Attendee Response to Guiding Questions of the September 2014 DOE Workshop on North Slope of Alaska Priorities

Ann Fridlind, NASA Goddard Institute of Space Studies (GISS)

1. What are key science questions or objectives relevant to the North Slope of Alaska region and the DOE Climate and Environmental Sciences Division that are poorly constrained now, but could be addressed with a more complete observation suite and/or associated modeling activities?

a. Using detailed 3D models, containing all known physics, can the behavior of common regional cloud types be explained when accounting for the uncertainties in model parameters and observations?

In the course of studying mixed-phase clouds at the North Slope of Alaska (NSA) site and in the Arctic region during SHEBA, the DOE ARM and ASR programs have supported a series of experiments (SHEBA, M-PACE, ISDAC) that allowed *closure studies* (e.g., Quinn et al. 1996) for ice formation in single-layer mixed-phase clouds. In a closure study, a model is first adopted which is hypothesized to contain all operative physics, such as a large-eddy-simulation (LES) code with embedded bin microphysics and prognostic ice nuclei. It is then necessary that all relevant model inputs have been measured. Finally, the predictions of the model are compared with observations of the target quantity (ice properties, in this case).

Through funding from ARM and ASR, the NASA GISS team performed closure studies for all three experiments (Fridlind et al. 2007, 2012; Avramov et al. 2011). We found that ice nuclei were grossly insufficient to explain observed ice in the M-PACE case, as also found by other teams (Morrison et al. 2008; Fan et al. 2009). In the ISDAC case, closure could not be ruled out, but ice nuclei measurements were unfortunately not made above water saturation during the only golden day flight over the NSA site, increasing uncertainty in that relevant input by a factor of ten. In addition, the ISDAC case exhibited a decoupled boundary layer, which proved challenging for LES without a very accurate determination of the horizontal flux divergence profile for heat. Finally, in the SHEBA case, previous analyses of ice nucleus number concentrations (2/L) were roughly 30 times too low to explain observed ice. However, the early ice nucleus measurements of the Counter-Flow Diffusion Chamber (CFDC; see section 2a) have since been deemed relatively unreliable (Paul DeMott, personal communication), they are no longer used in data aggregations (cf. DeMott et al. 2011), and they probably do not warrant further investigation. In summary, closure studies have thus far generally failed to confidently achieve closure between simulated and observed ice. Ice was generally underpredicted by roughly an order of magnitude and this was not a problem isolated to small ice crystals that were not measured well (cf. Fridlind et al. 2012). Thus, *ice nuclei appear insufficient to explain observed ice*.

Follow-on studies using the same M-PACE and SHEBA periods above, in addition to a similar ISDAC period, took the form of *model intercomparison studies* (Klein et al. 2009; Morrison et al. 2011; Ovchinnikov et al. 2014). The goal of model intercomparison studies is largely to compare models with one another rather than to test understanding of physics. When models were provided CFDC measurements of ice nuclei conditions for the M-PACE study, and resulting ice property predictions across models varied by five orders of magnitude, it was proposed to constrain ice formation in models by essentially fixing the ice number concentration (Klein et al. 2009). Given the uncertainties in ice number concentration, however, in-cloud ice number concentration was initially fixed to overlying ice nucleus number concentrations for the next, SHEBA-based intercomparison study (Morrison et al. 2011). For the most recent ISDAC-based intercomparison study, with somewhat greater confidence in ice size distribution measurements, ice number concentration was fixed to that observed with sensitivity tests using higher and lower concentrations. In addition, the ISDAC study specified ice particle physical properties and limited processes by excluding collision-coalescence (Ovchinnikov et al. 2014). These intercomparison studies are therefore not closure studies testing ice formation, but they do repeatedly indicate that mixed-phase cloud properties simulated are sensitive to the assumed treatment of ice formation.

Together, these past closure and intercomparison studies should motivate redoubled efforts to achieve cloud-scale closure with respect to ice formation in future studies. The studies have also identified several key parameters that uniquely modulate the evolution of shallow mixed-phase clouds: ice nucleus activity spectra, ice crystal morphological properties, and ice crystal size distribution.

b. Using detailed treatments of ice and liquid physical and radiometric properties, for realistically simulated and relatively simple cases, can reasonable closure be achieved among radar, lidar, spectral radiometric and other measurements and their forward-simulated counterparts?

This question may seem to lack immediate scientific importance, but at GISS we have found that seeking answers provides a powerful test of models, retrieval assumptions, measurements, and everything that may be in between. Versions of this question are being developed and pursued in ASR focus and interest groups (e.g., *Ice Properties* and *Mixed-Phase Cloud* groups) Adopting this foundation question as worthy of strenuous support could promote significant advances in both modeling and retrieval science that could otherwise take much longer to achieve owing to separation of research communities.

One thing we already know from GISS-based efforts thus far is that we cannot constrain ice crystal physical properties with available measurements (see 2b below). This may be less of a problem for retrievals, where reflectivity is an input impervious to assumptions about ice properties, than for simulations of cloud evolution, where ice water content and reflectivity are a powerful function of input ice properties even when they are not wildly different at all (cf. Fridlind et al. 2012). The problem is largest when ice properties are most diverse, as in the M-PACE case discussed above, where riming and vapor growth were simultaneous processes that produced a profound diversity of ice characteristics, from large frozen drizzle to nearly unrimed snowflakes, many rimed crystals, and heavily rimed crystals that grew unrimed, emanating side planes. However, even when the problem is arguably least, as in the SHEBA case above where aggregation was negligible and nearly all crystals were radiating plates, the diversity of ice properties remains large owing to florid growth under supercooled water-saturated conditions (Bailey et al. 2000) and the lack of any true quantitative constraint at all remains just as much of a hindrance.

2. For the science questions identified, what are the key observable parameters required?

a. Ice nucleus spectra as a function of nucleation mode and composition (objective: characterize the diversity and spatiotemporal variability of size-distributed composition and activity of ice nuclei)

In past field experiments, the only measurements of ice nucleus activity have been obtained from a single instrument: the Counter-Flow Diffusion Chamber (Rogers et al. 2001). The CFDC data is unquestionably uniquely valuable, but *additional measurement strategies are needed*. It is well understood that CFDC measurements alone are not adequate to constrain ice nucleation schemes (cf. Fridlind et al. 2012). One leading reason is that the CFDC does not measure ice nuclei spectra in any particular nucleation mode (e.g., deposition, condensation/immersion, contact) in the manner that a CCN counter measures droplet activation spectra, by design. The CFDC must cover both temperature and water vapor phase space, and must do so slowly. There is commonly rapid and unusual spatial variability encountered even under conditions that one would expect to be substantially uniform; in addition, measurements under pristine Arctic conditions may be under

CFDC detection limits more than 90% of the time, as during October M-PACE flights (cf. Fridlind et al. 2007).

A promising approach for expanding analyses of ice nuclei has recently been proposed: employing a robotic sampler to obtain and store filter samples for analysis in laboratories (see *ASR Ice Nucleation Focus Group* white paper). Laboratory measurement efforts have been leading recent advances in the ice nucleation field (e.g. Knopf and Alpert 2013 to give just one example). Such a sampler would allow analysis of ice nucleus composition and behavior in more than one laboratory research group, essentially bringing natural Arctic ice nuclei under the microscope. Providing a supply of natural nuclei avoids focusing exclusively on laboratory generated ice nuclei, which are not representative of natural conditions. Ideally, future measurement strategies will allow more comprehensive measurement of ice nucleus activity in the field using airborne instruments, but surface-based filter samples could provide a valuable bridge that could promote development of ice nucleus schemes for models in a region where ice nuclei are likely to be important.

b. Ice crystal physical and radiometric properties (characterize the diversity and spatiotemporal variability of the size-distributed properties of ice crystals)

Decades of Cloud Particle Imager (CPI) data have demonstrated profound diversity of ice crystal properties globally, including at the NSA site. Simulations across many model types have demonstrated sensitivity to parameters related to particle habit (e.g. fall speed). However, literally no data are widely available to modelers that would allow them to place any numerical constraints on the diversity of morphological characteristics of ice crystals of a given size, for instance. Model ice properties have historically been based on mass-dimension and area-dimension power laws derived from analysis of manually analyzed data that were both sparse and sometimes odd (e.g. rosettes with mostly with four arms). It is common to assume that dimension is true maximum dimension, whereas image data provide randomly oriented maximum dimension; the same goes for projected area. Furthermore, such power laws for a given habit are not consistent with geometric particle shapes, and do not provide information required to inform radiative transfer models (e.g. aspect ratio of particle components). Recently at GISS, collaboration with the McFarquhar group has allowed our first analysis of single-particle measurements, allowing development of internally consistent ice particle properties for bullet rosetttes sampled during ASR's SPARTICUS campaign (a goal of the ASR Ice Pro group). However, this data remains sorely sparse and lacks the most central measurement: particle mass. Fall speed is also not measured.

A promising approach for expanding ice crystal characterization at NSA would be to deploy surface instruments intended for single-crystal characterization (see *ASR Ice Properties Focus Group* white paper), such as the recent deployment of the Multi-Angle Snowflake Camera (MASC) at NSA. Supercooled mixed-phase near-surface clouds commonly occur in conditions that may remain ice-saturated to heights near the surface, such that size-distributed crystal properties at the surface may be substantially identical to those in-cloud. MASC is sensitive to particles larger than roughly 100 μm in maximum dimension, and will image with roughly 10–40 μm resolution. Analysis of MASC imagery allows quantitative analysis of size-distributed ice morphology (Garrett et al. 2012). MASC also measures a fall speed, although this may not be still air fall speed. If it were possible to extend the capabilities of such an instrument to measure single-particle mass, even if fall speed measurements were sacrificed to do so, this would be extremely valable (assuming accuracy and precision were adequate for purpose). The consequences of assumptions about the relationship of single-particle ice mass to other single-particle properties (size-distributed mean and diversity) permeate models and retrievals alike; *single-particle ice mass measurements are completely absent and widely needed*.

c. *Ice crystal size distribution*

Like single-particle ice mass, ice crystal size distribution assumptions permeate models and retrievals. Although airborne measurements of ice crystal size distribution do exist, size-distributed uncertainties for such measurements do not (Paul Lawson, personal communication). A promising approach for expanding ice crystal size distribution measurements at the NSA site would be deployment of a ground-based Counterflow Virtual Impactor, such as that deployed at the Storm Peak Laboratory.

d. Aerosol size distribution and size-resolved composition and hygroscopicity factor

A leading science question for those studying shallow mixed-phase clouds at the NSA site is whether variability of ice nuclei (IN) or cloud condensation nuclei (CCN) is more important. Although it is currently understood that changes in aerosol size distribution generally dominate changes in CCN locally, aerosol hygroscopicity changes may also be regionally dominant. Furthermore, recent research suggests that very small aerosols in marine-influenced regions may demonstrate uniquely low hygroscopicity. Measurements of size-distributed aerosol number concentration and hygroscopicity factor would be required to robustly address such leading science questions.

e. Lower atmospheric thermodynamic and dynamic properties

The Arctic region is subject to unique surface conditions. For instance, decoupled cloudy boundary layers are common in the Arctic, and have been a challenge to simulate, as demonstrated during the ISDAC model intercomparison study (Ovchinnikov et al. 2014). One promising approach for expanding the use of NSA data would be to develop a Value-Added Product (VAP) targeted to provide as much information as possible about near-surface dynamic and thermodynamic conditions, including turbulence dissipation rate profile where possible, inversion properties, etc. A second, related strategy, could be to use remote-sensing retrievals to provide high-time-resolution information about near-surface atmosphere evolution. Absence of availability during precipitating periods, or other such hindrances to 100% continuous VAP coverage, should not be considered a road block. It is readily possible to sample models in the same manner as observations are available if objective criteria are provided.

3. What modeling strategy would be effective to support these additional measurements toward addressing these science objectives?

Above we advocate for several modeling approaches suitable to prove understanding of and capability to model aerosol behavior in nucleating droplets and ice and to model regional cloud systems at the mesoscale. The full complement of data that is ideal for particular study types is increasingly well understood; the ASR ISDAC Science Plan provides an excellent example of listing the data required for each study type targeted by that campaign. Whereas discussion here focused on the microscale and mesoscale, other studies should obviously focus on the regional, seasonal and global scale. When considering ice microphysics alone, laser focus on unconstrained model components could be usefully intensified (e.g., collision-coalescence kernels). Similarly, a focus on boundary layer structure would be deeply valuable to a wide range of model types. The expense of observations motivates efficient planning for observational data sets to support specific study approaches; the concept of closure is often useful (e.g., the surface energy budget).

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