# Ice Properties and Processes (IcePro) Focus Group

**White paper, 30 January 2014**

## 1. Mission Statement

The mission of the ASR Ice Properties and Processes (IcePro) focus group is to better characterize the physical properties of ice clouds represented in climate and cloud/cloud systems-scale models, including their dependence on environmental factors (temperature, vertical velocity, aerosol composition and concentration, ice nuclei, convective strength, etc.), and thus improve the representation of processes that depend on these properties. IcePro is based on establishing a strong linkage between the multi-platform observations used to characterize ice particle properties and the models (having a variety of scales) that are needed to investigate how cloud microphysical and radiative properties change with environmental conditions. IcePro focuses not only on quantifying the mean and statistical distributions of ice cloud properties (determined from in situ data) and their linkages to process rates, but also on quantitatively estimating the uncertainties in ice cloud properties derived from ground truth in situ data and the consequences for associated process rates, parameterizations and model results.

## 2. Motivation

The Intergovernmental Panel on Climate Change (IPCC, 2013) has identified the response of clouds to climate change as a major source of uncertainty in evaluating future climate change scenarios. To adequately represent the radiative impact of clouds in such models, it is necessary to better quantify what controls the physical and radiative properties of clouds.

Ice and mixed-phase clouds exert a strong impact on the Earth's radiative budget by reflecting incoming solar radiation back to space (cloud albedo effect) and by absorbing and emitting longwave radiation (greenhouse effect). The sign of the climate feedback in models partly depends on the treatment of the radiatively important liquid phase and ice properties. A key to understanding and predicting the microphysical processes in ice clouds, which control cloud radiative properties, lies in characterizing the physical properties upon which they rest. Prior in-situ, laboratory and remote sensing studies have acquired a large database on the properties of ice clouds (e.g. total ice water content *IWC*, total particle concentration $N_i$, total extinction $\beta$, and particle size distributions or PSDs), but with varying degrees of accuracy that have not been well quantified. It is not well known how these properties vary according to geographic location, cloud type, cloud formation mechanism, vertical motion and other dynamical and meteorological factors. Such knowledge is needed in order to develop a process-oriented understanding of the microphysical and dynamical processes occurring in ice clouds and hence to develop accurate parameterizations for large-scale, mesoscale, cloud and large eddy simulation models.

Additional data describing ice clouds are needed in a variety of conditions. A full range of ground-based remote sensing, space-based remote sensing and in-situ measurements are required to fulfill this need because each offers advantages in terms of spatial coverage (satellite), temporal resolution (ground-based remote sensing), or detailed view of ice crystals (in-situ). However, bringing these disparate data sources together with the treatment of ice in current cloud and climate models requires advances in our understanding of the physical and radiative properties of individual ice crystals and of ice crystal populations globally. Further, it is critical to determine the uncertainties associated with these properties and investigate their optimal representation in models of varying scales.

A physically-based representation of the microphysical and radiative properties of ice clouds is especially needed. Ice crystals have varying shapes and sizes that are not spherical. But many models still represent ice particles as spheres when describing microphysical growth processes, which lead to errors in ice growth processes that determine the evolution of the PSD. For example, Mitchell (1988) illustrates how the assumption of spherical ice particles greatly distorts the height-dependence of PSD mean size and number concentration during steady-state snowfall and McFarquhar et al. (2002) shows how realistic shapes of ice crystals must be used to determine single-scattering properties. In models that do consider non-spherical particles, area- and mass-dimensional power laws are commonly used in the modeling of cloud microphysics and optics. However, the adequacy of such relationships to describe a wide range of microphysical processes (such as sedimentation, riming, aggregation, and break-up, or the dependence of deposition/sublimation on particle shape), in addition to the radiative properties of particle populations, remains poorly known (e.g., van Diedenhoven et al., 2011). Even for vapor growth alone at a single temperature, power law methods have difficulties capturing the simultaneous change in mass, area, and fall-speed with time (Harrington et al., 2013a,b). Uncertainties in such relationships, and how they cascade to larger scales to affect the modeled evolution of cloud, are poorly constrained (e.g., Avramov et al. 2011; Fridlind et al. 2012; Sulia et al. 2013). Further, the influence of vertical motions and dynamics on the cloud microphysical properties, the ice cloud life cycle, and the resulting cloud/radiation interactions are poorly understood. Particle properties are known to be shaped by temperature, relative humidity, and riming/aggregation/deposition/sublimation history, as well as perhaps ice nucleation substrates, resulting in a plethora of individual ice particle properties. The importance of diversity within individual ice particle populations to cloud microphysics and radiation is poorly established.

## 3. Science Goals

Through improvements in the characterization of ice physical properties and their uncertainties, the overarching goals motivating the formation of IcePro are as follows:

1) enable improved performance in climate modeling and cloud-scale modeling
2) enable improved performance in ground- and satellite-based remote sensing.

## 4. Research Objectives

The research objectives of IcePro include the following:

1) Analyze in-situ observations of ice cloud microphysics through different IOPs to derive statistical databases of single particle properties and parameterizations of ice cloud properties as a function of the atmospheric parameters characterizing the environment in which the observations are obtained, complete with associated uncertainty estimates;
2) Utilize advances in remote sensing to characterize ice particle aspect ratios and ice particle shape in general for various environmental conditions;
3) Develop a framework for determining acceptable uncertainty levels associated with various ice particle physical and optical properties. Part of this effort will include spectral radiative closure studies to provide constraints on ice particle physical and optical properties;
4) Conduct model sensitivity studies at various scales to examine the dependence of ice cloud coverage and water path on atmospheric parameters, and the dependence of cloud radiative forcing on ice cloud properties.

## 5. Approaches

The science objectives of IcePro are diverse but all are related to improving the representation of ice cloud properties in climate models and higher-resolution cloud-scale models. We will achieve these objectives through the following planned activities:

1) Use of aircraft in-situ observations from past ASR/ARM/AAF field campaigns to determine the properties of both individual ice particles and populations of ice particles. Understanding individual ice particle properties, such as habit (shape), aspect ratio, surface roughness, projected area and mass are important for modeling electromagnetic and remote sensing properties (e.g., scattering, extinction, asymmetry parameter) of different ice species. Further, characterizing the distribution of ice particles, such as PSDs, mass- and area-dimension relations, *IWC*, $\beta$ and $N_i$ are important for quantifying cloud microphyiscs needed for improved cloud model representation. In-situ data in geographic regions such as the Arctic (M-PACE and ISDAC), the Tropics (TWP-ICE) and mid-latitudes (STORMVEX, SPARTICUS, MACPEX and MC3E) will enable IcePro to study both individual ice particle properties and their distributions. The observation uncertainties will cause uncertainties in area- and mass-dimensional relationships, hence coefficients that describe power laws and size distributions should be selected from surfaces of equally realizable solutions in the coefficient phase space (e.g., McFarquhar et al. 2014). Uncertainty estimates on both the single particle properties and composite properties will be made based on current understanding of the accuracy of the probes used to acquire the data (e.g., Korolev et al. 2011, 2013; Lawson 2011; Jackson et al. 2014a, b; Wang et al. 2014). Since the probability frequency distributions (PDFs) of ice particle properties are dependent on temperature, degree of riming, cloud type, geographical location, and cloud evolution stage, joint-PDFs will be analyzed. Among other methods, correlations between PSD attributes will be removed using a

normalization method developed for raindrop size distributions (Williams et al. 2014) which will reduce the number of model free-parameters and should be useful for cloud modeling. Gaps in geographical locations and meteorological conditions where additional in-situ data are needed to characterize the ice particle properties will be identified. Finally, derived quantities such as single-scattering properties, effective diameters, mass-weighted terminal velocities and aggregation efficiencies will be derived and characterized in the same manner. This effort will be conducted in close collaboration with those running the models in which these properties are needed, so that the derived databases and parameterizations have maximum utility for models with a variety of scale. Confirmed participants who will support this effort include McFarquhar, Mitchell, Harrington, Dong, Williams, Ovchinnikov, Fridlind, and van Diedenhoven.

2) While it is known that ice crystal habits and PSDs influence crucial cloud processes including crystal growth, evaporation rates, latent heat release, ice fall speeds, and cloud radiative properties, existing ASR/ARM retrievals and models, for the most part, make general assumptions about habits and shapes rather than independently inferring habit information. As the ASR science plan (http://asr.science.energy.gov/science/) outlines, current remote sensing retrieval algorithms of cloud microphysics rely on uncertain assumptions about ice crystal habit (shape) and PSDs, and thus cloud models struggle to efficiently represent the ice habit and PSD evolution, which is important to cloud lifetimes. Although aircraft in-situ probes can provide information on ice hydrometeor habits and PSDs, they usually are limited in space and time and not available routinely. The ASR science plan identifies a need to observe the ice crystal habit using new measurements from scanning radars. One of the activity items of this focus group is development of ground-based remote sensing techniques to retrieve ice particle habit information, and to demonstrate the impact of improved measurements of in-situ properties on retrievals. Confirmed participants who will support this effort include Dong.

3) Spectral radiative closure studies will also address the objectives of the focus group. The spectral distribution of radiation measured by surface instruments is sensitive to the amount, sizes, and habits of the ice cloud particles above the site, and can provide a key evaluation of ice cloud properties produced by models and retrievals. Ice particle projected areas and masses, PSDs, and crystal shape models all impact the absorption and extinction optical properties of ice clouds. Radiative analysis will provide a common framework to develop a diverse and instructive suite of case studies that spans a range of atmospheric conditions and spatial/temporal scales, as well as support the effort to determine the uncertainty with which the radiative and microphysical properties of ice cloud should be known to accurately calculate surface and top of the atmosphere radiation budgets. For example, radiative transfer models can be used to calculate the broadband and spectral shortwave and longwave fluxes with the input of observational ice cloud properties, which can be compared against ARM surface and top of the

atmosphere (GOES and CERES) radiative observations. With the recent deployment of a number of spectral shortwave radiometric instruments, such as the SAS-Ze, SAS-He, SWS, and RSS, ARM spectral measurements now provide virtually continuous coverage of the thermal IR, near-IR, and visible regions. In particular, the deployment of the AERI and SWS-Ze at SGP, located feet apart and with similar field of views, provides excellent synergy with respect to attaining a comprehensive understanding of the radiative impact of observed cirrus clouds. The spectral detail and coverage of the shortwave zenith radiance measurements will provide excellent constraints for determining certain ice cloud properties, such as effective diameter, absorption and scattering properties, size distributions and ice crystal shapes. Infrared measurements will address the findings of a recent study by Mitchell (2011) that illustrates how the optical properties of ice clouds are not uniquely defined by the "effective diameter" and IWC. This may lead to the development of an upgraded ice optical property parameterization in the RRTM radiation code. In addition, ground-based radiation measurements at the NSA site, in combination with aircraft in-situ data acquired during ISDAC offer the opportunity for further radiative closure studies. This will support a key component of the focus group's main goal of improving the representation of ice particle properties in climate models, namely that of the radiative effects of ice clouds used in simulations. Confirmed participants in this effort include Mlawer, Lubin, Mitchell, Fridlind, van Diedenhoven, McFarquhar, and Dong.

4) There is a strong need for those running models to test new approaches that are being developed to take advantage of recent advances in observing ice particles, specifically approaches that predict particle properties which are different from traditional schemes assuming pre-defined ice categories. Thus, these new parameterizations of ice cloud microphysical properties (e.g., Harrington et al. 2013a, b; van Diedenhoven et al. 2014) need to be implemented to determine the impact of the new schemes on cloud microphysical and radiative properties and radiative forcing. Part of this effort will require the development of a framework for translating uncertainties in ice particle properties to uncertainties in cloud and radiative properties and radiative forcing. Sensitivity tests will need to be added to existing model set-ups, in which ice properties derived by members of IcePro will be substituted in the specification for models. The models will make use of the prepared ice properties to the maximum extent possible, whether using mass- and area-dimensional relations, or further using a PDF of ice properties based on the spread obtained from single-particle image probe measurements analyses. Confirmed participants in this activity include Fridlind, Harrington, Morrison, Ovchinnikov, McFarquhar and Mitchell.

**6. Milestones**:

In order to accomplish the goals of IcePro, there have been a number of specific activities that have been identified for completion, together with a number of deliverable products. These are summarized below.

**Deliverable D1: Development of single-particle databases from in-situ data**
**Objective**: Use in-situ data acquired by several different instruments during several different field projects to develop a database that describe aspect ratio, particle habit and projected area and mass
**Personnel**: McFarquhar, Mitchell, Um, and Dong
**Timeline**: Most work in years 1 and 2, but continuing in subsequent years as more data become available

**Deliverable D2: Characterization of ice particle properties on environmental conditions**
**Objective:** Characterize how mean and distribution functions of PSDs, mass-dimension relations, area-dimensional relations, IWC, $\beta$, mean aspects ratios and total ice particle concentrations vary with environmental conditions, as well as characterizing uncertainties in these relationships and uncertainties due to processing/measuring of microphysical quantities
**Personnel**: McFarquhar, Mitchell, Um, and Dong
**Timeline**: Will continue in all 5 years because of large amount of past and future data that must be analyzed

**Deliverable D3**: **Radiative closure studies from ISDAC**
**Objective**: Rigorously determine degree to which radiative closure exists using available ISDAC cloud microphysical data and surface shortwave irradiance measurements at NSA
**Personnel**: Lubin, McFarquhar, Fridlind, van Diedenhoven, Mitchell
**Timeline**: Start in year 1, complete by year 2

**Deliverable D4: Radiative closure studies using data from SGP**
**Objective**: Rigorously determine degree to which radiative closure exists using available surface, remote sensing and in-situ measurements collected over the SGP site
**Personnel**: Mlawer, Mitchell, and Dong
**Timeline**: Begin in year 1, most work in years 2 and 3, but continuing in subsequent years as more data become available.

**Deliverable D5: Demonstrate impact of improved ice properties on retrievals**
**Objective**: Use aircraft in-situ measurements to evaluate ground- and space-based retrieved ice cloud microphysical properties
**Personnel**: Dong
**Timeline**: Evaluation of ground-based retrievals will be nearly done in year 1, and work on evaluating satellite retrievals will start in years 1 and 2.

**Deliverable D6: Development of ground-based remote sensing techniques to infer ice particle habit information**
**Objective**: Improve assumptions that go into ground-based remote sensing retrievals and determine impact on ability to infer particle habit information
**Personnel**: Dong
**Timeline**: Years 1 and 2

**Deliverable D7: Upgrade CAM5 microphysics to make it self-consistent**
**Objective**: Make the CAM5 microphysics self-consistent by using improved mass-diameter and area-diameter expressions to formulate the processes.

**Personnel**: Morrison, Mitchell
**Timeline**: Emphasized in years 2 and 3

**Deliverable D8**: **Evaluate high-resolution simulations of MC3E systems**
**Objective**: Compare high-resolution model simulations of MC3E deep convective precipitation systems with radar and aircraft measurements
**Personnel**: Tao, McFarquhar, Fridlind, Dong
Timeline: Emphasized in years 1 and 2

**Deliverable D9: Determine modeling impact of new ice property parameterizations**
**Objective:** Implement the new parameterizations of ice particle properties into models targeting various scales and report impact of new schemes on cloud microphysical and radiative properties and radiative forcing
**Personnel**: Fridlind, Harrington, Morrison
**Timeline**: Throughout all 5 years, with concentration on different environments in different years

**Deliverable D10: Develop framework for translating uncertainties in ice particle properties to model output**
**Objective**: Develop a framework for translating uncertainties in ice particle properties to uncertainties in modeled cloud and radiative properties and radiative forcing
**Personnel**: Fridlind, Harrington, Morrison, McFarquhar, Dong and Mitchell
**Timeline**: Development of framework in years 1 and 2, testing in subsequent years

**Deliverable D11: Linking ice optical properties with microphysical observations**
**Objective**: Link ice optical properties computed from models and scattering codes with microphysical observations such as PSDs
**Personnel**: Williams, Nesbitt, McFarquhar, van Diedenhoven, Fridlind, and Dong
**Timeline**: Starting in year 1 and continuing

**Deliverable D12: Determine gaps in existing microphysics databases**
**Objective**: Identify any gaps that still exist in ice cloud property database and parameterization, possibly conducting or proposing additional field or laboratory measurements that are needed to fill in these gaps
**Personnel**: All
**Timeline**: Year 5

## 7. Participants:

*Xiquan Dong, University of North Dakota*
*Ann Fridlind, NASA GISS*
*Jerry Harrington, Penn State*
*Dan Lubin, Scripps Institution of Oceanography*
*Sergey Matrosov, NOAA*
*David Mitchell, DRI*
*Greg McFarquhar, University of Illinois*

*Eli Mlawer, AER Hugh Morrison, NCAR*
*Mikhail Ovchinnikov, PNNL*
*Wei-Kuo Tao, NASA GSFC*
*Junshik Um, University of Illinois*
*Bastiaan van Diedenhoven, NASA GISS*
*Chris Williams, University of Colorado*

## 8. Performance Metrics

To the best of our knowledge, no metric has yet been developed for characterizing how well ice particle properties must be known. Our group will attempt to develop a framework for evaluating how well the physical properties (e.g., PSDs and fall speeds in terms of maximum dimension or particle mass; shape features influencing susceptibility to riming, aggregation, break-up or multiplication) and optical properties (e.g., aspect ratios, surface roughness, asymmetry parameter, and absorption and extinction coefficients) need to be known and then develop a framework for evaluating the degree to which candidate parameterizations fulfill established goals based on a combined analysis of observations and simulation results. In addition, the following performance metrics for IcePro are listed:

- Deliver a database of single particle properties that can be delivered to the ARM archive as PI products (end of 2$^{nd}$ year)
- Deliver mass-dimension and area-dimension relations, and size distribution attributes to the ARM archive as PI products that will be useful for further model studies (end of 3$^{rd}$ year)
- Complete the first model intercomparison study in which model ice properties are quantitatively and fully specified based on observations. Compare these simulations with control simulations (without improved ice properties) to access impacts on model performance (end of 2nd year)

## 9. Synergy with Other Groups

There is a strong linkage between IcePro and QUICR. Remote sensing both takes and gives to ICEPRO by using improved ice properties for better retrievals and sometimes retrieving ice property information.

## 10. References

IPCC, 2013: Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Avramov, A., A.S. Ackerman, A.M. Fridlind, B. van Diedenhoven, G. Botta, K. Aydin, J. Verlinde, A.V. Korolev, W. Strapp, G.M. McFarquhar, R. Jackson, S.D. Brooks, A. Glen, and M. Wolde, 2011: Towards ice formation closure in Arctic mixed-phase boundary layer clouds during ISDAC. *J. Geophys. Res.,* **116**, D00T08, doi:10.1029/2011JD015910.

Fridlind, A.M., B. van Diedenhoven, A.S. Ackerman, A. Avramov, A. Mrowiec, H. Morrison, P. Zuidema, and M.D. Shupe, 2012: A FIRE-ACE/SHEBA case study of mixed-phase Arctic boundary-layer clouds: Entrainment rate limitations on rapid primary ice nucleation processes. *J. Atmos. Sci.,* **69**, 365-389, doi:10.1175/JAS-D-11-052.1.

Harrington, J. Y., K. Sulia, and H. Morrison, 2013a: A Method for Adaptive Habit Prediction in Bulk Microphysical Models. Part I: Theoretical Development. *J. Atmos. Sci.*, **70**, 349–364.

Harrington, J. Y., K. Sulia, and H. Morrison, 2013b: A Method for Adaptive Habit Prediction in Bulk Microphysical Models. Part II: Parcel Model Corroboration. *J. Atmos. Sci.*, **70**, 365–376.

Jackson, R.C., G.M. McFarquhar, J. Smith, M. Beals, R. Shaw, J. Jensen, J. Fugal, and A. Korolev, 2014: An assessment of the impact of anti-shattering tips and artifact removal techniques on cloud ice size distributions measured by the 2D cloud probe. *J. Atmos. Ocean. Tech.*, submitted.

Jackson, R.C., and G.M. McFarquhar, 2014: An assessment of the impact of anti-shattering tips and artifact removal techniques on bulk ice cloud microphysical properties derived from the 2D cloud probe. *J. Atmos. Ocean. Tech.*, submitted.

Korolev, A.V., and E. F. Emery, J. W. Strapp, S. G. Cober, G. A. Isaac, M. Wasey, D. Marcotte, 2011: Small ice particles in tropospheric clouds: fact or artifact?, *Bull. Amer. Meteorol. Soc.,* **92**, 967–973.

Korolev**,** A.V, E. F. Emery**,** J. W. Strapp**,** S. G. Cober**,** and G. A. Isaac 2013: Quantification of the effects of shattering on airborne ice particle measurements, *J. Atmos. Oceanic. Technol.*, in press.

Lawson, R.P., 2011: Effects of ice particles shattering on the 2D-S probe, *Atmos. Meas. Tech.*, **4***,* 1361-1381.

McFarquhar, G.M., P. Yang, A. Macke, and A.J. Baran, 2002: A new parameterization of single-scattering solar radiative properties for tropical ice clouds using observed ice crystal size and shape distributions. *J. Atmos. Sci.*, **59**, 2458-2478.

McFarquhar, G.M., T.-L. Hsieh, M. Freer, J. Mascio, and B.F. Jewett, 2014: The characterization of ice hydrometeor gamma size distributions as volumes in $N_0/\lambda/\mu$ phase space: implications for microphysical process modeling. *J. Atmos. Sci.*, Under review.

Mitchell, D.L., 1988: Evolution of snow-size spectra in cyclonic storms. Part I: Snow growth by vapor deposition and aggregation. *J. Atmos. Sci.*, **45**, 3431-3451.

Sulia, K., J.Y. Harrington, and H. Morrison, 2013: A method for adaptive habit prediction in bulk microphysical models. Part III: Applications within a two-dimensional kinematic model. *J. Atmos. Sci.*, **70**, 3302-3320.

Van Diedenhoven, B., A.M. Fridlind, A.S. Ackerman, and B. Cairns, 2012: Evaluation of hydrometeor phase and ice properties in cloud-resolving model simulations of tropical deep convection using radiance and polarization measurements. *J. Atmos. Sci.,* **69**, 3290-3314, doi:10.1175/JAS-D-11-0314.1.

Van Diedenhoven, B., A.S. Ackerman, B. Cairns, and A.M. Fridlind, 2014: A flexible parameterization for shortwave optical properties of ice crystals. *J. Atmos. Sci.,* in press, doi:10.1175/JAS-D-13-0205.1.

Wang, J., X. Dong, and B. Xi, 2013: A new method of correcting Nevzorov measured Ice Water Content in cirrus layer of DCS. *J. Geophys. Res.*, Submitted.

Williams, C.R., V.N. Bringi, L. Carey, V. Chandrasekar, P. Gatlin, Z.S. Haddad, S.J. Munchak, W.A.Petersen, R. Meneghini, S.W. Nesbitt, S. Tanelli, A. Tokay, and A. Wilson, 2014: Describing the shape of raindrop size distributions using uncorrelated raindrop mass spectrum parameters. *J. Appl. Meteorol. and Climatol.,* in press.