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Mixed-Phase Arctic Clouds Experiment (M-PACE)

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Executive Summary

Significant, interrelated, atmospheric, oceanic and terrestrial changes have been occurring in the Arctic in recent decades. These changes are broad-ranging, impacting every part of the arctic environment. Arctic clouds have been identified as playing a central role in several hypothesized feedback processes. Yet, nowhere in the Northern Hemisphere are the interactions among clouds, the over- and underlying atmosphere, and the ocean surface more complex, have a greater potential climatic impact, and, at the same time, less understood than they are at high latitudes.

The recent SHEBA experiment revealed that mixed-phase clouds appear to dominate the low-cloud fraction within the Arctic. Moreover, it was found that the Arctic mixed-phase clouds are distinct from their lower latitude cousins. Unfortunately, SHEBA did not manage to produce a comprehensive data set needed to study these poorly understood arctic clouds. Numerical modeling studies suggest that the ice phase heavily influence cloud evolution, and the cloud microphysics also are intimately tied to cloud-scale dynamics and the underlying surface energy budget (i.e., sea ice coverage and thickness). Moreover, the radiative characteristic of these clouds are not fully understood.

An integrated, systematic observational and modeling study can help bridge the gaps in understanding that currently exists between mixed-phase cloud microphysics, cloud dynamics and thermodynamics, and cloud evolution. What is currently lacking is a comprehensive observational data set needed for model evaluation and hypothesis testing. Therefore, the major objective of the Mixed-Phase Arctic Cloud Experiment (M-PACE) *is to collect the focused set of observations needed to advance our understanding of the dynamical and processes in Arctic mixed-phase clouds, including the cloud microphysical processes and radiative transfer through clouds.*

The ultimate goal of this project is to produce a better understanding of mixed-phase ASC. This goal will be achieved in two ways: (1) Use the in situ observations from aircraft platforms, combined with remote sensing measurements, to improve our understanding of key mixed-phase stratus cloud properties. (2) Use LES cloud models to examine causal relationships with regard to how dynamics and microphysics evolve in tandem. The detailed observations of the cloud processes will be used to evaluate and improve model performance, while the improved model output will be used to guide the observational retrievals.

Acronyms and Abbreviations

1-D	one-dimensional
AERI	atmospheric emitted radiance interferometer
AIRS	Atmospheric Infrared Sounder (NASA)
ARM	Atmospheric Radiation Measurement
ASC	arctic stratus cloud
BL	boundary layer
CCN	cloud condensation nuclei
DOE	U.S. Department of Energy
ERM	eddy-resolving model
FIRE-ACE	First ISCCP Regional Experiment-Arctic Cloud Experiment
GCM	general circulation model
GPS	Global Positioning System
IFN	ice freezing nuclei
IN	ice nuclei
IR	infrared
ISCCP	International Satellite Cloud Climatology Program
LES	large-eddy simulation
MFRSR	multifilter rotating shadowband radiometer
M-PACE	Mixed-Phase Arctic Clouds Experiment
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NSA	North Slope of Alaska
NSF	National Science Foundation
PDL	polarization diversity lidar
PNNL	Pacific Northwest National Laboratory
PSU	The Pennsylvania State University
SEARCH	Study of Environmental Arctic Change
SHEBA	Surface Heat Budget of the Arctic
TES	Tropospheric Emission Spectrometer (NASA)
UAF	University of Alaska, Fairbanks
UAV	unmanned aerial vehicle
UND	University of North Dakota

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1.0 Introduction

Significant interrelated atmospheric, oceanic, and terrestrial changes have been occurring in the Arctic in recent decades (SEARCH SSC 2001). These changes are broad ranging, impacting every part of the arctic environment. The recent NSF-funded Study of Environmental Arctic Change (SEARCH) program Science Plan document (SEARCH SSC 2001) singled out arctic clouds in one of its four hypotheses as needing more study:

> "*The third hypothesis is related to the first two: Feedbacks among the ocean, the land and the atmosphere are* critical *to Unaami. These feedbacks could determine the role of Unaami and the Arctic in climate change. Such feedbacks include surface albedos and cloud changes as well as air chemistry processes and the global ocean overturning circulation.*"

The SEARCH report identified the need for process studies to understand the major physical processes in the ongoing Arctic change. Only when individual components are well understood can the new knowledge from the different processes be combined to study the impact of the physical changes on the ecosystems and societies, potentially important feedbacks.

Nowhere in the Northern Hemisphere than at high latitudes do the interactions among clouds, the over- and underlying atmosphere, and the ocean surface demonstrate more complexity, have a greater potential climatic impact. Nowhere else too are these factors so poorly understood, largely due to a paucity of field observations coupled with difficulties in remotely sensing arctic clouds from satellites. Although our knowledge of arctic clouds has improved in recent years through field experiments (i.e., National Science Foundation [NSF]-funded Surface Heat Budget of the Arctic [SHEBA] and National Aeronautics and Space Administration [NASA]-funded First ISCCP Regional Experiment-Arctic Cloud Experiment [FIRE-ACE]) and improvements to numerical techniques, there still exist large gaps in our knowledge of arctic cloud processes. For example, mixed-phase stratus clouds that occur frequently in the Arctic are poorly understood. Not only does the ice phase heavily influence cloud evolution, but the cloud microphysics also are intimately tied to cloud-scale dynamics, the underlying surface energy budget (i.e., sea ice coverage and thickness) and climate, the parameterization of which in climate models is hard. Such parameterization difficulties are exacerbated in the Arctic because strong, stably stratified layers may be encountered in the lowest 1 km of the atmosphere and even within the cloud decks themselves. Moreover, the radiative characteristic of these clouds are not fully understood.

1.1 Cloud Impacts on the Arctic Environments

Arctic clouds play an important role in the Arctic climate system. During summer, fall, and spring cloud fractions are typically in excess of 70% over the arctic pack ice and near the Alaskan coast with stratiform clouds the dominant cloud type (Curry et al. 1996; Intrieri et al. 1999; Key et al. 1999, Schweiger et al. 1999). Cloud cover over the sea ice typically maximizes in the summer (Herman and Goody 1976) whereas coastal Alaskan cloudiness maximizes in October (Dissing and Wendler 1998). This large spatial and temporal cloud coverage has a large impact on the radiative budget of the Arctic system (Curry et al. 1996; Jiang et al. 2000; Harrington and Olsson 2001a). For example, using model output and data from Russian drifting ice stations, Walsh and Chapman (1998) showed that the cloud radiative forcing of the central Arctic varies from negative values of –59 W m^{-2} during summer to a positive 20 to 30 W m^{-2} during the cold season, leading to an annual mean in the net cloud radiative forcing of about 3 W m^{-2}. Hence, clouds tend to have a net warming effect on the region of the Arctic Ocean. Because these large cloud fractions have a strong influence on the radiative budget, the surface radiative fluxes are quite sensitive to perturbations in cloud properties and amount. Model estimates show that alterations in annual cloud fraction and in liquid cloud effective radii (by only ~ 3 μm) can lead to changes in the surface net flux of up to 40 W m^{-2} (Curry et al. 1993). Furthermore, Harrington and Olsson (2001a) have shown that net surface fluxes vary by as much as 80 W m^{-2} depending on the value of ice effective radius used in a model. Perhaps more importantly, that work showed that altering the ice effective radius produced a change in the sign of the surface net flux (i.e., warming versus cooling) during the fall.

These sensitivities of the arctic radiation budget to perturbations in cloud properties can affect other components of the arctic system. For example, in a set of simplified modeling studies, Curry and Ebert (1990) and Curry et al. (1993) estimate that changes in the net radiative budget through modest perturbations in liquid and ice cloud microphysics can cause up to a 3 m change in equilibrium sea-ice thickness. Such reductions in ice thickness may modify the frequency of leads and open water that then affect both the sea-ice albedo (Curry et al. 1995a) and the water vapor (Curry et al. 1995b) feedback mechanisms. Both mechanisms are proposed as potentially important pathways in arctic climate change scenarios. Indeed, recent in situ (McPhee et al. 1998) and satellite (Johannessen et al. 1999) measurements strongly suggest that the perennial sea ice may be changing significantly. Measurements during SHEBA showed a thinner-than-normal sea-ice thickness while satellite measurements tend to show a substantial reduction in the total area of multi-year ice. McPhee et al. (1998) estimate that as much as 2 m of fresh water may have been added to the Arctic Ocean during 1997 and these authors suggest the ice-albedo feedback as the potential cause.

The exact physical causes behind such observations are, of course, in question. Cloudiness may play some role through radiative influence. For example, Curry et al. (1997) have suggested that fall cloudiness affects the freeze-up of the Arctic Ocean. Moreover, general circulation model (GCM) studies (e.g., Lynch-Stieglitz 1995; Gregory and Morris 1996) show that low-level stratus impact climate simulations. Though this may be the case, interactions between changes in cloud cover and the other feedback pathways are not understood at present. In fact, exactly how cloud cover would respond to changes in sea ice is not understood. One modeling study (Royer et al. 1990) with the French spectral GCM showed that cloud cover responds differently to a reduction in sea-ice concentration depending upon the cloud and convection parameterizations. In their sensitivity studies, cloud cover either increased or decreased with a reduction in sea-ice cover.

Besides cloudiness, both the sea-ice albedo and water vapor feedback mechanisms are linked to changes in the arctic hydrological cycle and to changes in the thermohaline circulation. (e.g., Miller et al. 1994; Nakamura 1996). Further, the hydrological cycle and oceanic processes are linked to cloudiness through precipitation that affects fresh water input into the Arctic Ocean. This link is vital because, unlike other oceanic regions, the Arctic Ocean receives a much larger portion of its fresh water in the form of runoff instead of directly through precipitation (Broecker et al. 1990). Recent estimates suggest that river runoff provides approximately

35 cm yr^{-1} of fresh water input (Aagaard and Carmack 1989) whereas net precipitation (precipitation – evaporation) adds between 16 and 20 cm yr^{-1} directly to the ocean (Cullather et al. 2000). As one might expect, this addition of fresh water to the Arctic Ocean leads to strong stratification of the upper ocean layers. Such stabilization through runoff may alter deep-water formation in the North Atlantic (e.g., Aagaard and Carmack 1989) and it also adds to the stability of the sea ice covering the Arctic Ocean (Walsh et al. 1998). Processes that affect deep-water formation can alter the thermohaline circulation, and therefore affect the transport of thermal energy northward, which effectively warms the Arctic (Manabe and Stouffer 1988; Nakamura 1996). For example, the ice albedo feedback mechanism (Curry et al. 1995a) would likely alter the hydrological cycle by affecting meridional moisture and thermal energy advection (modifying local precipitation amounts) and total meltwater amounts over the terrestrial Arctic. This would affect both river runoff totals and direct precipitation inputs of fresh water that may then feedback to the sea ice (Nakamura 1996).

Other terrestrial processes further complicate these hydrological effects. Recently, it has been hypothesized that shrubs on the arctic tundra modulate the arctic climate (Sturm et al. 2001). Since shrubs act as a catch for wind-blown snow, the depth of the snow pack around shrubs tends to be deeper, which encourages further shrub growth through warmer winter surface temperatures. Sturm et al. 2001 hypothesize that this would lead to deeper snow packs and, hence, even greater runoff during the spring melt. Hence, arctic cloudiness is inextricably linked to major processes that affect the large-scale evolution of the arctic atmosphere, sea ice, and ocean. This issue is, perhaps, even more pertinent given the fact that arctic precipitation appears to have increased over the past few decades (e.g., Karl et al. 1993); however, evidence shows that precipitation has decreased over Arctic Alaska (Curtis et al. 1998). Though this may be the case, since sparse measurements of arctic precipitation exist, and since precipitation gauges are plagued with problems regarding the correct measurement of snowfall (such as overestimates due to blowing snow), significant uncertainties do exist regarding snow fall totals over the Arctic (Walsh et al. 1998; Serreze and Hurst 2000).

In addition to all these natural feedbacks in the Arctic climate system, climate simulations with several different models show a substantial sensitivity at high latitudes to climate perturbations such as might be caused by anthropogenic forcing (e.g., Manabe et al. 1992; Grotzner et al. 1998). It has long been known that there are major intrusions of polluted air into the Arctic basin and that they often contain high concentrations of cloud condensation nuclei (Borys and Rahn 1981; Rahn 1981; Patterson and Marshall 1982). Moreover, during the recent SHEBA campaign, the air mass was found to be highly polluted in terms of cloud condensation and ice freezing nucleus (IFN) concentrations above the boundary layer while extremely clean below on several occasions (Curry et al. 2000; Rogers et al. 2001). Harrington et al. (1999) and Jiang et al. (2000) have shown that an increase by only a factor of three in IFN concentrations, which may occur during episodes of increased pollution, can transform a very dynamically stable supercooled stratus cloud layer into a broken optically thin cloud layer. Such changes in cloud properties will impact the surface energy budget, which in turn impacts sea-ice evolution.

1.2 Arctic Cloud Process

Although cloudiness is an important issue in Arctic climate and though much good work has been accomplished in this area (e.g. Curry et al. 1996), we still lack knowledge regarding the internal physical processes of arctic clouds. Work has only recently begun on attempting to understand the small-scale physical processes in arctic mixed-phase clouds (e.g., Harrington et al. 1999), diamond dust (e.g., Girard and Blanchet 2001), stable arctic boundary layers (Kosovic and Curry 2000), and so forth.

The recent Arctic field programs Surface Heat Budget of the Arctic (SHEBA) and First ISCCP Regional Experiment (FIRE; ISCCP is the International Satellite Cloud Climatology Program) Arctic Cloud Experiment (ACE) sought to address clouds, radiation, and the surface energy balance, and their interactions with the physical processes that determine the sea-ice mass balance in the Arctic Ocean. While the final results from these experiments are not yet in, much has been learned (special issue of *Journal of Geophysical Research* Vol. 106, 2001), and work is progressing (Curry et al. 2000).

SHEBA, like previous research (see review by Curry et al. 1996), has shown us that the Arctic is a complex environment, especially when cloud processes are considered. During the warm season (June and July) stratus clouds are primarily liquid and can exist in multiple layers with stable regions between them (e.g., Goody and Herman 1976; Curry 1986). Clear-sky ice crystal precipitation occurs during the colder months of the year (Curry et al. 1990), in a primarily stable environment, and can significantly influence the radiative budget of the surface (e.g., Curry et al. 1993). Perhaps most importantly, mixed-phase clouds appear to dominate the low-cloud fraction within the Arctic (on average 73% for the SHEBA period, present at all months of the year; Intrieri et al. 2002). Such clouds have a complex physical structure. For example, Figure 1 shows lidar data from SHEBA that illustrates a common arctic mixed-phase stratus structure: Liquid topped clouds that precipitate ice. These mixed-phase stratus clouds are not well understood and are especially difficult to represent accurately in large-scale models. Not only does the ice phase heavily influence cloud evolution (e.g., Pinto and Curry 1995), but the cloud microphysical processes themselves are intimately tied to smaller scale dynamics (e.g., Harrington et al. 1999), which are also hard to parameterize. Such difficulties are increased in the Arctic because stably stratified layers may be encountered within the lowest 1 km of the atmosphere (e.g., Kahl et al. 1989) and within the stratus decks themselves (e.g., Hobbs and Rangno 1998). Moreover, these clouds also present significant observational challenges. The radiatively dominant liquid phase (Delamere et al. 2000) is present in very low concentrations, frequently at levels below the noise floor of the deployed instruments, or masked by the presence of the larger ice crystals. It is well known in the GCM community that the pace of progress in the parameterization of clouds is largely controlled by the limitations of our understanding of cloud processes. Thus, the scientific and observational challenges presented by these mixed-phase clouds needs to be overcome to advance the representation of arctic cloud effects in GCMs.

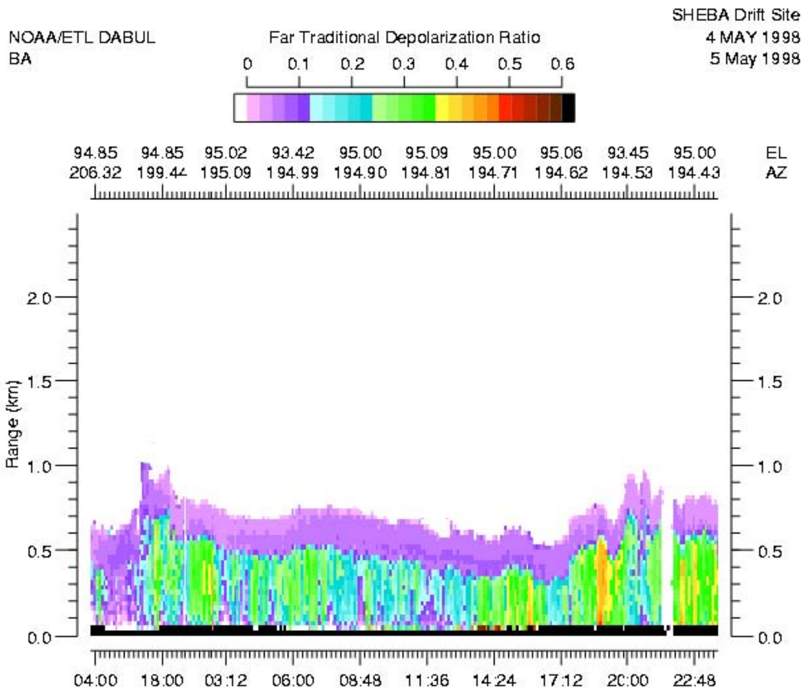

Figure 1. Lidar depolarization ratio measured for mixed-phase stratus during May 4-5 of SHEBA. Values above 0.1 indicate the presence of ice. (Courtesy of Janet Intrieri, NOAA/ETL.)

Our understanding of these large-scale, coupled processes is hampered by the fact that mixed-phase stratus are prevalent during fall, spring, and even summer and winter (Intrieri et al. 1999, 2001; Curry et al. 2000). However, our current knowledge of cloud processes cannot sufficiently account for this prevalence of mixed-phase clouds, although some ideas have been put forward. Observations show that these clouds can be persistent (Curry et al. 1997). Recent analyses of flight data by Hobbs and Rangno (1998) showed that many mixed-phase arctic clouds attain a steady state consisting of a liquid-topped cloud that continually precipitates ice. Such a structure now appears to be common as shown by the SHEBA lidar data (Intrieri et al. 1999) and by the Department of Energy Atmospheric Radiation Measurement (DOE ARM) North Slope of Alaska (NSA) radar and lidar data. The nature of such a cloud structure is intriguing since the clouds include a significant ice phase that depletes cloud water through the Bergeron-Findeisen process. An active Bergeron-Findeisen process can produce rapid ice precipitation that dries, and sometimes dissipates, the cloud layer (Walko et al. 1997). In more recent analyses it has been hypothesized that the longevity of arctic mixed-phase clouds results from a balance between cloud-top radiative cooling and ice removal by precipitation (Pinto 1998; Harrington et al. 1999).

Although our knowledge of mixed-phase stratus is sparse, it appears that the nature of the balance that leads to long-lived mixed-phase clouds strongly depends on the crystal concentrations in the cloud. Ice crystal concentrations vary over a relatively large range (Hobbs and Rango 1998; Curry et al. 1990; Borys 1996) that affects ice particle size and, therefore, precipitation rates and cloud longevity (Harrington et al. 1999; Harrington and Olsson 2001b). During autumn and spring, when mixed-phase stratus are most prevalent, temperatures are high enough that ice nuclei (IN) are responsible for primary ice nucleation, while secondary ice production mechanisms appears likely in the -2.5 to -8 C temperature range (Rangno and Hobbs 2001). Recent modeling studies have shown that mixed-phase stratus, in general, are sensitive to modest changes in IN concentrations (see Harrington et al. 1999; Jiang et al. 2000; Harrington and

Olsson 2001b; Lohman 2002). Each of these studies illustrate that increases in IN concentrations of just two to three times the ambient values can transform a solid, largely liquid stratus deck into a broken, optically thin cloud system. Over the solid pack ice, and near coastal regions, areas of open water (such as leads and polynyas) impact local processes by moistening and heating the boundary layer (BL; Pinto and Curry 1995) and by possibly adding extra IN (Rogers et al. 2001). Even with the inclusion of large-scale moisture and heat sources, the sensitivity of mixed-phase clouds to IN appears to be strong (Jiang et al. 2000).

Ice precipitation itself plays a role in mixed-phase arctic stratus cloud (ASC) evolution because precipitation redistributes moisture and heat within the BL. Ice precipitation can cause strong sublimation cooling and moistening below the main cloud deck and, thus, rapid stratification of the lower BL (Harrington et al. 1999). Such stratification not only reduces the strength of BL turbulence, but it also significantly restricts fluxes of heat, moisture, and momentum towards the surface (Harrington et al. 1999). Furthermore, periods of rapid glaciation convert many small drops (~ 100 cm^{-3}) to fewer large ice crystals (~ 2 l-1), which alters the infrared emission from cloud top by as much as 50% (Harrington and Olsson 2001a). This reduction in cloud-top radiative cooling causes buoyancy production of downdrafts to weaken, leading to further thinning of the cloud deck (Harrington and Olsson 2001b).

Much of our current understanding of mixed-phase ASC processes has been derived from model simulations. In some cases, one-dimensional (1-D) models have been used (e.g., Pinto and Curry 1995) while the most detailed studies use eddy-resolving models (ERM) or large eddy simulations (LES), some with explicit microphysics (e.g., Olsson et al. 1998; Harrington et al. 1999). One study was even done without a supporting observational data set (Harrington et al. 1999) and was designed more on conjectural grounds. This history attests strongly to the fact that few data sets exist on arctic mixed-phase clouds with which to evaluate our numerical models of cloud and boundary-layer processes. Although this is in general true, the recent SHEBA has improved this situation. SHEBA has produced a large data set of atmospheric, sea ice, and oceanic data during an annual cycle over the Arctic Ocean. In addition, the FIRE-ACE flights over SHEBA produced data with which cloud models can be compared. While this data set is unique, it contains only one good mixed-phase cloud modeling case (May 4, 1998) with most of the cases being largely, or completely, liquid (see Curry et al. 2000).

1.2.1 Scientific Objections

We have attempted to paint a picture which illustrates that (1) mixed-phase ASC, and layered clouds in general, are only beginning to be understood and (2) that remote-sensing techniques are now at a sufficient stage of development that coupling observations with LES models of mixed-phase clouds can be exceedingly beneficial. Moreover, because this area of research is only in its infancy, very few systematic studies have been done to achieve an understanding of why mixed-phase clouds behave as they do. An integrated, systematic observational and modeling study can help bridge the gaps in understanding that currently exist between mixed-phase cloud microphysics, cloud dynamics and thermodynamics, and cloud evolution. Currently lacking is a comprehensive observational data set for model evaluation and hypothesis testing. *Therefore*, the major objective of the Mixed-Phase Arctic Cloud Experiment (**M-PACE**) *is to collect the focused set of observations needed to advance our understanding of the dynamical and processes in mixed-phase clouds, including the cloud microphysical processes and radiative transfer through clouds.*

The ultimate goal of this project is to produce a better understanding of mixed-phase ASC. This goal will be achieved in two ways: (1) Use the in situ observations from aircraft platforms, combined with remote-sensing measurements, to improve our understanding of key mixed-phase stratus cloud properties; (2) Use LES cloud models to examine causal relationships with regard to how dynamics and microphysics evolve in tandem. The detailed observations of the cloud processes will be used to evaluate and improve model performance, while the improved model output will be used to guide the observational retrievals. These goals can be accomplished through the following scientific questions:

- *What is the structure of the cloud-scale circulations and how does this relate to the macro- and microphysical characteristics of the cloud?*
- *How are liquid and ice partitioned spatially and temporally in mixed-phase ASC and is this partitioning important for the process of glaciation and cloud evolution? How are the ice crystals partitioned according to sizes and shapes? Do our cloud-scale models accurately capture the co-existence of liquid and ice processes, particularly the role of sedimentation in the vertical structure of liquid and ice?*
- *How do mixed-phase microphysics and radiation couple with, and feedback to, the mean and turbulent state of the arctic boundary layer? What is the nature of the coupling between ice precipitation (which dries the cloud layer) and cloud-top radiative cooling (which increases supersaturation) in these clouds and how does this interaction impact cloud dynamics? Is ice precipitation from these cloud layers a first-order cause of the complex BL structure observed beneath, and within, mixed-phase ASC?*
- *Is the longevity of mixed-phase ASC determined by short temporal phenomena (such as microphysics and cloud dynamics) or longer temporal effects (such as the large-scale, meso- and synoptic, convergence/divergence of water vapor and energy)?*
- *How do the mixed-phase clouds respond to varying concentrations of aerosol, particularly CCN and IN?*
- *How can the representation of these important mixed-phase clouds in large-scale models be improved based on the understanding of physical processes obtained in the field campaign?*
- *How can the advection into a single-column model grid box be represented, and what are the temporal and spatial averages of radiative fluxes at the top of the column?*
- *Can we synthesize modeling and observations to improve radar and lidar retrievals of cloud microphysical properties in mixed-phase clouds?*
- *How well do our current ground-based remote-sensing instruments characterize the various cloud types in the Arctic?*

1.2.2 Experiment Design and Observational Requirements

The field experiment is proposed to take place at (and over) the North Slope of Alaska (NSA) site during the month of October in 2004. We have chosen this site and period for the following reasons. The Department of Energy Atmospheric Radiation Measurement Program (DOE ARM) has a large research infrastructure, with excellent remote-sensing sites at Barrow and Atqasuk (See Figure 2). Furthermore, Barrow's cloudiness peaks during the month of October (Dissing and Wendler 1998) and, as analysis of the ARM radar and ceilometer data shows, much of this cloudiness is low-level stratus. Examination of the ARM radar and ceilometer data suggests that most of these low-level stratus clouds, which precipitate snow continuously, are mixed-phase in their upper regions Intrieri et al. 2002). Moreover, both the SHEBA and ARM observations reveal that these precipitating mixed-phase clouds persist for days on end. Such observations suggest that there has to be large-scale moisture convergence and/or surface moisture flux to compensate for the precipitation flux. The two ARM sites will be supplemented with a well-equipped remote-sensing ground site at Oliktok Point and a radiosonde station at Toolik Lake in the interior south of Oliktok Point. This configuration of four radiosonde sites will allow calculation of large-scale moisture fluxes into the polygon.

Figure 2. Experimental layout. The two ARM sites are located at Barrow and Atqasuk; the two supplemental sites will be at Oliktok Point and the NSF Toolik Lake Field Station.

The objectives of the experiment can only be met if high-quality in situ data is collected in concert with the remotely sensed data. This requires a research aircraft well-equipped for cloud physics measurements to provide flight-level in situ measurements over the ground sites and also to document the spatial variability between the ground stations. Table 1 lists the research facilities anticipated to participate in the experiment. These facilities are described in more detail in the remainder of this section.

Table 1. Major facilities to be deployed during M-PACE.

	Facility PI	Location
DOE ARM Climate Research facilities at Barrow and Atqasuk		Barrow and Atqasuk
U. of North Dakota Citation (in situ aircraft)	Verlinde (PSU)	Prudhoe Bay
DOE-UAV Program Proteus (remote-sensing aircraft)	McFarquhar (U. of Illinois)	Fairbanks
U. of Alaska, Fairbanks depolarization lidar	Sassen (UAF)	Barrow
PNNL Atmospheric Remote Sensing Laboratory	Mather (PNNL)	Oliktok Point
ARM rapid-scan AERI	Turner (PNNL)	Oliktok Point
Aerosonde	Curry/Pinto	Barrow

2.0 DOE ARM Site Instrumentation

The following is a listing of all the ARM instruments at Barrow and Atqasuk (note that the indicated instruments are not available at Atqasuk):

- Atmospheric Profiling
  - Radiosonde system (Barrow only)
  - Microwave radiometer
  - 915-MHz radar wind profiler and radio acoustic sounding system (Barrow only)
- Clouds
  - Vaisala ceilometer
  - Millimeter-wavelength cloud radar (Barrow only)
  - Micropulse lidar
  - Microwave radiometer
  - Whole-sky imager
- Radiometers
  - Atmospheric emitted radiance interferometer: Extended-range (Barrow only)
  - Cimel sun photometer
  - Infrared thermometer
  - Multifilter rotating shadowband radiometer (MFRSR)-related instruments
    - Multifilter radiometer
    - MFRSR
    - Normal incidence multifilter radiometer
  - Broadband instruments
    - Pyranometers
    - Pyrgeometers
    - Pyrheliometers
    - Ultraviolet-B radiometer
  - Radiometric instrument systems
    - Upwelling radiation
    - Downwelling radiation
- Surface meteorology – 40-meter tower

2.1 Oliktok Point Instrumentation

PNNL Atmospheric Remote Sensing Laboratory (PARSL)

- Atmospheric profiling
  - Radiosonde system
  - Microwave radiometer

- Clouds
  - Vaisala ceilometer
  - Millimeter-wavelength cloud radar (95 GHz)
  - Scanning millimeter-wavelength radar (35 GHz)
  - Dual wavelength scanning lidar
  - Microwave radiometer
  - Total-sky imager

- Radiometers
  - Cimel sun photometer
  - Infrared Thermometer
  - MFRSR
  - Broadband instruments
    - Pyranometers
    - Pyrgeometers
    - Pyrheliometers

- Radiometric instrument systems
  - Upwelling radiation
  - Downwelling radiation

- Surface meteorology

2.2 Aircraft

2.2.1 University of North Dakota Citation

The aircraft needed for this project has to be capable of carrying several chemical/aerosol and remote-sensing measuring devices in addition to the full complement of atmospheric state and microphysical instruments. The scientific objectives require full characterization of the cloud condensation nuclei (CCN) and ice freezing nucleus spectra, as well as the small-scale structure and vertical motions (needed for supersaturation estimation) of the clouds (i.e., as depicted by a millimeter cloud radar). The University of North Dakota (UND) Citation has been selected as the platform. The aircraft will be based at Deadhorse Airport in Prudhoe Bay. The instrumentation to be deployed on this aircraft is listed in Table 2.

Table 2, UND Citation instrumentation for M-PACE.

Instrument	Measurement
Rosemont 102 probe	Temperature
Rosemont 1201F1	Static pressure
Cooled mirror (EG&G)	Dew point
Laser hygrometer	Dew point
Rosemont Iie detector	Supercooled water
CSIRO King probe	Liquid water content
Nevzorov probe	Total water
FSSP 100	Cloud droplet spectrum
PMS 2D-C	Cloud particle imaging
SPEC CPI	Cloud particle imaging
PMS 2D-P or HVPS	Precipitation particle imaging
CCN counter	Cloud condensation nucleus counter
CFDN-IN counter	Ice nucleus counter

2.2.2 The DOE UAV Proteus

The Proteus will operate out of Fairbanks, primarily as a remote-sensing aircraft flying above the low-level clouds. It will, however, be used as an in situ platform for glaciated clouds above the boundary layer. The Proteus instruments package is given in Table 3.

Table 3. Proteus instrumentation for M-PACE.

Instrument	Measurement
Active remote sensing	Millimeter cloud radar (Nadir) Cloud detection lidar (Nadir)
Passive remote sensing	Spectral radiance package Broadband radiometers Solar spectral flux radiometers Scanning high-resolution interferometer
In situ	State parameters Cloud, aerosol and precipitation Spectrometer Cloud-integrating nepholometer Video ice particle sampling Nevzorov probe

2.2.3 Aerosonde

A small, unmanned, aeronautical vehicle, funded by NSF, will also provide observations in support of M-PACE. Potential instruments for the aerosonde are given in Table 4. Due to the limited payload ability of the UAV, not all these can be flown at the same time. This UAV has a proven record in the Arctic.

Table 4. Aerosonde instrumentation for M-PACE.

Instrument	Measurement
Wind-finding technique	Wind components
2 Vaisala RS90 sensors	(P, T, q)
Piezoelectric plate	detect icing
KT11 pyrometer	Surface temperature down to -40 C
Olympus digital camera	Surface conditions
GPS	Location and altitude
HHPC-6 large particle counter	Aerosol concentrations
Video ice particle sampler	Ice particle images

2.3 Depolarization Lidar (Barrow)

The polarization diversity lidar (PD; see Table 5 for specifications) was developed as a testbed for polarization lidar techniques within the initial instrument development phase of the ARM program (Sassen 1994). This versatile dual-wavelength, high-resolution (1.5-m), scanning lidar system is still state of the art. The lidar table is also equipped with a proven X-band safety radar system that interrupts the laser if aircraft approach within 5 degrees of the laser beam. The polarization lidar technique is a power tool for inferring the phase and shape of hydrometeors (Sassen 1991): it is the only remote-sensing technique able to unambiguously identify cloud thermodynamic phase. The PDL measures backscatter depolarization at both laser wavelengths, which is particularly useful in identifying aerosol type.

Table 5. Two-color polarization diversity lidar (PDL) system: Current specifications.

Operational	
Wavelength (Nd:YAG)	0.532 + 1.06 um (simultaneous)
Peak energy	0.35 J each color
Maximum PRF	10 Hz
Pulse width	9 ns
Beam widths - Transmitter - Receiver	0.5 mrad 0.2-3.8 mrad high-speed shutter
Receiver diameter	30 cm (2 telescopes)
Detectors - visible	2, Gated PMTs
IR	2, SAPDs
Maximum scan rate	5.0*s -1

Data Handling	
Number of channels	4 (simultaneous)
Sample width (resolution)	1.5 m maximum
Range gates	8 k maximum
Pulses averaged	1 – 10
Maximum throughput	164 k samples/second
Digitizer resolution	8 bits
Storage	8 mm tape
Polarization Properties	
Transmitted	Vert. (Vis) + Horiz. (IR)
Received	Vert. + Horiz. (Vis. + IR)
Additional equipment: a. Camcorder camera b. X-band safety laser-shutdown radar	

Funding has been obtained from DOE to station the PDL at the North Slope of Alaska ARM site for an extended period, so that periodic mini-field campaigns can be conducted throughout the year under changing Arctic weather conditions. Special attention will be given to cirrus and mixed-phase clouds, cloudless precipitation that develops from open leads in the nearby Arctic Ocean, and the exotic aerosols ranging from Arctic haze to Asian dust storm particles.

Before barging the lidar van up to Barrow in the summer of 2004, the PDL will be improved through the addition of a nitrogen Raman receiver channel under support from the National Science Foundation. Raman lidar technology permits the direct determination of the extinction coefficients produced by aerosols and clouds, and so is an important supplement to the normal elastic, or Mie, lidar research capabilities.

3.0 Flight Plans for M-PACE

The objectives of the field experiment will be to collect data of:

1. Horizontal structure and variability of the cloud microphysics and dynamics.
2. Vertical profiles of microphysics, particularly over the ground-based remote-sensing sites.
3. Coincident radiance/irradiance data above/below cloud layers with in situ microphysical data.
4. Impacts of multiple cloud layers on cloud characteristics and measurements.
5. Impacts of variable surface characteristics on cloud properties.
6. Scattering-phase function of different types of clouds.
7. Water vapor profiles in cloudy and clear condition.
8. Clear-sky emissivity.
9. Atmospheric structure at corners of grid box during cloudy events.

3.1 Experiment #1: Persistent Boundary-Layer Cloud – Legs between Oliktok Point and Barrow

Situation: Single-layer cloud (either mixed-, or liquid-phase) in boundary layer deeper than 1 km with maximum thickness estimated to be 2 km (see radar image below).

Science objectives: Almost all of the objectives of M-PACE (dynamic structure, microphysical variability, impacts on radiative fluxes).

UND Strategy: Series of flight legs to measure structure of boundary-layer cloud.

i. Porpoise from above cloud to as close to ground as possible to sample the horizontal and vertical variability (descent about 5 m/s, will give us about 5 up and downs in 260 km between Oliktok Point and Barrow or vice versa), flight scientist will note approximate altitudes of liquid and ice layers in cloud.

ii. Fly at middle of uppermost layer anticipated to be liquid from Barrow to Oliktok Point.

iii. Fly at middle of uppermost layer anticipated to be ice (below liquid layer) from Oliktok Point to Barrow.

iv. Fly another porpoising leg to assess how structure might have changed from Barrow to Oliktok Point.

v. When possible, fly leg above boundary-layer cloud to measure IN from either Barrow or Oliktok Point.

NOTE: This will most likely be connected with Experiment #6, so that spirals over Barrow and Oliktok Point will also be made to better determine vertical structure and evaluate ground-based remote-sensing retrievals.

NOTE: For particularly good days, we can refuel at Barrow or Deadhorse and continue flight tracks

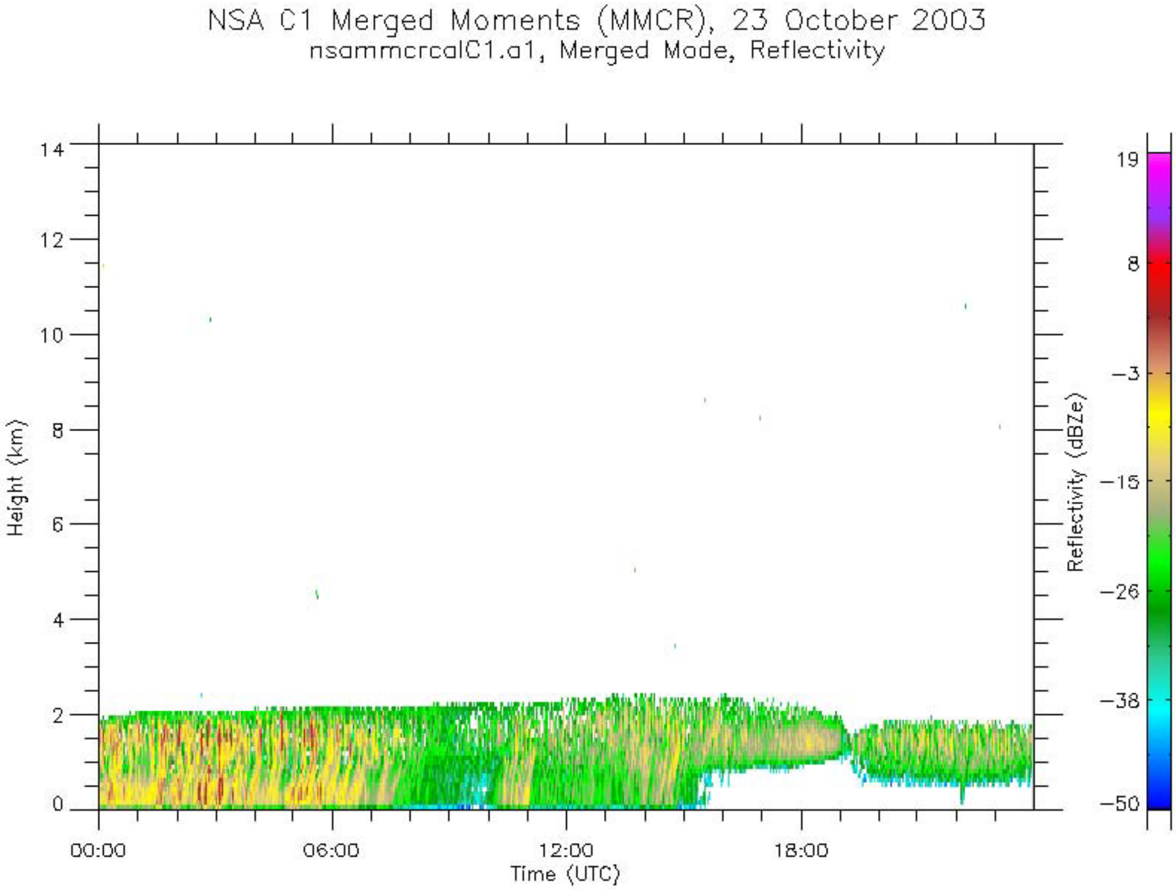

Figure 3. MMCR reflectivity profile of clouds meeting Experiment #1-type conditions. Note this case has a double cloud layer in the lower two kilometers.

Proteus Strategy:

i. Straight legs over boundary-layer cloud at least as high as dead zones of active remote sensors; go down as close as possible to clouds while allowing comfortable separation from Citation on porpoising legs

NOTE: This may be connected to Experiment #5, which involves remote measurements of scattering-phase function and to Experiment #9, which is figure 8 flight tracks over Barrow/Oliktok Point to evaluate AERI upwelling radiance measurements

3.2 Experiment #2: Boundary-Layer Cloud Overlay by Cirrus or Ice Virga with Clear Space in between – Legs between Oliktok Point and Barrow

Situation: Boundary-layer cloud (either mixed or liquid phase) probably between 1 and 2 km thick with a cirrus or ice virga cloud above (assuming there is clear space in between the two).

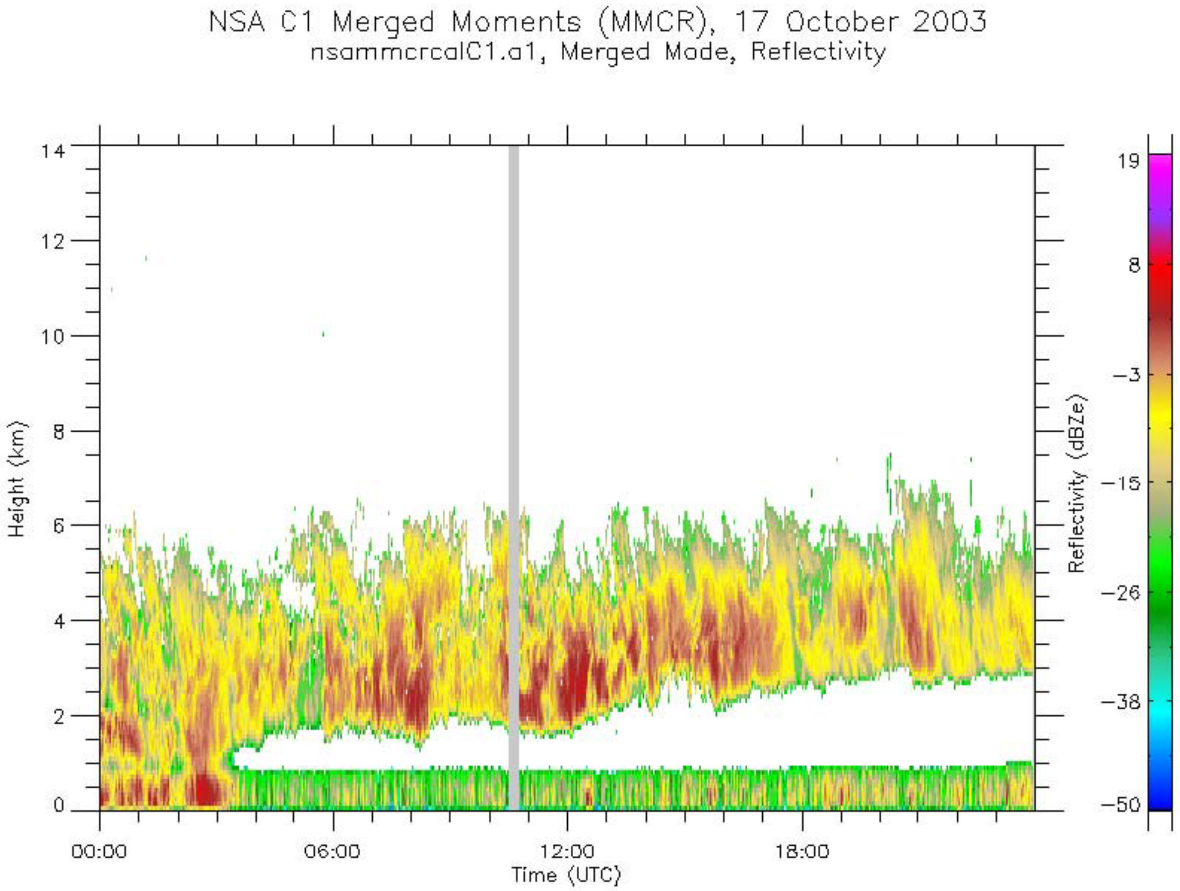

Figure 4. MMCR reflectivity profiles of clouds meeting Experiment #2-type conditions. There is a steady stratus layer in the boundary layer overlaid by a persistent cirrus layer. The two cloud layers are separated by hydrometeor-free air.

Science Objectives: Almost all of the M-PACE objectives (dynamic structure, microphysical variability, impacts on radiative fluxes).

General Strategy: On take-off, UND spirals over Oliktok Point advecting with the wind, from as close to ground as possible all the way to the top of the cirrus/ice virga cloud (note in particular any observations of supercooled liquid in cirrus layers because will affect Proteus & UND sampling strategy). We envision two distinct scenarios: the upper cloud deck being either glaciated or mixed-phase.

Upper Layer Glaciated

UND Strategy:

i. Follow strategy for Experiment #1.

Proteus Strategy:

i. Proteus flies the first leg above the cirrus at an altitude as close as possible to the tops of the cirrus such that radar and lidar have full coverage of cloud.

ii. Spiral for 20 minutes (descent speed set by the thickness of the cirrus) through the cirrus to the base of the cirrus at Barrow.

iii. Fly leg between cirrus and boundary-layer cloud (may go through virga) to Oliktok Point.

iv. Porpoise from Oliktok Point to Barrow at speed that we get about 10 cycles in the 260 km between these points (or fewer cycles if clouds are too thick).

v. Repeat as needed/possible (especially if UND refuels).

Upper Layer Has Significant Liquid Water

UND Strategy:

i. After the initial spiral, porpoise through the upper-level cirrus.

ii. On return leg, porpoise through boundary-layer cloud, flight scientist again noting regions where liquid and ice tend to dominate.

iii. Liquid cloud leg as in Experiment #1.

iv. Ice cloud leg as in Experiment #1.

v. Porpoise through boundary-layer cloud.

NOTE: Anticipate rapid refueling to continue these observations for good cloud conditions

Proteus Strategy:

i. As for Glaciated Cloud, except no porpoising and spiral speed to be determined by safety considerations (i.e., pilot can fly as fast as he feels needed).

3.3 Experiment #3: Gradient Flights – Legs Perpendicular to Coast

Situation: Single-layer cloud (either mixed or liquid phase) in boundary layer deeper than 1 km with maximum thickness estimated to be 2 km (Experiment #1 type) or boundary-layer cloud (either mixed-, or liquid-phase) probably between 1 and 2 km thick with a cirrus or ice virga cloud above (Experiment #2 type).

Science Objectives: Study impact of CCN/IN populations and underlying surface characteristics on cloud properties.

General Strategy: Both aircraft same as experiments #1 and #2, except that rather than flying between Barrow and Oliktok Point, flights will be made perpendicular to the coast so that data can be collected to investigate relationships between IN, cloud properties, and varying surface conditions (open ice, frozen ice, and snow-covered surfaces and also gradients in aerosols that are produced from pollution sources in northern Alaska). Legs start well offshore and continue at least 150 km inland.

3.4 Experiment #4: Satellite Evaluation – Legs under-Flying Satellite Path

Situation: Under-fly Atmospheric Infrared Sounder Satellite in NASA A-train.

Science Objectives: Provide data to evaluate techniques for distinguishing clouds from ice in the Arctic.

General Strategy: Flight tracks similar to Experiment #3.

UND Strategy:

i. Fly porpoising maneuvers to get idea of vertical variability of cloud properties that will be helpful for producing satellite retrieval algorithms.

Proteus Strategy:

i. For HY-VIS, Proteus needs to under-fly AIRS (Atmospheric Infrared Sounder) on NASA A-train orbit on Aqua and Tropospheric Emission Spectrometer (TES) on Aura to validate high-spectral-resolution IR instruments in orbit and to refine techniques for distinguishing clouds from ice in the Arctic (S-HIS and AIRS made such a comparison during SGP in Arctic).

ii. Need straight line leg parallel to satellite sub-track, timed to coincide with the overpass (select an orbit with nearby sub-track and with uniform atmospheric/surface conditions).

3.5 Experiment #5: Observations of Scattering-Phase Function (Proteus) – At Surface Sites

Situation: Persistent cloud deck. Can be combined with any other cloudy condition experiment.

Science Objectives: Direct measurements of scattering-phase functions for different cloud conditions.

General Strategy: Exclusive Proteus objective. Can be done while waiting to coordinate leg with UND, or after UND returned to base.

Proteus strategy:

> i. Fly in banked orbit (50°) so that can make direct observations of the scattering phase functions above cloud.

3.6 Experiment #6: Surface-Based Remote-Sensing Evaluation – At Surface Sites

Situation: Persistent cloud deck. Done combined with all other cloudy condition experiments whenever the aircraft are over surface-base remote-sensing sites.

Science Objectives: Provide data for evaluation of remote-sensing retrieval techniques.

General Strategy: This will be done for all periods of flight legs when aircraft are at the locations of the ground-based sites.

UND Strategy:

> i. Preferably ascending spirals, advecting with wind, starting at location of ground-based site through the depth of cloud so that we do not sample our own contrail.

Proteus Strategy:

> i. When initial spiral from UND identifies no significant liquid water in upper-level cloud, Proteus will spiral through the upper-level cloud and UND would only spiral through lower-level cloud.

NOTE: both aircraft will either ascend (preferably) or descend so that aircraft can maintain a safe separation distance.

3.7 Experiment #7: Clear-Sky Emissivity Sampling (Proteus) – At Surface Sites

Situation: Clear-sky conditions.

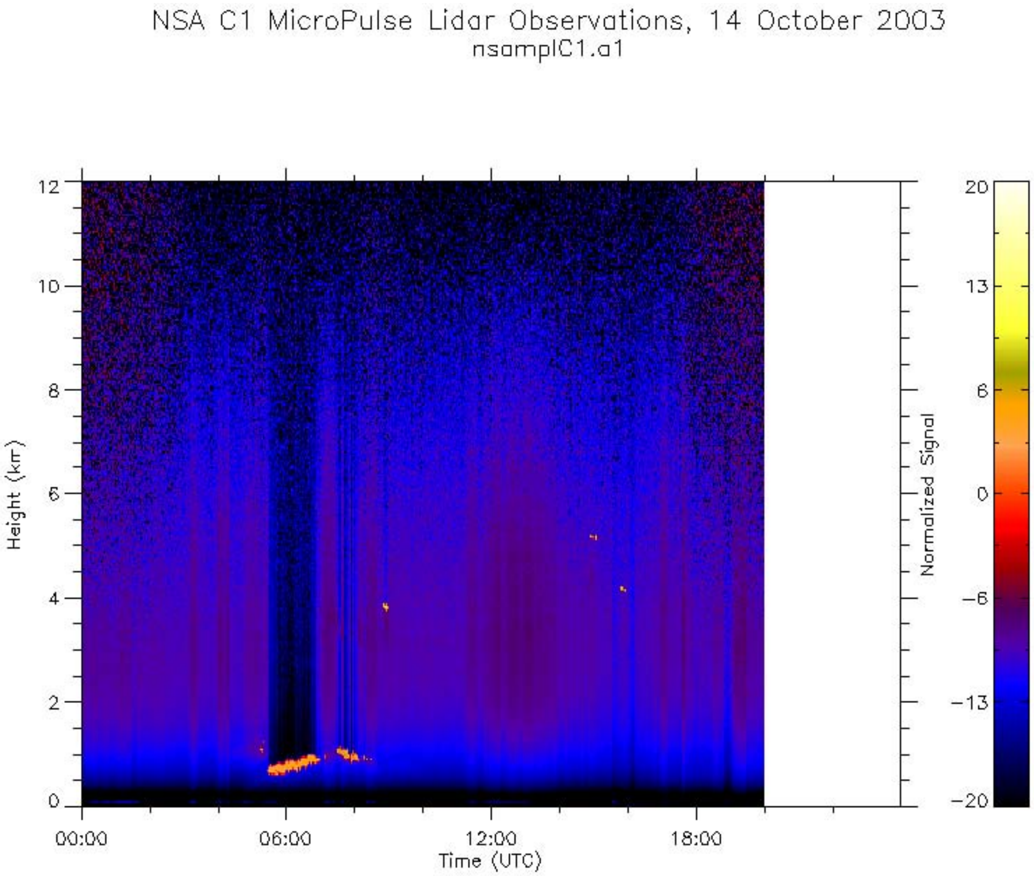

Figure 5. MPL profiles for a day with mostly clear-sky conditions at Barrow.

Science Objectives:

i. Provide high-quality data of surface emissivity from S-HIS to add in satellite-based IR retrievals, looking at small-scale variability in emissivity; camera on board Proteus will help determine surface conditions from these images.

ii. Provide high-quality data to examine origin of small difference in downwelling IR emission observed by AERI and predicted by calculations, which might be due to AERI or due to unaccounted absorber in the atmosphere.

General Strategy: Only the Proteus will fly.

Proteus Strategy:

i. Objective i: Proteus flies between Oliktok Point and Barrow with S-HIS looking down, scanning across track.

ii. Objective ii: Proteus flies stair-step pattern with S-HIS looking up, first level as close to ground as possible, then moving progressively upward so we can compare downwelling radiance observed by S-HIS with calculations at these altitudes to see where this absorption is located

3.8 Experiment #8: Water Vapor Verification Vertical Profiles (Proteus) – At Surface Sites

Situation: Clear skies.

Science Objectives: Provide data for evaluation of HYVIS water vapor.

General Strategy: Flights to be done when not seriously impacting other M-PACE objectives.

Proteus Strategy:

i. Proteus flies stair-step pattern with S-HIS looking up, first level as close to ground as possible, then moving progressively upward so we can compare downwelling radiance observed by S-HIS with calculations at these altitudes to see where this absorption is located.

3.9 Experiment #9: Evaluate AERI Radiances over Boundary-Layer Clouds – At Surface Sites

Situation: Persistent boundary-layer cloud deck with or without cirrus/ice virga cloud above.

Science Objectives: Evaluate AERI radiances over boundary-layer clouds.

General Strategy: This will be done for some flight legs when aircraft are at the ground-based sites.

UND Strategy:

i. Preferably ascending spirals, advecting with wind, starting at location of ground-based site through the depth of cloud so that we do not sample our own contrail.

Proteus Strategy:

i. Fly Figure 8 patterns (fairly large patterns in order to get the statistical sampling of the variabilities) to sample radiance above the upper-level cloud and between cloud layers when more than one cloud layer exists.

3.10 Experiment #10: Persistent Thick Cloud – Legs between Oliktok Point and Barrow

Situation: Boundary-layer cloud and cloud above with no significant reflectivity gap between the cloud layers.

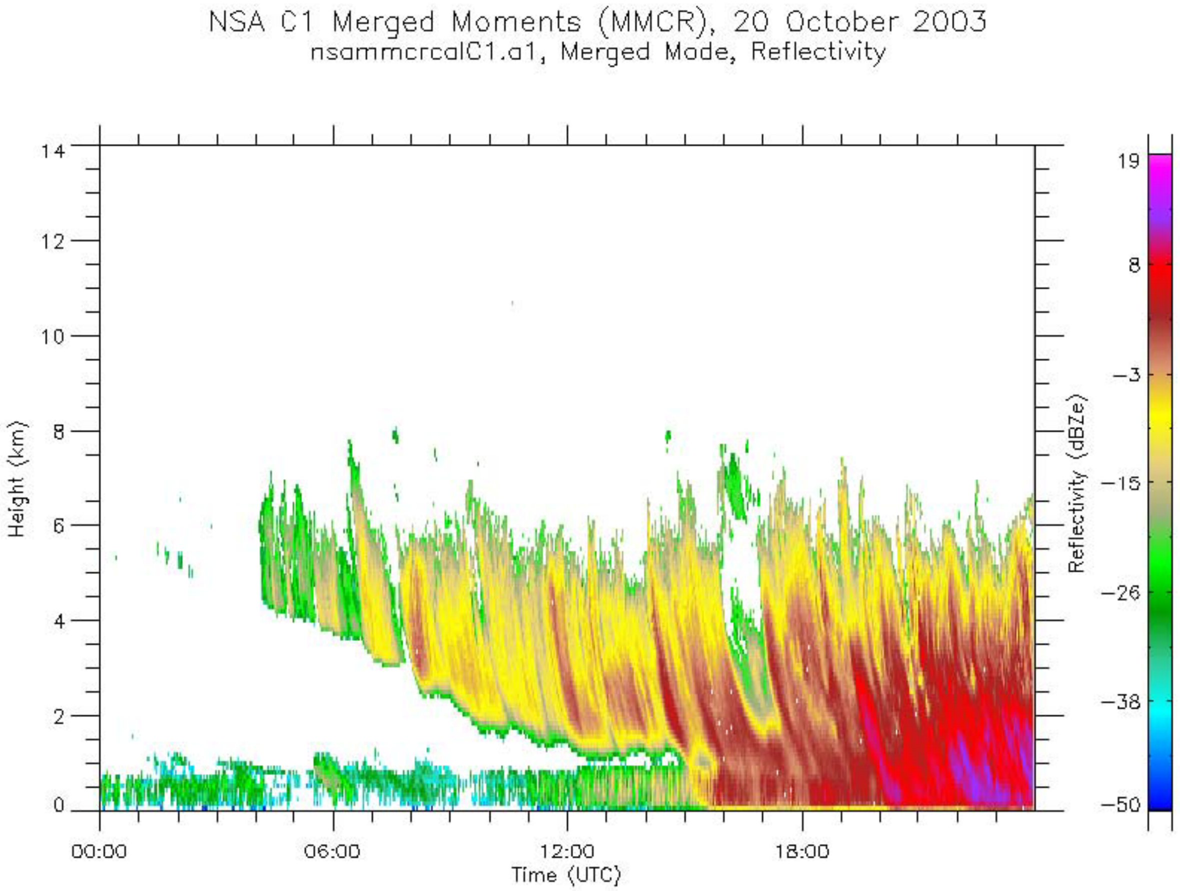

Figure 6. MMCR reflectivity profiles of clouds meeting Experiment #10 type conditions. There is a steady stratus layer in the boundary layer overlaid by a persistent cirrus layer. The two cloud layers merge together later in the day to meet the experimental conditions.

Science objectives: Almost all of the objectives of M-PACE (dynamic structure, microphysical variability, impacts on radiative fluxes).

General Strategy: UND spirals up from Oliktok Point advecting with the wind, making notes of whether significant amounts of liquid water are present in the upper-layer clouds.

Upper-Layer Glaciated

UND Strategy:

i. Porpoises for the remainder of the cloud leg.

ii. Return near the top of the identified lower-level cloud from observations of level where we suspect there may be liquid water (based on observations on spiral on way up).

iii. Flies below the level where we suspected liquid (and in areas where we suspect ice).

iv. Porpoises through what we have identified as the lower-layer cloud.

Proteus Strategy:

i. First leg is at the minimum height above the cirrus layer.

ii. Porpoise through the upper-level cloud.

iii. Repeat steps i) and ii).

Upper-Cloud Layers Mixed-Phase

UND Strategy:

i. Porpoises for the remainder of the cloud leg.

ii. Return near the top of the identified top-most level where we identified liquid water in the spiral on the way up.

iii. Flies below the top-most liquid water level in areas where we expect ice.

iv. Return in the next-to-top-most level where we identified liquid water in the spiral on the way up.

Proteus Strategy:

i. Fly the first leg above the cirrus at an altitude as close as possible to the tops of the cirrus such that radar and lidar have full coverage of cloud.

ii. Fly in banked orbit (50°) so can make direct observations of the scattering-phase functions above cloud.

iii. Fly figure 8 patterns (fairly large patterns in order to get the statistical sampling of the variabilities) to sample radiance above the upper-level cloud and between cloud layers when more than one cloud layer exists.

iv. Alternate between ii) and iii).

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