included both regenerative ice production and parcel warming within a dynamical framework, also showing that it is primarily the capture
by the supercooled rain drops of the secondary ice 'splinters' liberated during the riming process that brings about rapid glaciation and dynamic stimulation. No cases were considered which simulate seeded situations.

Scott and Hobbs (1977) used a one-dimensional dynamical framework to study the evolution of mixed-phase continental and maritime clouds and likewise demonstrated the importance of the capture nucleation of supercooled rain drops for forming graupel. By contrast with the types of clouds considered here, their simulated clouds were relatively shallow and could not allow for the development of the broad drop size distributions typically encountered in warm-based continental cumulus congestus rising beyond the freezing level. Also, their treatment of seeded cases was restricted to nuclei acting in the deposition mode.

A simplified analytical treatment of the type of glaciation microphysics thought likely to prevail naturally in the deep convective clouds of Florida was provided by Hallett et al. (1978). These clouds are typified by warm cloud-base temperatures (at least 20°C) and relatively high liquid water contents (of order 5 g m⁻³) distributed widely in drop size by the time the cloud top passes through the thermodynamic freezing level. The mechanism invoked to explain the observed glaciation behaviour of these deep convective clouds is based on the production of secondary ice splinters during the riming of millimetre-sized graupel particles (Hallett and Mossop 1974; Mossop and Hallett 1974) and the aerodynamic capture of the splinters by supercooled rain drops to produce new riming centres. The criteria laid out by Hallett and Mossop (1974) and by Mossop (1978) for effective splinter generation were that the temperature should be between −3 and −8°C, the relative fall speed of the graupel particles should exceed about 1 m s⁻¹ (implying a minimum graupel diameter of about 1 mm), and the accreted droplet size spectrum should include diameters both below 13 μm and above 25 μm.

Analytical examination of this regenerative scheme by Hallett et al. (1978) showed explicitly how the given initial concentration of graupel could increase by three orders of magnitude in times less than five minutes. This provided insight into the physical factors which can contribute to the rapid ice evolution, but ignored certain microphysical limitations, prohibiting its application to seeding effectiveness and heat production.

A goal of the current work is to extend the formulation of these concepts of regenerative glaciation to include primary nucleation events and the limited availability of rain water, as well as to calculate the rates and magnitudes of the heating generated by the specific microphysical processes. The approach is to take specific concepts of glaciation behaviour, as deduced from the earlier observations, and quantify the set of 'essential' mechanisms. The host of other conceivable mechanisms which are of second order in effect is generally ignored. Such conceptual modelling aims at isolating the minimal set of discrete events which are required to 'explain' the general set of observations. Extensions to more detailed and quantitatively realistic calculations seem justified only once we are assured that the essential physics has been included.

The model developed here is entirely microphysical in nature, designed to investigate the cloud particle interactions in detail and permit a resolution of the latent heat release mechanisms unhindered by simultaneous time variations in dynamical parameters. Although no dynamical framework is intended, the model is in effect Eulerian in a spatially uniform environment (i.e. one containing no gradients of particle concentrations, temperature or heating). These seemingly restrictive mathematical assumptions nevertheless permit inferences from the model results that have application to a dynamical framework. The scope of our efforts is limited to estimating the relative time scales required for ice evolution and heating under nucleation conditions appropriate to both naturally and artificially initiated glaciation.
2. THE CONCEPTUAL MODEL

Our hypothetical cloud is considered to be composed of two size categories each of liquid and ice; that is, small particles (\( \sim 15 \mu m \) diameter) having no appreciable fall speed and large particles (\( \sim 1 \) mm) having significant fall speeds. In this respect our formulation is similar to the microphysical portions of the models employed separately by Koenig (1977) and by Chisnell and Latham (1976). Whereas each of these workers was concerned primarily with the production of ice in natural (unseeded) clouds influenced by secondary ice processes, the emphasis here is placed on determining the specific roles played by the various ice-forming processes in the liberation of heat in clouds experiencing the sudden injection of high concentrations of ice nuclei.

![Diagram](image)

Figure 1. Schematic representation of the microphysical interactions assumed to prevail during glaciation.

Details of how the various microphysical processes are interrelated can be understood from Fig. 1. The sizes of the two drop categories, as well as the values of other parameters used in these calculations, are presented in Table 1. Since these clouds have warm bases and offer great depth through which the warm-cloud processes of cloud drop nucleation, condensation and coalescence create a broad size distribution of supercooled liquid water at the initiation of the glaciation process, the initial value of the total liquid water content is taken as 5 g m\(^{-3}\). The water content in each drop-size category is calculated from this total value by specifying the value of the partitioning parameter \( \lambda_R \) (the fraction of the total liquid content in the rain category), holding the total constant. The initial number concentration of the cloud drops is then computed from the cloud liquid water content (CLWC) by
MECHANISTIC LIMITATIONS DURING GLACIATION OF CUMULUS

TABLE 1. Values of parameters used in the calculations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice nuclei</td>
<td></td>
</tr>
<tr>
<td>Diameter</td>
<td>$0.03 \mu m$</td>
</tr>
<tr>
<td>Diffusivity ($D_D$)</td>
<td>$5 \times 10^{-5} \text{cm}^2\text{s}^{-1}$</td>
</tr>
<tr>
<td>Cloud drops</td>
<td></td>
</tr>
<tr>
<td>Diameter ($2R_C$, mass mean)</td>
<td>$15 \mu m$*</td>
</tr>
<tr>
<td>Fall speed</td>
<td>0</td>
</tr>
<tr>
<td>Number concentration ($N_C$, initial)</td>
<td>Computed (Eq. 1)*</td>
</tr>
<tr>
<td>Number fraction ($f_c$) having diameter $&gt; 25 \mu m$</td>
<td>0.1 (Hallett et al. 1978)</td>
</tr>
<tr>
<td>Rain drops</td>
<td></td>
</tr>
<tr>
<td>Diameter ($2R_R$, mass mean)</td>
<td>$1 \text{mm}$*</td>
</tr>
<tr>
<td>Fall speed ($V_{in}$)</td>
<td>$500 \text{cm} \text{s}^{-1}$ (Beard 1976)</td>
</tr>
<tr>
<td>Number concentration ($N_R$, initial)</td>
<td>Computed*</td>
</tr>
<tr>
<td>Small ice</td>
<td></td>
</tr>
<tr>
<td>Electrostatic capacity of splinters for deposition growth ($C_s$)</td>
<td>$35 \mu m$</td>
</tr>
<tr>
<td>Electrostatic capacity of single crystals for deposition growth ($C_{tc}$)</td>
<td>$35 \mu m$</td>
</tr>
<tr>
<td>Large ice (graupel)</td>
<td></td>
</tr>
<tr>
<td>Diameter ($2R_G$)</td>
<td>$1 \text{mm}$†</td>
</tr>
<tr>
<td>Fall speed ($V_G$)</td>
<td>$140 \text{cm} \text{s}^{-1}$ (Auer 1972)†</td>
</tr>
<tr>
<td>Interaction efficiencies</td>
<td></td>
</tr>
<tr>
<td>Accretion ($E_C$)</td>
<td>0.5</td>
</tr>
<tr>
<td>Capture ($E_{cc}$)</td>
<td>0.1 (conservative estimate)</td>
</tr>
</tbody>
</table>

* The relationship between drop size, liquid water content and number concentration is maintained internally consistent through equations of the form given by Eq. (1) in the text. Whereas the drop size indicated here was originally calculated from measured values of water content and number concentration (Hallett et al. 1978), the model is more conveniently operated maintaining the specified drop diameter and calculating the initial number concentration from the respective cloud or rain liquid water content input to the model.

† The reduction in the fall speed of the graupel particles compared with that of the rain drops, maintaining their sizes equal, represents a parametrization of the composite changes in size, density and fall speed that the particles actually undergo during the transformation from rain to mature graupel particles. Other choices may lead to slightly different numerical results, but without alteration of the conclusions.

\[
N_C = \frac{\text{CLWC}}{M_C}, \quad \quad \quad (1a)
\]

where

\[
M_C = 4\pi \rho_L R_C^3/3 \quad \quad \quad (1b)
\]

is the mass of individual drops having liquid density $\rho_L (= 1 \text{ g cm}^{-3})$ and radius $R_C$. The initial rain drop concentration $N_R$ is similarly obtained from the given rain liquid water content (CLWC) and rain drop radius ($R_R$).

For this application two modes of nucleation are possible for AgI seeding, contact and depositional nucleation (compare, for instance, Katz and Pillié (1974) and Sax and Goldsmith (1972)). In the case of contact nucleation, we start with no initial ice whatsoever and an initial concentration $N_{NC}$ of contact nuclei specified for each run. The contact nuclei are allowed to diffuse by Brownian motion to the supercooled cloud and rain populations at the respective rates

\[
J_{nc} = 4\pi D_N N_{NC} N_C R_C \quad \quad \quad (2a)
\]

and

\[
J_{nr} = 4\pi D_R N_{NC} N_R R_R \quad \quad \quad (2b)
\]
where $D_N$ is the particle diffusivity. Once contact with the supercooled drops is made, freezing is immediate and the particular nucleus is lost to the remaining nucleus population.

In the case of depositional nucleation, an initial concentration of vapour-grown ice crystals is taken equal to the specified concentration of deposition nuclei. The time for the embryonic ice crystals to grow to several tens of micrometres in size, large enough to have an appreciable efficiency for capture by the rain drops, is considered short compared with the other processes.

As the nuclei, acting by either mode, begin to form ice early in the glaciation process, the small ice particles (frozen cloud drops in the case of contact nucleation, vapour grown 'ice crystals' in the case of depositional nucleation) are swept out of the cloud volume by the large rain drops. This hydrodynamic capture proceeds at a rate

$$J_{ca} = E_{ca} \pi R_R^2 V_R N_R N_I,$$  \hspace{1cm} (3)

where $E_{ca}$ is the efficiency for capture of small ice particles by large rain drops, $V_R$ is the relative fall speed of the rain drops, and $N_I$ is the number concentration of small ice, either the frozen cloud drops or the vapour grown ice crystals, depending on the mode of nucleation chosen. Note that the value for the capture efficiency is taken conservatively as 0.1 in lieu of any measured values.

Following contact with either form of ice or with a contact nucleus, a supercooled rain drop freezes 'immediately' to form a frozen rain drop or, since it now acts as a riming centre, a large graupel particle. Such graupel particles are able to sweep out the supercooled drops with an efficiency $E_G$ and rate

$$J_a = E_G \pi R_G^2 V_G N_G N_C,$$  \hspace{1cm} (4)

where $R_G$ is the radius of the graupel particle (taken equal to that of the rain drop), $V_G$ is the graupel fall speed and $N_G$ is the graupel concentration.

Consistent with the laboratory finding of Hallett and Mossop (1974), the rate of splinter production, $J_s$, is proportional to the accretion flux $J_a$ of Eq. (4):

$$J_s = \alpha f_s J_a,$$  \hspace{1cm} (5)

where $f_s$ is the fraction of the total cloud drop population (used in calculating $J_a$) having diameters greater than 25 $\mu$m and $\alpha$ is the fraction of the riming collisions which yield a splinter. (Although $\alpha$ may exceed 1/50 under optimal conditions (Mossop 1978), we use the conservative mean value of 1/200.)

The splinters so formed are then made available to the general population of small ice capable of being captured by the supercooled rain drops at the rate given in Eq. (3). This forms the powerful regenerative ice generating process which can lead to rapid glaciation at the expense of the rain drop population.

Having now identified the various rates of interactions between the given species of cloud particles, we can determine the changes in the concentrations of the various species by simple continuity relationships. If $N_{FC}$, $N_{IC}$, $N_S$, $N_G$, and $N_C$ designate, respectively, the concentrations of frozen cloud drops, vapour grown ice crystals, splinters, graupel and supercooled cloud drops, then

$$dN_{FC}/dt = J_{IC} - J_{ca,FC},$$  \hspace{1cm} (6)

$$dN_{IC}/dt = -J_{ca,IC},$$  \hspace{1cm} (7)

$$dN_S/dt = J_s - J_{ca,S},$$  \hspace{1cm} (8)

$$dN_G/dt = J_{FR} + (J_{ca,FC} + J_{ca,IC} + J_{ca,S}),$$  \hspace{1cm} (9)
where the second subscript on \( J_{ca} \) indicates the respective form of ice concentration to be used in place of \( N_f \) in Eq. (3). The final relation simply preserves the sum of large particles:

\[
dN_R/dt = -dN_L/dt
\]

Implicit in most of the individual microphysical processes is heat generation, since for every supercooled cloud drop frozen (by heterogeneous nucleation) or swept up by accretion and for every rain drop collision with a small ice particle or contact with a nucleus, latent heat of fusion is released. Similarly, as ice particles form by whatever method, they can receive mass from the vapour phase. Growth by vapour deposition adds latent heat of sublimation, but is partially countered by evaporation of liquid water when present. Since liquid and ice do coexist during the early stages of glaciation, all vapour growth in this treatment is made to liberate heat proportional to the heat of fusion.

The rates with which heat \( Q \) is released due the freezing of cloud and rain drops is given simply by forming the products of the latent heat of fusion \( L_f \) with the respective masses of the individual particles and their rates of formation. Thus,

\[
(\text{cloud freezing}) \quad dQ_{fc}/dt = L_f M_c J_{nc},
\]

\[
(\text{accretion}) \quad dQ_{a}/dt = L_f M_c J_a,
\]

\[
(\text{rain freezing}) \quad dQ_{fr}/dt = L_f M_R dN_R/dt.
\]

For heating due to vapour deposition onto the small ice particles, the rate is simply proportional to the latent heat, the number of particles and the mass growth rate of individual particles:

\[
(\text{frozen cloud}) \quad dQ_{dfc}/dt = L_f N_{fc}(4\pi R_c G \Delta \rho),
\]

\[
(\text{ice crystals}) \quad dQ_{drc}/dt = L_f N_{rc}(4\pi C_{rc} G \Delta \rho),
\]

\[
(\text{splinters}) \quad dQ_{ds}/dt = L_f N_{sg}(4\pi C_{sg} G \Delta \rho),
\]

where \( G = 0.13 \text{ cm}^2 \text{s}^{-1} \) is an effective diffusivity for vapour deposition at \(-10 \degree \text{C} \) (see Fletcher 1962, p. 267), \( \Delta \rho = 2.2 \times 10^{-7} \text{ g cm}^{-3} \) is the difference in vapour density between cloud and ice (water saturation is assumed initially, but then \( \Delta \rho \) is linearly reduced to zero as the liquid water content of the cloud approaches zero), and \( C_{rc} \) and \( C_{sg} \) are the electrostatic capacities of the vapour grown ice crystals and splinters, respectively. The overall or total rate of heating of the cloud due to glaciation is simply the sum of the individual rates given in Eqs. (12) through (17).

Integrations of the various differential equations are performed numerically by forward differencing with time steps of one second. The numerical procedure was tested successfully against the conditions and results of the analytical solution given by Hallett et al. (1978).

3. Natural glaciation

As a buoyant tower of cloudy air rises above the thermodynamic freezing level, an increasing fraction of the in-cloud aerosol acts to initiate the ice phase. It is beyond the scope of the present study to consider quantitatively the cumulative nature of the primary nucleation events, so we start with a conservatively low concentration of either contact or
depositional ice nuclei. We aim here to show that whenever the conditions are favourable, naturally induced glaciation can be expected to reach completion within realistic times scales even at relatively high temperatures.

In the complete absence of any secondary ice production, as might occur in clouds lacking large cloud drops (e.g. cold continental clouds) or in temperature regions outside the limits for generation, ice crystal number concentrations cannot exceed the concentration of ice nuclei active at the parcel temperature or warmer. We consider here only contact nucleation, since the rate of ice formation is slower by this mode than by any other at the same concentration level, due to the limitations imposed by the Brownian diffusion of the contact nuclei to the drops. When the concentration of contact nuclei presumed to be active under the cloud conditions specified in the inset of Fig. 2 is taken to be $10^{-4}$ per litre, ice evolves in the manner depicted in Fig. 2(a). The build-up of frozen cloud and rain drops is clearly limited by the availability of ice nuclei when secondary ice generation is not

Figure 2. The calculated evolution of ice and rain during natural glaciation initiated by $10^{-4}$ per litre contact nuclei. (a) Without any secondary ice production. (b) With secondary ice produced at the rate of 1 splinter for every 200 cloud drops > 25 µm diameter accreted.
active. Any graupel formed comes about almost exclusively from the capture of the frozen cloud drops by the supercooled rain drops (dashed curve). No mechanism exists in this case for freezing any significant fraction of the rain drop population.

If secondary ice splinters are allowed to form by the rime-splintering hypothesis of Hallett and Mossop (1974) at the rate of 1 splinter for every 200 large (>25 μm diameter) cloud drops rimed, then the various forms of ice increase with time in the manner depicted in Fig. 2(b). Clearly the dominant species is the splinter ice at all but the earliest times. Although the concentration of graupel builds up initially as in the case of no secondary ice, it subsequently increases exponentially until the rain drop population, the only source of the graupel in this model, becomes exhausted. The time scale for the glaciation, somewhat arbitrarily defined as the time for the graupel and rain drop concentration curves to cross, is about 700 s in this case. The magnitude of the glaciation time has little predictive value in itself, of course, since the model contains no dynamical framework (time-dependent parameters). The estimated time is nevertheless consistent with observations and indicative of the power that regenerative glaciation mechanisms can have for converting an initially all liquid cloud to ice.

The reasonable time scales to glaciate a cloud by this mechanism arise only if the ice can evolve simultaneously by primary nucleation and the regenerative feedback processes. Primary nucleation events alone are orders of magnitude too slow at the warm temperature considered, but under conditions conducive to secondary ice production (temperature between −3 and −8 °C and a broad cloud drop spectrum present) and to regeneration (updraught speed low enough to keep graupel in the secondary ice production zone for several hundred seconds), the primary nucleation need serve only as a 'trigger' to the regenerative glaciation.

The exponential time scales for graupel and splinter evolution are determined by the characteristics of the regenerative mechanism, not those of the primary nucleation. In Fig. 2(b) for instance, we see that during the 'steady-state' portions of the process the graupel can build up about one decade in concentration every 90 s, a value that depends largely on the secondary ice production rate and the collection efficiencies for accretion and small ice capture. In agreement with the conclusions of Chisnell and Latham (1976) we also see that the exponential time constants for graupel and splinter evolution are equal, a manifestation of their serial involvement in a single regenerative phenomenon. It is to be emphasized that, because of the powerful amplifying effect of the regenerative process, the overall glaciation is relatively insensitive to the concentration of the primary nuclei. This point was also brought out by Chisnell and Latham using a somewhat more parametrized nucleation scheme.

Mechanistically, at times greater than about 100 s after the first primary nucleation event, it is the capture of the secondary ice splinters by the supercooled rain drops that contribute most to the formation of the graupel particles. As illustrated in Fig. 3, the ordinate of which represents the ratio of the individual rates of rain drop freezing by each of the respective mechanisms (depicted in Fig. 1) to the composite rate, the graupel formation rate is controlled by the primary nucleation events only during the first few seconds. Although not explicitly demonstrated in Fig. 3, the Brownian scavenging of the nuclei by the large numbers of cloud drops leads to the preferential nucleation of the cloud drop population. This indirect mechanism of rain drop nucleation by capture of primary frozen cloud drops dominates the build-up of the graupel particles until (about 100 s) the population of splinter particles exceeds that of the frozen cloud drops. The preferential capture of the splinters by the supercooled rain drops subsequently forms the dominant mechanism for the conversion of the supercooled rain to graupel. Through such analysis we can appreciate the details of the conversion mechanics and understand precisely how the
presence of supercooled rain drops facilitates the glaciation of convective clouds, a conclusion well founded from numerous earlier works (e.g. Cotton 1972; Chisnell and Latham 1976; Koenig 1977).

The earlier study of Hallett et al. (1978) presented numerous cloud penetration cases which provide observational support for the presence of supercooled drops and validity of these glaciation concepts. Using those same general techniques for measuring the concentrations of the ice and water particles in a more recent case study, we present microphysical data from a series of cloud penetrations over south Florida on 6 July 1976 in Fig. 4. The particular cumulus in question had a base at about 20°C and had just grown through the flight level at −11°C prior to the first pass (left side of Fig. 4). No ice of any type was found initially, only supercooled cloud and rain drops (interpreted as 'splash drops' on the Formvar replicator). Four minutes later, during the second pass through the cloud, all of the splash drops had disappeared and were apparently replaced by a commensurate concentration of graupel particles. At the same time, many columnar ice crystals were found and the rain drops had all but disappeared.

The rapidity with which this initially all liquid cloud turned to ice is typical for deep cumuli. Although the microphysical mechanism of glaciation is relatively rapid, it nevertheless requires the graupel to reside within the temperature bounds (−3 to −8°C) for appreciable secondary ice production for several hundred seconds in order to maintain regeneration. This imposes a possible dynamical restriction which may have led to the observations (Hallett et al. 1978) and simulation results (Koenig 1977) that rapid glaciation is favoured by weakened updraughts.

From the earliest observation of Koenig (1963) in warm-base continental clouds, rapid glaciation has also been closely associated with the presence of large supercooled rain drops. This is so in all of the Florida observations of natural glaciation as well. The implication of the large drops in the glaciation process, along with the requirement of the cloud
drops for the production of secondary ice particles during graupel riming, shows an explicit need for both ends of the drop spectrum. The great depth of convective cloud below the freezing level ensures that a very broad drop size distribution will exist prior to the onset of glaciation and sets the stage for the efficient conversion of water to ice in these clouds.

This aspect of the regenerative glaciation model gives good correspondence with the observations. By running the model repetitively at varying values of $\lambda_R$, the fraction of the total liquid water content in the rain drop portion of the dichotomous spectrum, and calculating the glaciation time for each run, one obtains the trend shown in Fig. 5. The distinct minimum in the glaciation time that appears mid-way along the water distribution axis clearly illustrates the need to have both ends of the drop spectrum present. At either end, rapid natural glaciation is not favoured because of the lack of effective splinter production. At the far left ($\lambda_R \rightarrow 0$) the lack of rain drops means too few riming centres, whereas at the other extreme ($\lambda_R \rightarrow 1$) the lack of cloud drops implies too little riming of those graupel particles that do appear. In addition to proper temperature (−3 to −8°C), a broad drop size distribution is necessary for efficient glaciation. As brought out earlier, the natural glaciation of these clouds very likely depends crucially on the rather specific set of conditions conducive to splinter production.

Concurrent with the evolution of the ice phase in a cloud is the release of latent heat. Through the glaciation model we can readily estimate the rates with which the heat is given up by each of the several mechanisms of glaciation. As shown in Fig. 6(a) the earliest and dominant mechanism for releasing latent heat is the freezing of the rain drops. Heating due to the accretional sweep-out of the cloud drops by graupel becomes important only during the latter stages of ice evolution, after the rate of graupel formation has reached a maximum.
Figure 5. Computed glaciation time as a function of $\lambda_R$, the fraction of the total initial liquid water content in the form of rain.

The maximum in the total heating rate occurs essentially at the same time, near the calculated glaciation time of about 700 s (cf. Fig. 2(b)); study of Fig. 6(a) also shows that less than 10% of the maximal heating rate is available to the cloud until beyond about 600 s after initiation of glaciation. Although heat is 'accumulated' throughout the cloud glaciation (see Fig. 6(b)), it would not be until near the maximum in the heating rate that either the rate or the magnitude of the heat would be great enough to cause significant stimulation of the dynamic structure of the cloud. In the case of natural glaciation, especially when the updraught speed must be low enough to permit sufficient regeneration within the splinter production zone, ice and heat evolution times like 700 s mean that the heat very likely comes at a time in the life cycle of the cloud tower when the updraught profile has weakened and has become relatively disorganized. It may be expected that the heat is indeed released more or less as depicted, but is unable to counter the dynamic forces already causing the tower to dissipate.

4. SEEDING FOR DYNAMICAL EFFECT

We have seen in the preceding section that in the case of warm-based deep convective clouds, as develop in the summertime Florida environment, secondary ice generation can provide a very effective mechanism for rapid glaciation. In considering seeding strategy in such an environment, one faces the problem of understanding how in the presence of such efficient natural glaciation it is still possible to achieve a cloud response through the controlled introduction of ice nucleating substances. By artificially inducing the ice phase to originate earlier in the life cycle of the tower and forcing the latent heat to be released more rapidly while the updraught is still strong and organized, is it possible to circumvent some of the limitations inherent in the case of naturally induced glaciation? This section will deal
Figure 6. The release of latent heat during natural glaciation. (a) Rate of heat release. (b) Magnitude of accumulated heat.

with the ramifications of seeding a rapidly rising tower for the purpose of augmenting its buoyancy and dynamic structure.

As in the case of natural glaciation, the primary mechanism responsible for the rapid conversion of supercooled rain to graupel is likely to be the hydrodynamic capture of the secondary ice splinters resulting from graupel riming. The regenerative nature of the process posed at once a strength and a limitation to the conversion of water to ice; a strength in the sense that the glaciation rate increases exponentially, a limitation in the sense that the constituents of the process must remain in the critical production zone long enough to feed on themselves. The restriction to relatively low updraught speeds for the glaciation to proceed most rapidly is severe in the natural case.

By the timely interjection of many small ice particles into a still rapidly growing tower,
it should be possible to force the rapid conversion of the supercooled rain to graupel by much the same mechanism as that which dominates natural glaciation, without the restriction imposed by low updraught speeds. In essence, we expect the added ice particles to act as surrogate splinters that are hydrodynamically captured by the rain. The graupel particles so formed then become instrumental in sweeping out much of the remaining cloud water. The combined effects of rain freezing by ice particle capture and of cloud drop freezing by accretion form a potentially powerful means of rapidly converting supercooled water to ice, releasing the latent heat at a time when it can still be useful for augmenting the cloud updraught strength.

Observationally, we can see from repeated passes through a growing tower, the evolution of the various cloud elements following seeding with falling AgI flares. A specific case from the Florida studies is presented in Fig. 7 in which the seeding was accomplished during the first pass (left side of Fig. 7) when no ice particles of any type were detectable by the Formvar replicator. Even though no rain drops ('splash drops' in Fig. 7) are evident in the very top of this deep cloud (i.e. during Pass 1), they may have existed lower down and did not appear at the flight level (\(~ -11^\circ C\)) until the second penetration some 80s later. A similar length of time was presumably required for the nucleation and growth of the ice particles, mostly columnar ice crystals, which are evident in very high concentration in the data of the second pass. Given the high concentrations of ice crystals coexisting simultaneously with significant numbers of large supercooled rain drops, it is inevitable that collisions between the two species will result in the rather rapid conversion of the rain to graupel, as is apparently taking place by the third pass.

Use of the microphysical glaciation model developed in section 2 demonstrates that even in the presence of an efficient natural secondary ice generation mechanism, operating simultaneously with the seeding, the addition of ice-forming nuclei to the cloud nevertheless
Figure 8. The calculated evolution of ice and heat following glaciation induced naturally (dashed curves) and by seeding (solid curves). (a) Small ice particle evolution. (b) Graupel evolution. (c) Accumulation of total heat with time.
appreciably shortens the time necessary to glaciate and warm the cloud. In Fig. 8 we show a worst-case situation in which a relatively high concentration (0.1 per litre) are assumed to be immediately active by deposition while we seed with 100 nuclei per litre acting in the contact mode.

The results of the calculations show how each of the ice particle species and the heat evolve with time. As seen in Fig. 8(a), even though the concentration of ice crystals resulting from the natural deposition nuclei is initially high, the concentration of frozen drops more than compensates as a result of the very much higher concentration of contact nuclei from seeding. The great number of frozen cloud drops, available for capture by the supercooled rain drops, rapidly stimulates the regenerative glaciation mechanism based on the secondary production of splinters (Fig. 8(a)) and the capture conversion of rain water to graupel (Fig. 8(b)). A direct response of this rapid forced glaciation is the liberation of the available latent heat in a time scale more than a third less than that for the natural case (Fig. 8(c)). As in the case of natural glaciation, seeding under conditions conducive to secondary ice production can lead to significant multiplicative effects that shorten the time scale of the ice and heat evolution (Weinstein and Takeuchi 1970).

Within the context of a rapidly evolving cumulus tower even a hundred seconds reduction in heat input time could be significant to the subsequent growth of the cloud, since the period of time in which active updraughts exist at seeding altitudes is itself often only a few hundred seconds. Moreover, since natural glaciation at temperatures warmer than about $-10^\circ$C favours the weaker dynamic regime of the tower cycle, the actual length of the time to add the latent heat of fusion to the cloud may be substantially shortened relative to the calculated value. The observed fact that deep convective clouds glaciate readily at warm temperatures with relatively few natural nuclei should not therefore preclude the possibility of modifying them dynamically by seeding active towers earlier in their life cycles.

The numerical calculation leading to the conclusion that seeding can operate to speed up the ice generation process beyond what can be accomplished through efficient natural glaciation is consistent with observations in the Florida environment. Sax et al. (1979) have shown, on an ensemble basis, that the increase in the mean concentration of graupel particles over essentially identical time periods is greater (to better than a 5% significance level) in the case of seeded clouds than in that of nonseeded clouds.

Given some degree of confidence in our understanding of the glaciation microphysics operating in deep convective clouds, it may be possible to account for some of the tremendous natural variability found in the real atmosphere. It has been thought that the cloud microphysics alone cannot hope to explain more than a fraction of what is observed, but if the conditions for rapid glaciation and heat release are indeed highly specific, then one should expect to find cases of anomalous behaviour when the natural fluctuations in the numerous variables align favourably. For the most part the boundary conditions under which the microphysics operate are provided by the cloud dynamic structure, while rapid heating, provided by the glaciation microphysics at the appropriate time in a strongly time-dependent cloud, serves to enhance the buoyancy on which the dynamic structure so vitally depends.

A possible example of just such an interaction between the dynamics and microphysics of a deep convective cloud is the case study by Keller and Sax (1981) of a newly rising tower becoming 'seeded' naturally by the infusion of ice remaining from an earlier tower of the same cloud. The rapid growth following the entrainment of the debris from the old tower may well have resulted from the abnormally rapid glaciation of the new, water-rich tower and the consequent high rate of latent heat release. Variability in cloud evolution may well be related to the likelihood of similar injections of ice from earlier developments and dependent on the relative juxtaposition of new and old cloud systems.
Figure 9. Dependence of the time to achieve significant heating on the fraction of liquid water in the form of rain for both contact and depositional nucleation.

Considering now the problem of 'triggering' ice formation through seeding, we show in Fig. 9 that the use of deposition nuclei, if active within the temperature range of interest, has many advantages over the use of nuclei which must first be scavenged (contacted) by water droplets. The time for a significant quantity of heat* to be added to the cloud region seeded by a given concentration of nucleant is always less in the case of depositional activity and can be considerably less if the cloud water content is distributed such that precipitation-sized drops comprise the bulk of the water mass. In that case, the scavenging time is long, due to the low spatial density of drops, so the contact mode is very inefficient. In such situations, as might exist for example in organized convection developing over water areas where the drop size spectrum may be quickly transformed outward through coalescence processes to the precipitation sizes, seeding with an agent such as dry ice to initiate (through homogeneous freezing) a prolific source of ice crystals should prove more productive than the use of an agent such as silver iodide which, at warm temperature, may well have to rely on a scavenging mechanism to initiate ice formation. On the other hand, in the expected absence of large drops, as for example in the case of cold-based continental clouds, the important hydrodynamic sweep-out mechanism for graupel (and heat) generation will be absent. In this case also, dry ice seeding may work to advantage (although more slowly) through the conversion of water to ice by depositional growth on the initial crystals formed.

* The choice of $10^4 \text{J m}^{-3}$ as the measure of significant heating is based on the fact that this heating density would tend to raise the air temperature by 1 °C at sea level (or 2 °C at 500 mb), a magnitude likely to have a discernible effect on the dynamic structure of a cloud. In actuality, only a fraction (about $1/4$, see Appendix) will be available for sensible warming or enhanced circulations, since some of the liberated heat goes to evaporate condensed water (ice) mass.
5. CONCLUSIONS

The essential concepts of glaciation, taking place in deep convective clouds, have been identified and explored quantitatively in a simple microphysical model. With a glaciation mechanism based on the rime-splintering hypothesis of Hallett and Moseop (1974) for the generation of secondary ice particles and on the capture nucleation of supercooled rain drops in a regeneration scheme, it has been shown that rapid glaciation should be expected to occur naturally at relatively warm temperatures when the primary nucleation and regenerative processes take place simultaneously. Primary nucleation, slow in itself, is necessary for initiation of glaciation and serves to trigger the regeneration mechanisms, leading to large ratios of ice to ice nucleus concentrations within only a few hundred seconds. The exponential time scale for the glaciation is determined by the regeneration, not the primary nucleation processes. The times to glaciate a cloud naturally exhibit a minimum when plotted against the fraction of the total liquid water in the form of rain, indicating the need for both ends of the drop spectrum being present. The lack of either cloud or rain drops limits the production of secondary ice splinters.

The production of heat, primarily from the freezing of the supercooled rain by capture of the splinter ice and of the cloud water swept up by the newly formed graupel particles, roughly parallels the ice evolution, reaching significant levels on a time scale commensurate with that for the glaciation itself. It is speculated that the heating comes relatively late in the life cycle of the cloud tower, since regenerative glaciation imposes an upper limit to the updraught speed, causing the new sensible heat to appear only after the updraught organization is already spent; by this time the added heat and buoyancy are probably ineffective in stimulating new circulations.

The primary effect of seeding could be to augment dramatically an otherwise deficient supply of small ice particles available for hydrodynamic capture by the supercooled rain drops. This idea is shown to be consistent with new observational data from repeat aircraft penetrations of a glaciating cloud seeded with AgI. The latent heat, now being released rapidly when the updraught of the seeded tower is still strong and well organized, could generate buoyancy useful for invigorating the dynamic structure of the cloud within that narrow time-frame.

Quantitative analysis shows the two-stage process by which an active tower is forced to glaciate to be crucially dependent upon the presence of the supercooled rain, regardless of the primary nucleation mode active at the time. If contact nucleation is the dominant mode for the particular seeding agent, both ends of the drop spectrum must be present, a condition not so restrictive if depositional nucleation dominates. It is clearly important that we improve our knowledge of which mode of nucleation is operative in any given situation.

The conceptual modelling considered here, though lacking a dynamical framework, provides insight into the glaciation mechanisms prevailing in deep convective clouds and suggests that timely seeding can materially speed up the glaciation and heat liberation processes, even when secondary ice is being generated simultaneously. These ideas, based on the release of fusional heat within the narrow time window available for effectively altering supercooled cumuliform towers having short and unsteady life cycles, have significance for evaluating the natural and artificial seeding of deep convective clouds.

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This page contains a section from the text titled "Appendix: Fraction of Added Heat Available for Cloud Warming". The text discusses the magnitude of any temperature rise that occurs in response to the sudden input of heat into the parcel, by whatever mechanism, is of importance from the point of view of increasing cloud buoyancy. The text outlines a method to calculate the heat available for cloud warming and provides equations to determine the temperature change. The appendix includes a discussion on the specific heat of air, air density, and latent heat of evaporation, and how they contribute to the temperature change in the cloud. The references listed at the end of the appendix include works by Auer, Beard, Chappell, and Chisnell, which provide further insights into the subject matter.


