1 Introduction

This position paper develops arguments for devoting greater attention to studies of how ice originates in clouds and how that ice modifies processes like the formation of precipitation, interactions with radiation, and chemical processes in clouds. In recent years, relatively little effort has been directed toward the fundamental aspects of this problem, despite its importance. A new emphasis on this problem is warranted by recent advances in instrumentation, modeling, and related studies of ice physics. We outline here the components of a possible initiative to study ice formation in clouds and the consequences of the subsequent evolution of that ice. This is a preliminary statement, to be refined via community discussion and meetings discussed at the end of this document.

2 Justification

As ice forms in clouds, it influences all important characteristics of those clouds: precipitation formation, interactions with radiation, latent heat release and evaporative cooling, chemical processes, charge separation, water vapor content, icing potential, particle scavenging, water redistribution, appearance, etc. Understanding the process of ice formation has been known to be important since the early work of Bergeron and Findeisen, yet we still remain ignorant of many significant aspects of the problem. We know that ice may appear as a result of ice nucleation by particles or as a result of the generation of ice by existing ice through secondary processes like ice splinter production or fragmentation. However, we remain in a poor position to predict the primary ice concentration that will form in given situations via nucleation, and only in the case of the Hallett-Mossop processes are the required conditions characterized well enough to support predictions of generation rates. Even in the latter case, although ample laboratory evidence has characterized the process, the mechanism remains in question.

There is an increasing need to characterize the ice generation process in models. Most representations of ice generation use some variation of the Fletcher curve to represent primary ice nucleation, despite the near universal opinion among cloud physicists that such use of the Fletcher curve is unjustified because it is inconsistent with recent evidence, a misinterpretation of the original intent of the formula, and an oversimplification of the ice production process. Sources and transport of ice nuclei are not included, and geographic and altitude dependences are seldom represented. Secondary ice generation is often ignored despite its overwhelming importance in many cloud types.

These deficiencies arise mostly because nothing better has been developed to represent the basic processes, and so they point to significant gaps in our knowledge of fundamental atmospheric processes. The importance and relevance of these gaps has increased with recent improvements in global-scale and cloud-scale models and the important attempts to use such models for climate prediction. Whereas a few years ago the prevailing view was that microphysical
parameterizations in such models were not a serious weakness (because there were much more important problems to be solved), recent evidence now points to microphysical parameterizations as a significant uncertainty in models at many different scales. Both the earlier and recent arguments are based on weak evidence, usually along these lines: changes among different parameterizations, all of which are known to be incorrect, do or do not lead to significant changes in the results. However, the fundamental influence of ice on cloud properties is the strongest evidence that ice generation should be represented in some way that is realistic if the cloud properties are to be realistic.

Ice formation under conditions characteristic of radiatively important cirrus clouds has also been characterized only poorly. There is still uncertainty regarding the relative contributions of heterogeneous nucleation processes and homogeneous freezing in such clouds, but it is clear that new pathways for the production of ice become important at high altitude and low temperature. If the radiative properties of such clouds are to be characterized in ways that support climate prediction, the dependence of their optical properties on controlling characteristics like soluble and ice-nucleating aerosol particles needs to be understood in a way that supports prediction of future changes.

The most important result of improved understanding of ice formation will likely be improved understanding of precipitation formation, because ice is present and plays controlling or significant roles in most precipitating clouds. Precipitation in turn influences all other aspects of weather and the hydrological and biological cycles of the earth. Floods and droughts change the vegetation, affecting the global albedo, atmospheric circulation and dynamics. Dust storms may increase during droughts, leading to increased ice-nucleation potential. There are numerous examples of potentially important linkages such as these.

Although practical needs increase the timeliness of the study, the most compelling argument favoring its emphasis is that our ability to understand and predict almost all atmospheric phenomena involving clouds will remain seriously deficient until our understanding of ice formation improves significantly.

3 Fundamental problems of ice formation

The issue for this initiative is how best to approach needs of the kind noted in the preceding section. We believe they are best approached by undertaking fundamental as well as applied studies, because we need not only to improve how current knowledge is represented in models but also to address the serious weaknesses in our current understanding that cause us to distrust representations based on current information.

Limitations of computer power in the past usually have dictated the use of very simple modelling approaches to ice in clouds for applications like these: autoconversion schemes and specified size distribution functions, for instance, that are empirically based and most probably bypass important natural variability. With the increase of computer power and model tests that indicate important
sensitivities to details of ice evolution, it is becoming clear that a more realistic approach to ice evolution—a more cause-and-effect approach—is both possible and warranted. This brings higher relevance to fundamental research, because the more realistic inclusion of ice processes requires a better basic understanding of them.

The main practical problem is the specification of ice particle properties and size distributions, which are known to be highly variable. The corresponding basic problem is understanding how these develop so that their specification is possible. Ice evolution depends upon several variables (including temperature and the amounts and sizes of liquid drops) and is accomplished by several physical processes operating at the same time. Many of these are collisions between different kinds of hydrometeors that can lead to hydrometeor growth or breakup or the generation of new particles. Prediction of ice evolution as simply as possible is the goal, and this requires distinguishing the important from the negligible processes. The second part of the research then is to establish how the important processes operate and describe them quantitatively. Much of this is done through laboratory and theoretical results, though nucleation processes require measurement of the natural nuclei. The third part, the accuracy that the final specifications need to have for any particular model, is relatively easily settled by testing sensitivity. That is needed to help decide how detailed the descriptions of the important processes need to be.

A great deal is known about ice evolution in clouds, and a great deal is not known. It is known for instance that ice multiplication can be very important for generating ice in maritime cumulus but it is not known how significant it is in continental cumulus and it itself is not a well-understood process (or processes). Heterogeneous ice nucleation initiates the ice phase in cumulus but it is now known that homogeneous nucleation can be important in cirrus. The development of the ice phase in penetrative convection (cumulus that penetrate to and through the tropopause, which produce much of the precipitation and the vertical transports of water and energy) is important for many applications but is very complex and poorly understood.

It is interesting to note that it is not established whether the natural variability of heterogeneous ice nuclei is a significant factor in modulating precipitation from cumulus. The continued controversy of the effectiveness of cloud seeding with ice nuclei attests both to this and to the difficulties of assessing the responses of the more complex types of clouds. Nevertheless, heterogeneous ice nucleation is certainly important in some contexts and measuring heterogeneous ice nuclei and understanding their sources and mechanisms represents another of the major, basic problem areas for ice evolution.

The growth of individual ice particles within clouds appears to be relatively well understood compared with ice initiation and ice multiplication processes. However, another major difficulty in characterizing ice evolution is turbulence, both through turbulent mixing effects upon ice growth conditions and through turbulent transport of ice hydrometeors, leading to reduced ice contents in some parts of clouds and increased in others. An area that has been neglected too much is instrumentation for observing cloud properties and processes. An ar-
gument can be made (and we expect that most cloud physicists would agree) that inadequate ability to characterize natural clouds is the single most serious obstacle to progress in this field.

This has been intended as a broad outline of the most important, basic areas of inquiry concerning the evolution of the ice phase in clouds.

4 Timeliness of an initiative

Advances in model simulations for both quantitative weather forecasting and climate are advancing to the point where they will soon have grid spacings of one to a few kilometers. With this kind of resolution microphysical parameterizations become more important and the use of bulk and poorly formulated ones less reasonable. Investigators in the weather and climate communities are recognizing that microphysical parametizations are hindering progress. Advances in theoretical descriptions and numerical simulations are seriously impeded by the lack of detailed observations.

Importantly, there is also new instrumentation and techniques which have recently become available which greatly enhance our ability to advance our understanding of ice processes in clouds. Principal among these are instruments for research aircraft, remote sensing and aerosol particles.

New airborne instruments provide in-situ imaging of cloud particles with features resolved to $\approx 2\mu m$ and show concentrations up to thousands per liter. Airborne millimeter radar can show water and ice cloud structure and motions at size scales of a few meters. Multiparameter radar techniques using fuzzy logic are now under development that may be able to distinguish as many as eleven or more different microphysical conditions ranging from light to heavy rain and ice crystals to aggregates to graupel to hail. Aerosol instruments make it possible to detect ice nuclei that are active through condensation freezing and deposition and to collect them for studying their size and chemical composition. Suits of complementary instrumentation can provide simultaneous measurements of aerosol particles, cloud droplets, ice particles, cloud active nuclei (CCN and IN), thermodynamics, radiation, gases, airflow, structure and evolution. High resolution, fast response humidity, especially near saturation, can be measured from aircraft with laser line absorption techniques. Cloud particles can be separated and collected for measuring their mass, number concentration and residual (non-water) composition with a counter-flow virtual impactor. Real-time measurements of aerosol size, number and composition can be obtained with airborne time-of-flight mass spectrometry. In short, many of the primary ingredients that we think are necessary for a complete description of the composition and evolution of clouds are available for the first time.

While there are new instrument capabilities we recognize that there is still an urgent need for developing new instrumentation and observational techniques. Studies of cloud microstructure have been hindered by inadequate instrumentation for many years, so the effort to improve current capabilities and to understand the limitations of new and old instrumentation must continue as part
of the planned effort.

5 Some Objectives of the Initiative

The proposed initiative seeks to develop a better sense of where and at what rate ice formation occurs in the atmosphere, and it seeks to develop improved ways of representing ice formation in cloud, mesoscale, and global-scale models. We offer these objectives to focus studies under this initiative:

- To demonstrate a predictive connection between measured concentrations of ice nuclei (IN) and the initial concentrations that appear in clouds as a result of primary nucleation. This test of the validity of the IN measurements should be able to demonstrate, for example, that cases with high ice concentrations (relative to climatology for the region) are also cases with high IN concentrations. Meeting this objective may require refinement of the ways in which IN are measured.

- Understand the primary sources of IN and develop a representation for IN that accounts for the geographic, altitude, and temporal variations in IN concentrations. One hypothesis to be investigated is if IN concentrations are associated primarily with desert dust. If so, concentrations can be predicted world-wide via emerging representations of dust in GCMs and that dust can also be tracked from satellite observations. A similar study of the association with biogenic sources of IN would be possible.

- Learn where important microphysical processes take place. For example, local nucleation may occur in colder spots where evaporation cooling is greatest or where a cloud reaches its maximum altitude and adiabatic cooling. Similarly, shear regions, as in Kelvin-Helmholtz instability or in the interface between upshear updraft and downshear downdraft, where mixing of larger/smaller cloud droplets or supercooled cloud/ice crystals is taking place may lead to rapid changes on a microphysical scale. These considerations apply on the scale of deeper convective clouds as well stratocumulus layers and shallow convection.

- Determine how interactions between the liquid and ice phases influence ice formation. Examples include the cases of cirrus formation from supercooled haze and ice-supersaturated vapor or the roles of the cloud droplet size distribution and of large supercooled drops in secondary and perhaps also primary ice formation.

- Determine improved ways of representing primary and secondary ice formation in models. To a limited extent this could be undertaken with current knowledge, but significant improvement will likely require progress on the preceding objectives. Work toward this objective requires significant collaboration among participants in this study so that modeling needs are
considered in determining goals of field experiments, observations are collected that are meaningful at the scales needed in models, relationships are emphasized to parameters that are available in models, and any resulting parameterizations are consistent with the best interpretations of the observations. Specific foci of these studies will be to improve predictions of the development of precipitation and of the radiative properties of clouds.

Better understanding and modeling of these phenomena will help improve predictions of cirrus opacity, quantitative prediction of precipitation (particularly when entirely liquid phase and ice phase originated precipitation occur in close proximity), and better forecasting of electrical effects and icing conditions for aircraft, power lines and launch vehicles.

6 Some Possible Approaches

6.1 Field Experiments

The dictionary describes an experiment as being either a trial made in order to learn something or to test an idea. Most field experiments that have been conducted in clouds have contained a significant element of discovery even if the original experiment was hypothesis driven. Field experiments have provided valuable information on typical concentrations of ice in clouds and have shown the wide variability in those concentrations, but most sets of observations have not been comprehensive enough to document the fundamental processes that created those crystals. We seek to design a set of future experiments that moves us from general characterization of ice concentrations to a better understanding of the origins of that ice.

The quantities we wish to measure are the ice particle properties and size distributions, and the goal is to understand how these develop within the clouds so that we can predict how ice evolves as simply as possible. How can field experiments be used to meet this goal? The CPI should allow a better description of the temperature of formation of ice particles that can be attributed to primary ice nucleation and the concentration of those particles. The continuous flow ice nucleus counter used either on the ground near the clouds, or on the aircraft, should provide a much better measure of the concentration of IN. Also the presence of the primary ice can be related more readily with other cloud parameters, such as liquid water content and vertical velocity. The same is true for secondary ice production and the possible enhancement of ice production due to evaporation or physical and chemical changes in the IN. In particular, we need to determine which regions of cloud ice particles are produced. For this, it is crucial that observations of other cloud quantities be accurately made as well. The humidity in cloud is of the utmost importance, as is the cloud liquid water content and temperature.

Three “classic” approaches have been used in past field experiments: near-Lagrangian observations using a sailplane ascending with the updraft, observa-
tions in isolated rising cloud tops, and observations along air trajectories in wave or cap clouds. Wave clouds provide an excellent setting in which to learn about physical processes, such as heterogeneous nucleation, because the ice particles often form in relatively steady and well defined kinematic and thermodynamic situations. With research aircraft, in-situ and remote sensing instrumentation, it is possible to perform quasi-Lagrangian parcel-following experiments, starting upwind of the cloud edge, proceeding through the cloud, and continuing into the evaporation region. Although individual wave clouds are typically shallow (a few hundred meters deep), they also occur simultaneously at several different altitudes, and thus span a range of temperatures. They also occur frequently in mountainous regions, making it fairly easy to plan and execute field experiments.

Convective clouds are of critical importance on both a local and a global scale principally because of the precipitation they produce and because of the transport of heat and moisture. In addition, many of the interesting ice processes occur in cumulus clouds. So cumulus clouds throughout the world are particularly important for field experiments. There is a special appeal to studying the nucleation of primary ice in unmixed regions since the complications of mixing and evaporation would be avoided. However, particular attention should also be paid to the mixed regions since some theoretical arguments predict enhanced ice production in such regions. Results of theoretical and laboratory studies of ice processes will help to focus the field experiment. One hybrid approach that combines the “cloud top” strategy and the strategy of rising within the updraft is to use a high-performance aircraft to make a series of penetrations keeping as close to the top of the ascending turret as possible. This has the added advantage that updrafts and downdrafts will likely be sampled in the same penetration.

Additional experiments need to be designed to test quantitative aspects of secondary ice production processes. These studies were hampered in the past by the inability to detect small ice particles, but new instrumentation should make it possible to measure rates of secondary ice production and compare those to theoretical estimates.

One of the most important parts of a field experiment is the participation of students. We all remember our first flight on a cloud physics aircraft: the excitement of being so close to the objects we studied in class; the nervousness of approaching the massive wall of gray cloud; the thrill of learning first hand about downdrafts and updrafts; and the appreciation of the vast scales. There are many jobs to be done: field experiments would not be possible without students. With the planning for careful and focussed field experiments in the ice initiative comes perhaps the biggest challenge of them all: we need young, enthusiastic and bright students.

6.2 Laboratory experimentation

Laboratory experimentation has long been the backbone of the physical sciences. By providing controlled environments in which physical and chemical phenom-
ena take place, an experimenter derives quantitative data and insights that are not possible through field observations in the complex and ever-changing environment of the atmosphere. Indeed, much of the early progress in cloud microphysics was accomplished in the laboratory. With a variety of new technologies now available or on the horizon, laboratory studies will continue to play key roles in cloud physics, especially for expanding our understanding of ice in clouds.

In a general sense, laboratory studies function at several levels. First, experiments establish the environmental conditions under which certain important phenomena occur. For example, the relatively narrow set of conditions under which riming produces secondary ice splinters was determined in the laboratory through measurement of ice production rates while the temperature and properties of a simulated cloud were varied systematically. The quantitative relationships between experimental outcome (number of splinters, in this case) and imposed conditions that are derivable from such association experiments yield empirical and practical parameterizations that can be used in numerical models. Laboratory experiments using artificial ice nuclei have demonstrated a quantitative link between ice nuclei and primary ice, but such a link has not been demonstrated for natural nuclei, either in the laboratory or in the field. Future experiments should focus on this and similar areas of fundamental importance.

At the next level, laboratory experimentation can be used to isolate specific microphysical processes, test hypotheses and help determine mechanisms of action, especially when coupled to theory. The rates of key processes can be measured precisely in the laboratory and compared with model calculations, thus stringently constraining theory. For instance, despite continuing refinement of its internal details, the classical theory of homogeneous freezing has been shown, via many independent laboratory studies, to be applicable over an extremely wide range of conditions. An important goal for future laboratory experiments should be to yield comparable mechanistic insight into the heterogeneous freezing of cloud droplets containing solutes and ice nuclei during both growth and evaporation. Parameterizations derived from mechanistic studies are physically based and therefore robust, enabling enhanced prediction capabilities in diverse atmospheric settings.

Finally, laboratory studies are valuable for developing and characterizing instrumentation used for in situ and remote sensing measurements. In some important cases, the same techniques and instruments are used in both the laboratory and in the field, thus minimizing ambiguities and uncertainties when interpreting results. Recent examples include the video cloud scope, the microscopic imaging of cloud particles, and the counting and collection of aerosol particles (especially ice and cloud condensation nuclei). The laboratory provides an essential, cost-effective environment for developing, testing and calibrating field instruments on a routine basis, as well as for performing traditional experimentation.
6.3 Modeling Experiments

As computational power increases some cloud models are using grid resolutions approaching the inertial subrange (order of 10 m), a few mesoscale models are using horizontal grid resolutions typically used by cloud models (order of 1000 m), and there are projections that global models will use grid resolutions on the order of 1000 m in the next 20 years. As these models use finer resolutions they necessarily use more sophisticated microphysics parameterizations, which supposedly better represent the physics affecting earth’s atmosphere. The purpose of this short note is to expose some of the most severe problems with more sophisticated microphysics representations, focusing on models using spectral size distributions functions. Though, many of the problems also are of concern for models using numerous mass or size bins to represent size distribution functions.

As an interesting motivating issue as to why significant if not monumental advances in microphysics parameterizations need to be pursued for basic cloud physics studies to quantitative precipitation forecasts (QPF) is demonstrated by comparing solutions of supercell thunderstorm simulations or squall-line simulations with various microphysics schemes. In recent experiments (by this author) such solutions have been shown to vary by as much as changing 0 to 5 km shear by as much as 20 m/s as compared to changing size distribution slope intercepts for graupel / hail with ranges between observed bounds.

One of the two most concerning problems (in my opinion) is that essentially all models, and their physics parameterizations, are integrated on Eulerian grids, whilst many microphysics processes occur in a Lagrangian sense. When confined to Eulerian grid frameworks, modeler are forced to resort to grid point physics-parameterizing physics based on what is occurring instantaneously at a grid point. One of many examples of where this type of logic fails is auto-conversion from say ice crystals to snow aggregates or cloud droplets to rain drops. Typically, models make the conversion based upon ice crystal or cloud drop water content reaching a threshold (which may be formed as a function of mean diameter) and instantaneously converting the excess to aggregates or rain, respectively. In reality, there is an aging issue that must be considered. A powerful example is precipitation formation in stratocumulus clouds, which cover large portions of the planet. In stratocumulus clouds water contents are very low, yet they still precipitate, albeit lightly. With most conventional parameterizations, simulated stratocumulus clouds would never precipitate as water contents at grid points never reach large enough values for conversion to occur (unless ad hoc modifications are made). In reality, given sufficient growth time, light drizzle and snow often fall from stratocumulus. Other physics affected by this aging problem including densification of graupel, riming of ice crystals and aggregates, refreezing of mix phased hydrometeors, etc.

The second problem of significant concern is primary and secondary nucleation / production of ice crystals. It is amazing that modelers have grasped so tightly to the Fletcher curve (among other similar ones) produced almost four decades ago. This curve was developed from samples of observations and shows ice crystal concentrations increasing exponentially with decreasing tem-
perature. Most disturbing is that work done both before and since the time that curve was developed shows that actual ice concentrations often deviate by orders of magnitude at any temperature or location in a given glaciated cloud. This poses a problem in microphysics modeling as ice crystal concentrations are relevant in condensate redistribution, formation of graupel through riming, formation of snow aggregates, etc. Moreover, accurate ice concentrations and crystal sizes are essential to accurate representation of non-inductive charging in electrifying clouds. In summary much work is needed in developing primary and secondary ice crystal nucleation / production parameterizations from sound physical principles rather than from curve fits to large samples of observations.

Next, parameterizing ice crystal habit formation should be considered an important problem. Most models typically employ only one habit shape, the hexagonal plate. Different crystals habits grow by deposition at different rates in different temperature and vapor density excess over ice super-saturation regimes. (Moreover, secondary nucleation of ice crystals may occur owing to sublimation of needles.) Unfortunately, computing vapor density excess over ice super-saturation is an exceptionally difficult problem in Eulerian models, especially those that employ saturation adjustment schemes. Another issue is that some crystal habits such as columnar shaped habits rime more efficiently at much smaller sizes (order of magnitude smaller) than plates, sectors, and planar dendrites. Thus, it might be that columnar crystals are responsible for many of the nuclei for graupel that originate from crystals. Last, transformation from one habit to another also might be relevant.

Finally, hydrometeor redistribution owing to gravitational sedimentation is a serious problems with parameterizations using spectral size distributions, with errors (computed by this author) that range from 10 to 50 percent or more. For this reason, additional hydrometeor species such as drizzle between cloud and raindrops, several graupel density species, and distinction between graupel, frozen drops, small hail and larger hail might be useful. It may be important to design parameterizations, rooted upon physical arguments, to redistribute spectral hydrometeor distributions in a fashion similar to what is possible when a large number of mass or size bins are used.

The ultimate goal for the microphysics modeler is to develop schemes that do not require any tuning for various storm or precipitation systems. The reason for this is that tuning appears to admit to the skeptic to varying degrees that the physics are irrelevant and only solutions that 'look right' are sought, not ones that get there by the proper sequence of microphysical events (It is possible that important microphysics processes indicated by modeling by tuning might emerge; however, as described below, the conclusions may be impossible to prove.). The question every modeler is faced with is does a better looking solution contain more information than one that does not look so good, but may be representing the physics more correctly - hopefully this author's opinion is clear.

There are a few solutions emerging to mitigate some of the modeling problems described above, and other problems not herein described. However, it will take many years to determine the true relevance of these problems in real
clouds owing to difficulties in observing microphysical processes; typically they can only be inferred in real clouds with in situ observations by aircraft in very small regions along flight paths, at point locations on the ground, and remotely over vast volumes in a bulk sense using dual-polarization radar. Unfortunately, it is not clear if any of these alone or together will ever provide the necessary information for significant, four-dimensional, meaningful comparisons between models and observations of microphysics processes. Laboratory studies have and will continue to narrow data gaps between in situ / remote observations and information required for physically sound microphysics parameterizations.

7 The Next Steps

1. Form a Steering Committee. Charge would be to guide the development of the initiative. One of the first tasks would be to seek funds for activities over the next two years. Right after that, steps will have to be taken to lay the foundations for ICE with the funding agencies, attempting to get budgetary consideration for ICE even before the formal proposal is ready.

2. Form Working Groups of 3-5 people to prepare various aspects of the initiative. Themes for the WG’s are to be along two axes: A - science topic and B - methodology. Cross-membership should be the rule rather than the exception. Axis A topics might be nucleation’, first ice in clouds’ and precipitation growth’. Axis B topics might be laboratory measurements’, field measurements’ and modeling’. The charge to the WG’s would be something like: a) to define issues to be addressed and appropriate approaches to do so, and b) to identify available and needed resources, including specific steps toward student participation and the involvement of laboratories and scientists not traditionally associated with the ICE topics.

3. Organize a Gordon conference (or similar) in Summer 1999. Main purpose of this conference is to survey the field in a critical manner.

4. Hold a Planning Meeting in Fall 1999 or Spring 2000. This meeting should have the reports of the WG’s and based on those agree on the content and manner of execution of the ICE initiative. A written proposal for ICE should be the direct outcome of this meeting. With this schedule, the proposal might be expected to be ready for submission sometime between the end of 1999 and mid-2000.

5. A field experiment in 2000 or in 2001. Since the formal initiative is not likely to be reviewed, approved and funded before the end of 2000, at best, proposals for the field program will have to be written without the benefit of the ICE umbrella being in place. To what extent it will be possible to bring to bear on the planning and funding of the field program the work toward the ICE initiative will have to be seen.