Indirect and Semi-Direct Aerosol Campaign (ISDAC)

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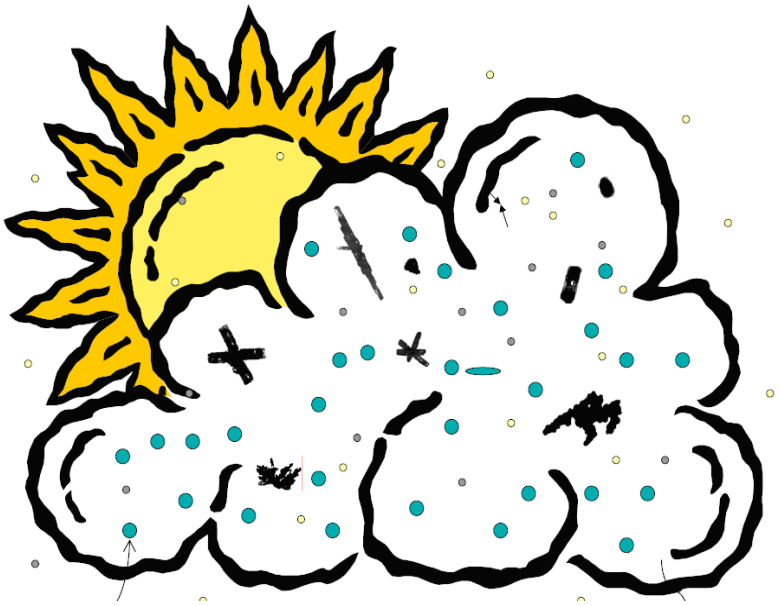
April 2008, North Slope of Alaska



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Abstract

We propose to deploy an intensive cloud and aerosol observing system to the ARM Climate Research Facility's (ACRF) North Slope of Alaska (NSA) locale for three weeks in April 2008. This period has been chosen because it is during the International Polar Year when many ancillary observing systems will be collecting data that will be synergistic for interpreting the Indirect and Semi-Direct Aerosol Campaign (ISDAC) data. It also provides an important contrast with the October 2004 Mixed-Phase Arctic Cloud Experiment (M-PACE). We will require 30 to 45 hours of flight time for an aircraft capable of measuring temperature, humidity, total particle number, aerosol size distribution, aerosol hygroscopicity, cloud condensation nuclei concentration, ice nuclei concentration, optical scattering and absorption, updraft velocity, cloud liquid water and ice contents, cloud droplet and crystal size distributions, cloud particle shape, and cloud extinction. In addition to these aircraft measurements, we propose surface deployment of a spectroradiometer for retrieving cloud optical depth and effective radius.

These measurements will be used by members of the ARM Science Team to answer the following key questions:

1. *How do properties of the arctic aerosol during April differ from those measured during the M-PACE in October?*
2. *To what extent do the different properties of the arctic aerosol during April produce differences in the microphysical and macrophysical properties of clouds and the surface energy balance?*
3. *To what extent can cloud models and the cloud parameterizations used in climate models simulate the sensitivity of arctic clouds and the surface energy budget to the differences in aerosol between April and October?*
4. *How well can long-term surface-based measurements at the ACRF NSA locale provide retrievals of aerosol, cloud, precipitation, and radiative heating in the Arctic?*

By using many of the same instruments used during M-PACE, we will be able to contrast the arctic aerosol and cloud properties during October and April. The aerosol measurements can be used in cloud models driven by objectively analyzed boundary conditions to test whether the cloud models can simulate the aerosol influence on the clouds. The influence of aerosol and boundary conditions on the simulated clouds can be separated by running the cloud models with all four combinations of M-PACE and ISDAC aerosol and boundary conditions: M-PACE aerosol and boundary conditions, M-PACE aerosol and ISDAC boundary conditions, ISDAC aerosol and M-PACE boundary conditions, and ISDAC aerosol and boundary conditions. ISDAC and M-PACE boundary conditions are likely to be very different because of the much more extensive ocean water during M-PACE. The uniformity of the surface conditions during ISDAC greatly simplifies the objective analysis (surface fluxes and precipitation are very weak), so that it can largely rely on the European Centre for Medium-Range Weather Forecasts analysis. The ISDAC cloud measurements can be used to evaluate the cloud simulations and to evaluate cloud retrievals. The aerosol measurements can also be used to evaluate the aerosol retrievals. By running the cloud models with and without solar absorption by the aerosols, we can determine the semi-direct effect of the aerosol on the clouds.

1. Project Description

1.1 Objectives:

This field campaign will provide measurements needed to address four key questions that have important implications for the treatment of clouds in climate models.

1. *How do properties of the arctic aerosol during April differ from those measured during the Mixed-Phase Arctic Cloud Experiment (M-PACE) in October?*
2. *To what extent do different properties of the arctic aerosol during April produce differences in the microphysical and macrophysical properties of clouds and the surface energy balance?*
3. *To what extent can cloud models and the cloud parameterizations used in climate models simulate the sensitivity of arctic clouds and the surface energy budget to the differences in aerosol between April and October?*
4. *How well can long-term surface-based measurements at the ARM Climate Research Facility (ACRF) North Slope of Alaska (NSA) locale provide retrievals of aerosol, cloud, precipitation, and radiative heating during in the Arctic?*

1.2 Background and Motivation

The ARM Program established a permanent site at the NSA locale for several reasons. (1) Climate models suggest large arctic climate sensitivity due to snow/ice albedo feedback. Snow and sea ice melt each year at the NSA. ARM measurements there could improve understanding of snow and ice albedo feedbacks and how they interact with clouds. (2) The atmosphere at the NSA is colder and drier than at the other sites, thus permitting important tests of radiative transfer codes using surface-based measurements. (3) Of the three permanent ACRF sites, stratiform clouds are most prevalent at the NSA. Stratiform clouds play important roles in cloud feedback. (4) Glaciated and mixed-phase clouds are common at the NSA, so that studies of glaciation are more convenient at the NSA than at the other sites. (5) Aerosols have a strong seasonal cycle at the NSA. This permits studies of both direct and indirect effects of aerosols.

Thus, many experiments have been conducted at the NSA or elsewhere in the Arctic, and much has been learned from them (Barrie 1986; Curry et al. 1996, 2000; Gultepe et al. 2000; Lawson et al. 2001; McFarquhar et al. 2005; Poellot et al. 2006; Verlinde et al. 2006). Rather than review the full breadth of understanding that has resulted from those experiments, we shall focus on the influence of aerosol on cloud microphysical and optical properties.

Previous studies of **arctic aerosol** have shown that (a) submicron mass concentrations exceeding 2 $\mu g\ m^{-3}$ are often found in stratified layers at altitudes up to 9 km (Barrie 1986) throughout the Arctic during winter and early spring; (b) this aerosol is predominately anthropogenic and transported from Europe and Asia (Shaw 1982, 1988; Norman et al. 1999); (c) more efficient scavenging during late spring and early summer leads to much lower submicron mass concentrations, particularly within 1 km of the surface (Wylie and Hudson 2002); and (d) local new particle production from dimethyl sulfide and organic emissions from open ocean water leads to higher number concentrations of ultrafine particles during summer than during winter (Ferek et al. 1995; Leck and Bigg 2005). Figure 1 shows the seasonal cycle of the monthly average cycle of cloud emissivity, cloud coverage, and the fraction of time that polluted conditions occur using four years of ground-based aerosol and radiation observations near Barrow, Alaska. There is a marked transition between March and May: clouds become more common and thicker while pollution events become increasingly rare (Garrett and Zhao 2006). It is this transition that may be most relevant for setting the timing of ISDAC. Figure 2 shows the submicron aerosol is primarily composed of sea salt and sulfate during winter, but with a large

fraction of unknown residual mass during summer. Measurements of aerosol absorption (Hansen et al. 1989, 1997a) at Barrow suggest at least some of the residual mass is black carbon. Single-particle analysis of 0.2-2 μm particles sampled from aircraft during March above Svalbard, Norway, in the North Atlantic (Hara et al. 2003) suggests that under the most polluted conditions the aerosol are predominantly composed of external mixtures of black carbon and sulfate, with internal mixing more common for background conditions. Sea salt is present only near the surface as externally-mixed particles, and mineral dust is a significant but not major fraction at times. Single-particle composition has rarely been determined at the NSA, even at the surface.

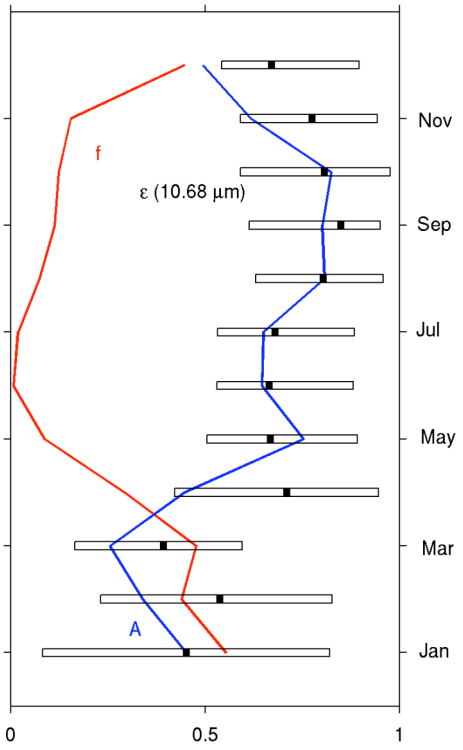

Figure 1: Monthly-average cloud-emissivity ε (shown as quartile plot), cloud coverage A (blue) and fraction of time polluted conditions occur (red) derived from ground-based observations at Barrow (details in Garrett and Zhao 2006)

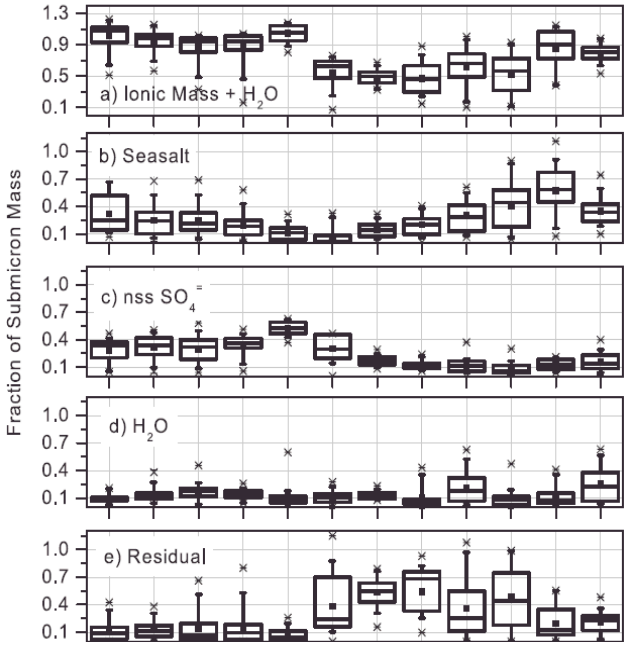

Figure 2: Fractional composition of submicron aerosol mass measured over three years at Barrow. From Quinn et al. (2002).

Arctic **cloud condensation nuclei (CCN)** measurements suggest considerable variability. Yum and Hudson (2001) found CCN concentrations at a supersaturation of 1% during May 1998 that were a factor of four greater than those found by Hegg et al. (1995, 1996) during both April 1992 and June 1995. Variability between days was a factor of two. Measurements near Iglooik, Northwest Territories, Canada, in February 1982, indicate CCN concentrations of ~ 80 cm^{-3} for stratiform clouds in polluted air, compared to ~ 30 cm^{-3} in cleaner air (Leaitch et al. 1984). Thus, CCN measurements for any given day are not necessarily representative of conditions for another day. On the basis of differences in measured aerosol concentrations, one might expect to find higher arctic CCN concentrations during winter and early spring than during summer and early autumn, but field measurements have yet to confirm this expectation.

Measurements of **ice nuclei (IN)** concentration in the Arctic (Borys 1989) suggest lower IN concentrations relative to total aerosol number for polluted conditions than for remote unpolluted conditions, which may explain the persistence of the arctic liquid cloud water. Rogers et al. (2001) found small (<0.16 per liter) IN concentrations most of the time during May 1998, with values exceeding 4 per liter occurring 40% of the time and IN concentrations exceeding 0.1% of total aerosol number 20% of the time. Variability spanned five orders of magnitude. Single particle analysis of ice crystal residuals indicated IN composed of silicate and carbon. Mean IN concentrations measured during the ARM M-PACE in October 2004 (Prenni et al. 2006) are a factor of 5-10 lower than those measured during May 1998 by Rogers et al. (2001), mainly because of more periods during M-PACE with small concentrations of IN.

Surface-based retrievals of **cloud type** for one year near the NSA (Shupe et al. 2005, 2006) suggest the presence of both supercooled droplets and ice crystals at any time of year (Figure 3). Liquid-only clouds are much more common during the summer months, occurring 40% of the time compared with less that 10% during winter months. Drizzle occurs only during April-September. Ice-only clouds occur about 40% of the time throughout the year, and mixed-phase clouds are common throughout the year. Multi-layer clouds are common, and mixed-phase and all liquid clouds often persist for days. **Liquid water paths** are generally greatest during August and September, when open ocean water is greatest, and are about half as great during April (Shupe et al. 2006), when open ocean water is minimal.

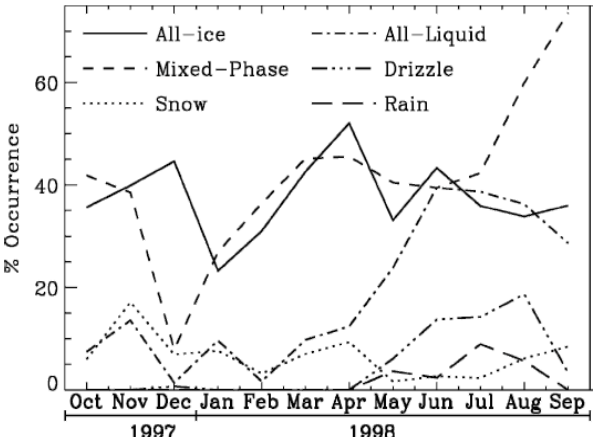

Figure 3. Cloud frequency from Surface Heat Budget of Arctic Ocean (SHEBA) experiment (Shupe et al. 2005).

A few in situ aircraft studies have related the measured aerosol to measured **droplet number** in the Arctic. Hegg et al. (1996) found that CCN concentration at 1% supersaturation explained 66% of the variability of droplet number concentration. Garrett et al. (2002) found evidence of aerosol influence on droplet number and drizzle on a flight in June 1998. Peng et al. (2002) found higher droplet number concentrations for higher accumulation mode aerosol number concentrations in arctic clouds. These conclusions are consistent with many studies of stratiform clouds in midlatitudes (Gultepe and Isaac 1996; Peng et al. 2002; Meskhidze et al. 2005). In situ measurements during the ARM M-PACE in October 2004 found droplet number concentrations of 50-100 cm^{-3} significantly lower than the 50-350 cm^{-3} concentrations measured during the First ISCCP Regional Experiment-Aerosol Characterization Experiment (FIRE-ACE) in April 1998 (Peng et al. 2002). This contrast between seasons presents an opportunity to use the ACRF NSA locale to study the aerosol indirect effect.

Although the sunlight available to produce an indirect effect at visible wavelengths is quite small in the Arctic except during the summer when much of the anthropogenic aerosol has

been scavenged, recent work (Garrett et al. 2002, 2004; Garrett and Zhao 2006; Lubin and Vogelmann 2006) has suggested a significant **longwave indirect effect** of aerosol, in which higher droplet numbers and smaller droplet sizes increase the longwave emissivity of clouds. The radiative forcing by this mechanism has been estimated to be several Wm^{-2}, but the uncertainty is high because no reliable proxy long-term measures of CCN are available in the Arctic. Previous studies relied on surface measurements of either total particle number (which is often dominated by particles too small to nucleate droplets) or visible extinction (which is often dominated by particles that contribute little to the total CCN concentration). The planned addition of a CCN instrument at the NSA is an important step toward addressing this measurement limitation, but aircraft measurements are needed to assess how representative the surface measurements are of CCN concentrations aloft, or how well retrievals using lidar backscatter and surface CCN measurements (Ghan et al. 2006) can improve upon the surface CCN measurements.

Field studies have also shown that the low IN concentrations observed in the Arctic often yield low crystal number concentrations. Rogers et al. (2001) found that for thin stratus clouds at temperatures between -15° and -20°C, crystal number concentrations were low (1 per liter), and supercooled water persisted for several days. However, it appears that at least one of several other **crystal production processes** is needed to explain measured ice crystal number concentrations well in excess of measured IN concentrations found in many arctic clouds at temperatures between -5° and -20°C (Hobbs and Rangno 1998; Rangno and Hobbs 2001), as illustrated in Figure 4. Even if IN concentrations were the same in all seasons, one might expect seasonal variations in crystal number due to seasonal variations in temperature and aerosol-induced changes in droplet number and droplet size. Based on aircraft observations, Rangno and Hobbs (2001) hypothesized that for slightly supercooled conditions (-5° to -10°C), low droplet number concentrations and hence large droplets can produce drizzle and crystal production by riming/splintering. For moderately supercooled conditions (-10° to -20°C), they hypothesized that low droplet numbers and hence large droplets can produce crystals by freezing and shattering or by colliding with and fragmenting crystals. These mechanisms could greatly accelerate the glaciation of and precipitation from arctic clouds, but we have no clear proof that they are in fact sufficient to explain the observations. Furthermore, although temperature may explain much of the observed seasonal variability in the frequency of liquid-only arctic clouds illustrated in Figure 3, the dependence of these ice production mechanisms on droplet size is sufficient to suggest a significant role for aerosol-induced droplet nucleation as well. Data collected during ISDAC will permit investigations of relationships between IN and ice crystal number given the state-of-the-art suite of aerosol and cloud microphysics instruments proposed.

The contrast between the April and October aerosol conditions at the NSA presents an ideal opportunity to test our understanding of **droplet nucleation**, **crystal nucleation** and **ice multiplication** mechanisms both through analysis of the aerosol, liquid and ice measurements to be collected and by evaluating the ability of cloud models to simulate differences between the clouds during the two seasons. Although conditions were unseasonably warm during the October 2004 M-PACE, persistent multi-phase boundary clouds blanketed the NSA region throughout October 8–12. Cloud-top temperatures dropped as low as -17°C during this period, and in situ observations from the Citation aircraft indicated ice water path (IWP)/liquid water path (LWP) values as high as 10–20% along with drop concentrations typically in the range of 50–100 cm^{-3}. These conditions, representative of 'Type V' in Figure 4, would contrast sharply with the 'Type IV' conditions expected in April. Thus, studies of the relationships between aerosols and cloud

microphysical properties from the ISDAC data will offer considerable insight into nucleation and ice multiplication mechanisms that cannot be obtained from the M-PACE data alone.

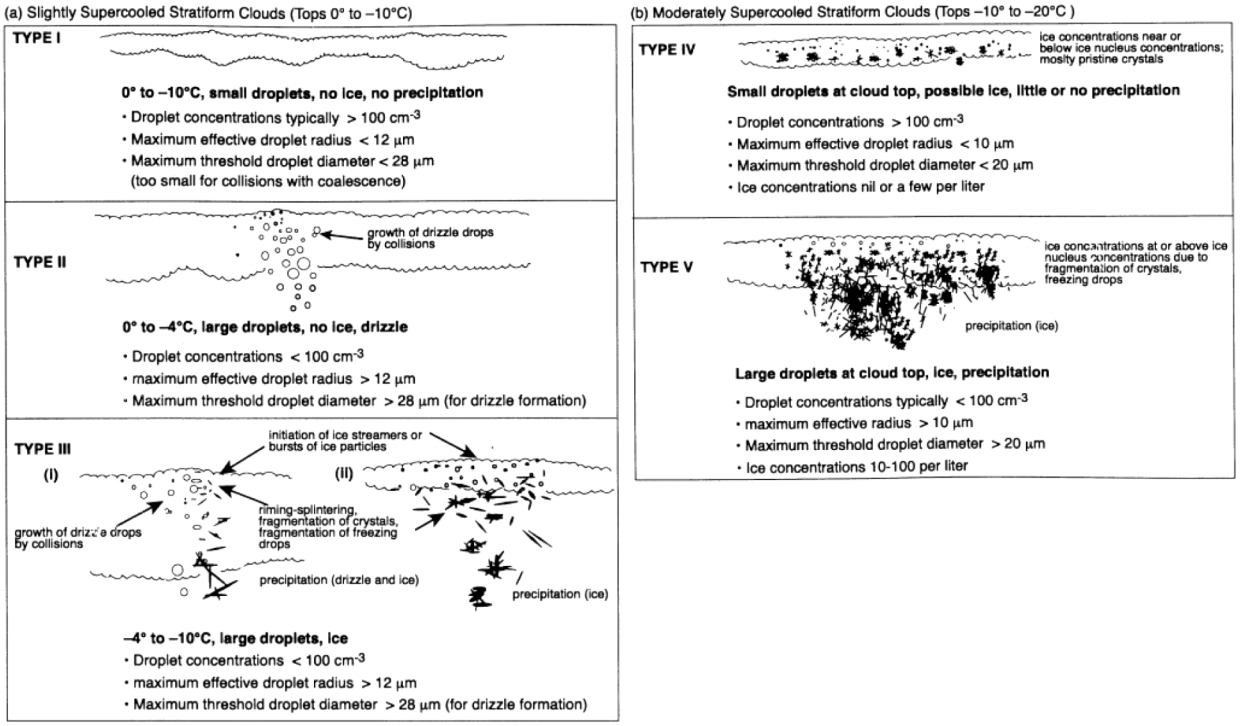

Figure 4.Ice formation mechanisms in slightly (a) and moderately (b) supercooled clouds (Rangno and Hobbs 2001).

April is ideal to conduct ISDAC for many reasons. First, April represents a transition between clean and polluted conditions with different studies reporting variations in the seasonal cycle of pollution (e.g., Quinn et al. 2002; Garrett and Zhao 2006). This might be related to varying influences of meteorology for different years, the influence of El Niño in 1998, differences between the surface and cloud layers and the fact that varying observation techniques emphasize contributions of varying particle sizes in defining pollution. Regardless, observations during April are preferable to those in March for ISDAC goals defined below because there is more sunlight, greater variability in aerosol/polluted conditions, and because April observations will allow an investigation into the competition between pollution and scavenging.

The ARM Cloud Parameterization and Modeling (CPM) group recently developed a modeling case study (M-PACE "Case B") based primarily on Flight 9b over October 9-10, representative of the stratus conditions encountered. Here, we briefly summarize preliminary findings from comparison of large-eddy simulations of Case B, using size-resolved microphysics with prognostic IN (see Fridlind et al. 2004 for model description), with the observations, which ultimately motivate additional study of stratus clouds under contrasting springtime conditions. When initializing with the Case B specifications, including subsidence and advective forcings, it was found that the small number of IN observed (0.2/L on average) produces, not surprisingly, very little ice compared with observations (Figure 5). Furthermore, processes proposed by Rangno and Hobbs (2001) to account for additional crystals (freezing drops and crystal fragmentation) had little impact. Two other possible ice production mechanisms in the literature were tested. When drop evaporation residues are considered to produce IN at the rate of 1 IN per 100,000 drops evaporated (Rosinski and Morgan 1991) or droplets spontaneously freeze during

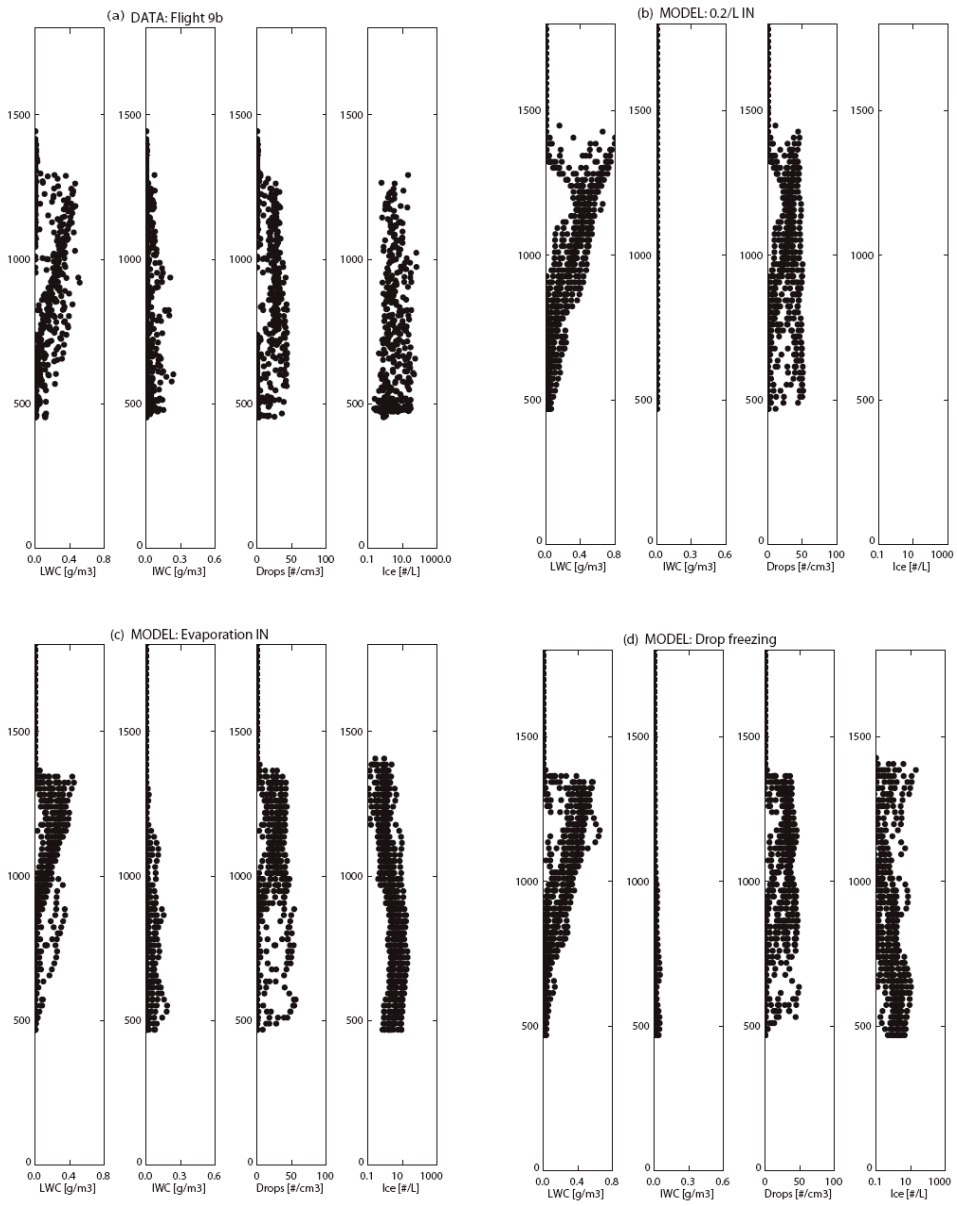

Figure 5. Comparison of Citation aircraft measurements, as a function of elevation in meters (a) with simulation results, for the case of ice formation via observed IN (b), in addition to the production of nuclei from drop evaporation residues (c) or the freezing of drops during the evaporation process (d).

the final stages of evaporation (Cotton and Field 2002), predicted ice concentrations in terms of both number and mass more closely resemble the observations. Work is under way to attempt to distinguish if either of these mechanisms is likely, by comparing modeled size distributions with observations in more detail. Many questions remain about the behavior of IN in the field, such as preactivation processes that are not preserved by the continuous flow diffusion chamber (CFDC) instrument. However, these preliminary modeling results from the M-PACE Intensive Operational Period (IOP) indicate that obtaining a set of observations similar to M-PACE but under the contrasting case of high droplet number concentrations could elucidate the mechanisms of ice formation that affect not only arctic clouds but also many other supercooled cloud types (e.g., Beard 1992).

The presence of absorbing material in the aerosol suggests the possibility of a **semi-direct effect**, in which absorption of sunlight heats the aerosol layer and inhibits cloud formation (Hansen et al. 1997). This mechanism has been previously explored at low latitudes (Ackerman et al. 2000; Koren et al. 2004). Whether the semi-direct effect plays a significant role in the Arctic depends on how long the absorbing aerosol remains in the arctic atmosphere as the sun rises during the spring. If the aerosol is scavenged by precipitation before the sun rises, the semi-direct effect will be negligible. However, if it persists into late spring it can absorb considerable sunlight and affect the relative humidity both through warming of the layer and by stabilizing the troposphere, reducing the turbulent transport of water vapor from the surface. Measurements of aerosol absorption in arctic clouds could be used in model simulations to address this issue.

The primary strength of ARM is its set of long-term surface-based **retrievals**. This set includes retrievals of aerosol extinction (Welton et al. 2000, 2002; Schmid et al. 2006), CCN concentration (Ghan and Collins 2004; Ghan et al. 2006), cloud base and cloud top (Clothiaux et al. 2000), LWP (Westwater et al. 2001), liquid water content (LWC), droplet effective radius, and droplet number (Frisch et al. 1995), water path, optical depth, and effective radius (column integrated) of the ice and water components of mixed-phase clouds (Turner 2005), and ice water content (IWC) (Matrosov 1999; Matrosov et al. 2002; Wang et al. 2004; Shupe et al. 2005). atmospheric emitted radiance interferometer (AERI) data from NSA and Kuparuk, combined with lidar and radiosonde measurements, also provide qualitative estimates of ice crystal concentrations for D < 70 μm (DeSlover et al. 1999; Mitchell et al. 2003, 2006), retrievals of effective particle size, LWP, IWP, and optical depth (Mitchell et al. 2006). From all these retrievals, vertical profiles of radiative heating are being derived. Retrievals are essential for evaluating cloud and radiative transfer models designed for climate models, and they have been used to isolate the aerosol influence on clouds. Aircraft measurements play a valuable role in the ARM Program by providing reliable values that retrievals can be compared with.

1.3 Science Questions

These considerations lead to the following primary and secondary questions that, if answered, would provide a solid foundation for parameterizations of arctic clouds in climate models. Given the page limitations, we cannot describe in detail how these questions will be answered—those details will be included in proposals written by the principal investigators (PIs).

1	*How do properties of the Arctic aerosol during April differ from those measured during M-PACE in October?*
1A	Are CCN and IN concentration in the Arctic higher during April than in October?
1B	What are the physical and chemical properties, including degree of internal mixing, of the arctic aerosol during April?
1C	How do the vertical distributions of the aerosol during April differ from those during October?
2	*To what extent do the different properties of the arctic aerosol during April produce differences in clouds?*
2A	Do the more polluted conditions during April in the Arctic enhance droplet number, crystal number, droplet dispersion, cloud optical depth, and longwave emissivity? How do these cloud properties depend on the degree of pollution?
2B	How do numbers of arctic IN vary as function of temperature and supersaturation, and

how does this compare against parameterizations used in models?

2C Does glaciation enhancement by increased IN dominate glaciation suppression by droplet size reduction associated with increased CCN?

2D What is the relationship between IN and ice crystal number and what role does ice multiplication play in determining ice crystal number concentration?

2E What are the spatial and temporal scales over which water and ice mix in mixed-phase clouds, and how does this depend on aerosol concentrations?

2F How do differences in large-scale meteorological forcing and surface conditions affect how cloud properties differ in the polluted April compared with October?

2G What role do aerosols play in explaining why springtime clouds observed during SHEBA persist so long, even though surface fluxes were weak and the ice precipitated?

2H What role does aerosol absorption of sunlight play in the dissipation of springtime arctic clouds?

2I Which processes contribute to the scavenging of arctic aerosol during spring?

3 *To what extent can cloud models and the cloud parameterizations used in climate models simulate the sensitivity of arctic clouds to the differences in aerosol between April and October?*

3A Can cloud models and parameterizations simulate the seasonal differences in the droplet number, crystal number, glaciation, riming, droplet dispersion, cloud optical depth, and longwave emissivity in the Arctic?

3B Can models and parameterizations successfully simulate the partitioning of cloud water and cloud ice in arctic clouds and the longevity of springtime arctic clouds?

4. *How well can long-term surface-based measurements at the ACRF NSA locale provide retrievals of aerosol, cloud, precipitation, and radiative heating during April in the Arctic?*

4A How does the performance of these retrievals depend on stratification, cloud thickness, and cloud phase?

1.4 Proposed Field Campaign

We propose to deploy an intensive cloud and aerosol observing system to the ACRF NSA locale for three weeks in April 2008. This period is chosen because it is during the International Polar Year and provides an important contrast with the M-PACE period, which had very different aerosol and surface characteristics than expected during April. We will require 30-45 hours of research flight time for an aircraft capable of measuring temperature, humidity, total particle number, aerosol size distribution, CCN concentration, IN concentration, optical scattering and absorption, vertical velocity, cloud liquid water and ice contents, cloud droplet and crystal size distributions, cloud particle shape, and cloud extinction. The minimum set of instruments for providing such observations has been identified based on experience obtained during M-PACE (e.g., McFarquhar et al. 2005; Poellot et al. 2006; Verlinde et al. 2006) and other projects (e.g., Korolev et al. 1999; Hobbs and Rangno 1998; Gultepe et al. 2000; Cober et al. 2001; Lawson et al. 2001). Several additions to the M-PACE instruments are needed for evaluating cloud models and for closure studies of aerosols and cloud droplet number, and IN and ice crystal number. In particular, we need improved observations of humidity, vertical

velocities and aerosol/ice nuclei numbers and compositions compared to what was available during M-PACE. In addition, we need faster time response measurements of the liquid-ice interface than available during M-PACE and improved estimates of the IWC in mixed-phase clouds. With the dew-point probes, the gust probes, aerosol and IN samplers, and the T-probe listed in the suite of probes for ISDAC, we believe have the required set of instruments needed to address aerosol-cloud issues during ISDAC.

The instruments to be deployed on the aircraft and the variables they measure are listed in Table 1.1 (acronyms in Appendix). Each instrument has a critical role. As shown by Klein et al. (2006), a subset of these instruments was used to derive cloud properties currently being used to compare model simulations and observations of M-PACE clouds. We are also proposing the surface deployment of a spectroradiometer for retrieving cloud optical depth and effective radius.

Table 1.1 Instruments on aircraft

Instrument	Measurements
Rosemont 102 probe	Temperature
Chilled mirror hygrometer	dew-point temperature
TDL hygrometer	dew-point temperature
Brechtel aerosol inlet	isokinetic aerosol inlet
TSI 3025	total particle concentration (> 3 nm)
DMA	aerosol size distribution (0.01-0.75 μm)
PMS PCASP-100X/DMT-SPP-200	aerosol size distribution (0.1-3 μm)
TDMA	Size-resolved aerosol hygroscopicity (0.015 - 0.6 μm)
DMT CCN counter	CCN concentration
CFDC	IN concentration
Radiance PSAP	optical absorption
Nephelometer	optical scattering
Rosemont 1221 gust probe	vertical velocity
Gerber probe	LWC
DMT CAPS	temperature, LWC, droplet number, cloud particle size distribution (0.5-1500 μm)
DMT CSI	total condensed water concentration
T-Probe	LWC, total condensed water concentration
SPEC CPI	cloud particle image 15-2500 μm
CIN	Cloud extinction coefficient, asymmetry parameter

The temperature and dew-point temperature are needed to determine specific and relative humidity, which are essential for distinguishing different ice nucleation mechanisms and for accounting for the effects of humidification on aerosol extinction. The differential mobility analyzer (DMA) and passive cavity aerosol spectrometer probe (PCASP) together measure the aerosol size distribution for the diameter range 0.01-3 μm. The measured size distribution can be combined with the size-resolved estimate of hygroscopicity from the time division multiple access (TDMA) to (a) test the Köhler treatment of the CCN spectrum, which can be compared with the CCN concentration measured at a selected supersaturation (Gasparini et al., 2006a), (b) test droplet nucleation models and parameterizations using the measured vertical velocity and droplet number concentration (Meskhidze et al. 2005), and (c) to provide aerosol inputs to cloud models. Although hygroscopicity measurements require much more time (15 minutes) than size distribution measurements (1.5 minutes), recent work by Dusek et al. (2006) suggests that most variability in CCN spectrum is due to variability in size distribution rather than hygroscopicity.

The TSI 3025 provides better time resolution (1 second) than the DMA and hence, can be used to scale the measured aerosol size distribution. The CFDC would provide measurements of IN concentration at a variety of selected supersaturations, which are needed as input for cloud models and can be used to distinguish between primary and secondary ice nucleation.

The cloud particle imager (CPI) provides high-resolution (2.3 μm) images of cloud particles on a CCD array which can be used to identify particle phase and ice crystal habit or habits that may give information about ice crystal nucleation mechanisms when compared to results of laboratory studies. Although the CPI has a smaller sample volume than some cloud probes, size distributions (SDs) can be estimated when integrating over longer (~ 1 minute) periods. The CPI SDs are needed for the 50 to 125 μm range not well sampled by other probes. The cloud aerosol and precipitation spectrometer (CAPS) combines a cloud and aerosol spectrometer (CAS), a cloud imaging probe (CIP), and a hot-wire liquid water sensor in a single probe. SDs of particles smaller than 50 μm will be obtained from the CAS. The CIP nominally provides SDs between 25 and 1550 μm, but in reality only between 125 and 1550 μm because optical array probes do not well measure particles smaller than 125 μm at typical aircraft speeds (Baumgardner and Korolev 1997). The CIP provides statistically significant observations of SDs for sizes above 125 μm; it also provides lower resolution (25 μm) images of ice crystals.

Although the CIP, CAS, CDP, and CPI measure SDs, bulk measurements of cloud mass and extinction are required to avoid assumptions about poorly defined mass-diameter and area-diameter relationships that depend on crystal habit. The cloud spectrometer and impactor (CSI) measures the total water content (TWC) within 1 mg m^{-3} by evaporating ice particles with D > 5 μm in dry air and has been extremely reliable in past ARM field campaigns. The TWC is identical to the ice water content (IWC) in an ice-phase cloud. The TWC combined with bulk measures of LWC from a Gerber or King probe would allow a determination of IWC in a mixed-phase cloud. The T-probe (Hallett et al., 2005) also provides TWC and LWC and hence IWC, but with the 0.1 s time (10 m horizontal for 100 ms^{-1} flight speed) resolution needed to isolate nucleation mechanisms. The T probe is needed for characterizing the fine scale interface between water and ice and provides finer resolution observations of IWC. The cloud integrating nephelometer (CIN) (Gerber et al., 2000) provides direct measurements of the radiative significance of the cloud (important for indirect effect studies), and in combination with the CSI and SDs can be used to determine the effective radius of the cloud particles. All of these instruments either have DER certification or are in the process of getting certified.

All data will be processed and placed in netcdf format in the **ACRF Archive**. For the CIN, estimates of extinction coefficient and the signals from four photomultiplier tubes from which estimates of asymmetry parameter can be derived with auxiliary information will be placed in the archive (T. Garrett of Utah responsible PI). For the CSI, estimates of TWC will be made available (G. Kok of DMT). Greg Kok will also process the CDP data and make SDs available for the archive. The SDs from the CAPS and CPI can be generated in netcdf form using software developed at the University of Illinois following procedures developed during the Tropical Warm Pool-International Cloud Experiment (TWP-ICE) to process the CAPS data (G. McFarquhar of Illinois). The CPI images will also be generated for the Archive (G. McFarquhar of Illinois). All state parameters, location and bulk LWC data will be processed and made available by the platform PI. The required boundary conditions for driving cloud models will be derived from the ECMWF analysis constrained with observations from this field campaign using variational analysis (S. Xie of Lawrence Livermore National Laboratory).

We will also deploy a spectroradiometer at the NSA surface for retrieving cloud optical depth (τ) and effective radius (r_e), and for quantifying aerosol impacts on shortwave radiation. This instrument, an Analytical Spectral Devices (ASD, Inc.) FieldSpec owned by the Scripps Institution of Oceanography, measures downwelling irradiance or zenith radiance from 0.35–2.5 μm, and thus covers 3 atmospheric windows in which downwelling radiation is sensitive to τ, thermodynamic phase, and r_e (Nakajima and King 1990; Dong et al. 1997; Pilewskie et al. 1998). Previous radiometric work on the indirect effect has used the AERI (Lubin and Vogelmann 2006; Garrett and Zhao 2006), but AERI retrievals are limited to IWPs between 5-250 g m^{-2}, LWPs between 5-80 g m^{-2}, and $\tau < 8$ (Turner 2005) for which the cloud radiates as a greybody with spectral dependence. Retrievals based on transmitted solar near-infrared spectral radiance are not subject to this limitation. However, AERI retrievals are advantageous in that they work in the range in which the microwave radiometer performs poorly, and 80% of liquid arctic clouds have LWP < 100 g m^{-2} (Dave Turner, ARM presentation). Therefore, the combination of the ASD and the AERI can provide microphysical retrievals under all cloud conditions. Further, the AERI time series of small ice crystal concentrations (i.e., the small particle mode of the SD) can be related to time series of the aerosol PSD at NSA and Kuparuk. If a subset of the aerosol population is initiating new ice crystals, the small mode of the PSD should be proportional to this subset. ASD measurements, in conjunction with broadband shortwave radiometers at NSA, will also reveal directly which component of the indirect effect–shortwave cooling or longwave warming–is dominant under any given meteorological condition. This determination of the sign of aerosol radiative forcing is critical information for the climate modeling community.

This set of instruments is similar to those deployed for M-PACE, but with a few substitutions, extensions and omissions. The CAPS probe replaces the forward scattering spectrometer probe and 2D-C used for M-PACE. The TSI-3025, DMA, TDMA, PSAP for measuring aerosols, the T-probe and CIN for measuring bulk cloud properties and the spectroradiometer are important additions. M-PACE instruments not deployed for ISDAC include observations used on multiple Aerosondes (wind, temperature, humidity and pressure sensors, aerosol counters and ice particle imagers).

In addition to the proposed measurements, this experiment will rely on the long-term measurements at the **ACRF NSA** site and Climate Monitoring and Diagnostics Laboratory (**CMDL**) Barrow facility. These measurements are listed below.

Table 1.2. Instruments and measurements at ACRF Barrow site. *=Atqasuk also.

Instrument	Measurements
Radiosonde	Temperature, humidity, winds profiles
Microwave radiometer*	Water vapor path, liquid water path
Microwave radiometer profiler	Temperature, humidity, LWC profile
915 MHz radar wind profiler/RASS	Winds, virtual temperature profile
Vaisala Ceilometer*	Cloud base altitude
Millimeter cloud radar	Cloud liquid water, cloud ice content profiles
Micropulse lidar (polarized)	Aerosol backscatter profile, depolarization ratio
AERI	Temperature, humidity profiles, water path, optical depth, and effective radius of the ice and water component of mixed-phase clouds
Cimel sunphotometer	Aerosol optical depth
Multi-Filter Shadowband Radiometer*	Aerosol optical depth multiple wavelengths
Normal incidence multifilter radiometer	Aerosol optical depth

Upviewing radiometers*	Downward longwave, solar radiance
Downviewing radiometers*	Upward longwave, solar radiance
Hotplate rain gauge*	Precipitation

Table 1.3. Instruments and measurements at CMDL Barrow site

Instrument	Measurement
Humidified nephelometer	Aerosol scattering as f(RH)
PSAP	Aerosol absorption
Condensation nuclei counter	Total particle number
PCASP	Accumulation mode size distribution
CCN	CCN concentration (one supersatation at a time)
Daily chemical analysis	Submicron mass, ion concentration
Radiometers	Radiance, aerosol optical depth
Snow gauge	Snowfall

Several different **aircraft flight patterns** are needed to achieve the objectives of the experiment. Although definite plans and profiles will be formulated at a meeting before the start of ISDAC, some initial plans are presented here. Vertical spirals over the Barrow site will be performed at the beginning and end of each flight to provide aerosol input data for the cloud models and to provide aerosol and cloud evaluation data for the retrievals. These data will also be used to describe the relationship between aerosols, IN and ice crystal concentrations. The background wind will be carefully examined to set flight patterns that avoid resampling of previously measured cloud areas that may be contaminated by aircraft-produced ice particles (Woodley et al., 2003). If sky is clear, one vertical spiral will be performed to sample aerosol up as high as the aircraft will fly. Horizontal legs of 15 minutes, each below and above each cloud layer, will be performed to better characterize the aerosol going into the clouds. At an aircraft speed of 100 ms^{-1}, these legs would span 90 km. 15-minute horizontal legs through liquid clouds will be performed to characterize the droplet size distribution in liquid and mixed-phase clouds. 15-minute horizontal legs through ice clouds will be performed to characterize the crystal size distribution in ice and mixed-phase clouds. It should be possible to fly all of these flight patterns in a 3-hour flight, depending on the number of cloud layers. Thus, 45 hours of flights will permit 15 flights, and 30 hours of flights will permit 10 flights. Although icing is always a concern in the Arctic, our experience during M-PACE suggests probes could sustain operation for at least 40-50 minutes at an average liquid water of 0.1 g m^{-3}; analysis of SHEBA data for April suggests lower LWCs and smaller droplets than those encountered during M-PACE, so that de-icing will probably not be necessary for horizontal legs through liquid clouds for less than 15 minutes. Actual flight profiles will be subject to aircraft and air traffic control limitations.

1.5 Expected Results

This field campaign will provide the data needed to achieve each of its four primary objectives. By using many of the same instruments used during M-PACE, we will be able to contrast the arctic aerosol and cloud properties during October and April. Table 1.4 summarizes the expected applications of ISDAC data. The context of these applications has been previously described in the background and motivation of the proposal. The aerosol measurements will be used with vertical velocity measurements in droplet models to test nucleation parameterizations (Meskhidze et al. 2005) and in cloud models driven by objectively analyzed boundary conditions to test whether the cloud models can simulate the aerosol influence on the clouds. The influence of aerosol and boundary conditions on the simulated clouds will be separated by running the cloud models with all four combinations of M-PACE and ISDAC aerosol and boundary

conditions: M-PACE aerosol and boundary conditions, M-PACE aerosol and ISDAC boundary conditions, ISDAC aerosol and M-PACE boundary conditions, and ISDAC aerosol and boundary conditions. ISDAC and M-PACE boundary conditions are likely to be very different because of the much more extensive ocean water during M-PACE. The uniformity of the surface conditions during ISDAC greatly simplifies the objective analysis (surface fluxes and precipitation are very weak), so that it can largely rely on the ECMWF analysis. The ISDAC cloud measurements will be used to improve understanding of crystal nucleation, to evaluate the cloud simulations and to evaluate cloud retrievals. The aerosol measurements will also be used to evaluate the aerosol retrievals which, once validated, can be used in long-term studies of aerosol effects on clouds. By running the cloud models with and without solar absorption by the aerosols, we will determine the semi-direct effect of the aerosol on the clouds.

The aircraft measurements are also sorely needed to evaluate and further develop cloud retrievals from the ground-based instruments at the NSA locale. ARM investigators have developed numerous methods for deriving cloud and precipitation properties from various combinations of radar, lidar, AERI, and microwave radiometer measurements. Each of these instruments provides a unique perspective on cloud properties based on the individual instrument specifications. A full characterization of cloud properties requires a coordinated retrieval framework that can incorporate each of these instruments under the appropriate conditions. Some of this retrieval coordination effort is under way within the ARM community in support of accurate, operational heating rate calculations. The ISDAC cloud measurements will be directly and statistically compared to the coordinated surface retrieval results. Particular focus will be placed on evaluating the ability of the surface retrievals to partition cloud water appropriately between phases and to accurately estimate the cloud liquid water under the low liquid water conditions expected in April. Furthermore, surface-based cloud retrievals can be coordinated with measurements of CCN, IN, and/or vertical velocities to examine various processes that impact the cloud properties, the cloud persistence, and the cloud-aerosol interaction.

Table 1.4. Applications of ISDAC Data (*from NCEP/ECMWF reanalysis model output)

Experiment	Data Input	Validation data
CCN closure	Aerosol size distribution Hygroscopicity distribution	CCN concentration
Droplet number closure	Aerosol size distribution Hygroscopicity distribution Vertical velocity	Droplet number concentration
CCN retrieval	Aerosol backscatter, scattering and relative humidity profile, surface CCN and humidification function	CCN concentration
Cloud extinction closure	Cloud particle size distribution	Cloud extinction and optical depth
Cloud water closure	Cloud particle size distribution	Total condensed water content
Cloud modeling	Aerosol size distribution profile Hygroscopicity distribution $IN(T,S_i)$ profile Meteorological profile, Surface fluxes & large-scale forcing profiles*	Cloud particle size distribution, LWC, IWC, temperature, humidity, cloud base, cloud phase, precipitation, cloud optical depth
Semi-direct effect	Aerosol size distribution Hygroscopicity distribution $IN(T,S_i)$ profile, aerosol absorption,	
Cloud property retrievals	Radar, lidar, AERI and microwave	Aircraft measurements of cloud

	radiometer measurements, ASD spectroradiometer	particle size, LWC, IWC, phase and optical depth
Relation between IN and ice crystal concentration	IN(T,S_i) in clear air input to a cloud, Humidity and temperature profiles, Ice crystal shape & size distribution, Observations of water-ice interface	Crystal habits compared against expected habits (lab experiments) from T, S_i to assess primary and secondary nucleation mechanisms

1.6 Management

ISDAC will be managed by the PI (Steven Ghan) and co-PIs who bring expertise in field experiments, instrumentation, modeling, and data analysis. Once ISDAC is approved, the team will meet to review its objectives, instrument selection, and aircraft selection given the funding available. One year before ISDAC, the team will make a final decision on the aircraft to deploy. Six months before ISDAC, a small team will travel to the staging site to arrange logistics. One month before the experiment the instrument mentors will integrate their instruments with the aircraft at its home base.

Responsibilities for each investigator are summarized in Table 1.5. The instrument mentors will be responsible for the calibration of their instrument, integration with the platform, operation during the campaign, removal of the instrument from the platform, data processing, and data archiving. Funding for each investigator is summarized in section 5.

Table 1.5 Investigator Responsibilities

Investigator	Responsibility
Steven Ghan	Leadership, cloud modeling, CCN retrieval
Mike Poellot	UND Falcon; mentor for Rosemont 102, chilled mirror & TDL hygrometers, aerosol inlet, TSI 3025, PCASP, PSAP, nephelometer, gust probe, Gerber probe
John Hubbe	DOE G-1; mentor for Rosemont 102, chilled mirror & TDL hygrometers, aerosol inlet, TSI 3025, PCASP, PSAP, nephelometer, gust probe, Gerber probe
Don Collins	Mentor for DMA, TDMA, CCN counter
Sarah Brooks	Mentor for CFDC
Greg Kok	Mentor for CAPS, CSI
John Hallett	Mentor for T-Probe
Greg McFarquhar	Mentor for CPI
Tim Garrett	Mentor for CIN
Dan Lubin	Mentor for spectroradiometer, cloud retrievals
Hans Verlinde	NSA site scientist
Ann Fridlind	cloud modeling
Shaocheng Xie	boundary conditions for cloud models
Connor Flynn	aerosol retrievals
Matthew Shupe	cloud retrievals
David Turner	cloud retrievals
David Mitchell	cloud retrievals

1.7 Relation to other programs

ISDAC will be coordinated with experiments to be conducted as part of three International Polar Year activities: International Arctic Systems for Observing the Atmosphere (http://www.ipy.org/development/eoi/proposal-details.php?id=196) the Hydrological Impact of Arctic Aerosols (http://www.ipy.org/development/eoi/proposal-details.php?id=140), and POLar study using Aircraft, Remote sensing, surface measurements and modeling of Climate,

chemistry, Aerosols and Transport (POLARCAT) (http://www.ipy.org/development/eoi/proposal-details.php?id=32). As part of POLARCAT, Phil Russell and Beat Schmid are proposing aircraft measurements of aerosol extinction over Barrow in the spring of 2008. There is also a proposal for a surface energy budget IOP for 2008, NSA sea surface temperature, which will include daily measurements of water equivalent precipitation, snow depth, snow optical properties, and temperature gradients through the snow and upper soil layer. If Dr. Curry's proposal is approved we would exchange data, and if ASP participates we would integrate the ARM and ASP contributions into a single aircraft or make coordinated flights with two aircraft.

2. Relevance to long-term goals of the DOE Office of Biological and Environmental Research

This field campaign would provide data needed to test aerosol and cloud retrievals and cloud models designed for application to global climate models. Evaluation of retrievals would improve confidence in long-term retrievals at the ACRF NSA locale, thereby extending the value of the data beyond the campaign period. Reliable long-term retrievals are necessary for detecting aerosol indirect effects on clouds. Evaluation of both single-column and cloud-resolving models will improve confidence in cloud parameterizations used for simulations of climate change. Arctic clouds have proven particularly difficult to simulate, at least in part because aerosol and IN effects on arctic clouds are extremely poorly understood. These data would fill the gap in the understanding needed to improve arctic cloud parameterizations.

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Acronyms

ACRF	ARM Climate Research Facility
AERI	Atmospheric Emitted Radiance Interferometer
AMF	ARM Mobile Facility
ARM	Atmospheric Radiation Measurement
ASD	Analytical Spectral Devices
ASP	Atmospheric Science Program
CAPS	Cloud Aerosol and Precipitation Spectrometer
CAS	Cloud and Aerosol Spectrometer
CCN	Cloud Condensation Nuclei
CDP	Cloud Droplet Probe
CFDC	Continuous Flow Diffusion Chamber
CIN	Cloud Integrating Nephelometer
CIP	Cloud Imaging Probe
CMDL	Climate Monitoring and Diagnostics Laboratory
CPI	Cloud Particle Imager
CSI	Cloud Spectrometer and Impactor
DMA	Differential Mobility Analyzer
DMT	Droplet Measurement Technologies
DOE	Department of Energy
DRI	Desert Research Institute
ECMWF	European Center for Medium Range Weather Forecasts
IOP	Intensive Operations Period
ISDAC	Indirect and Semi-Direct Aerosol Campaign
IWC	Ice Water Content
IWP	Ice Water Path
LWC	Liquid Water Content
LWP	Liquid Water Path
MFRSR	Multifilter Rotating Shadowband Radiometer
M-PACE	Mixed-Phase Arctic Cloud Experiment
NSA	North Slope of Alaska
PCASP	Passive Cavity Aerosol Spectrometer Probe
PI	Principal Investigators
PMS	Particle Measurement Systems
PSAP	Particle Soot/Absorption Photometer
PSD	Particle Size Distribution
RASS	Radio Acoustic Sounding System
SHEBA	Surface Heat Budget of the Arctic
SPEC	Stratton Park Engineering Company, Inc.
SST	Sea Surface Temperature
TDL	Tunable Diode Laser
TDMA	Tandem Differential Mobility Analyzer
TWP-ICE	Tropical Warm Pool International Cloud Experiment
UND	University of North Dakota