# A FIRE on the Ice:
# The FIRE Phase III Arctic Implementation Plan

*Drafting Panel:*

Chris Bretherton
Judith Curry
Chris Fairall
James Hudson
George Isaac
Donald Lenschow
Michael King
Steven Krueger
David Randall (Chair)
William Rossow
Bruce Wielicki

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## Executive Summary

FIRE, the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment, has conducted four successful field missions in support of a program of research that includes remote sensing and modeling studies of clouds and radiation as they relate to climate.

FIRE is now preparing to go to the Arctic in order to study a variety of Arctic cloud systems under spring, summer, and possibly autumn conditions. At the same time, analysis of previously collected FIRE data will continue. The primary motivations for the Arctic phase of FIRE are:

- Arctic boundary-layer clouds are poorly simulated by current climate models;
- the physical processes at work in the Arctic cloudy boundary layer are poorly understood;
- Satellite remote sensing algorithms currently cannot accurately retrieve Arctic surface and cloud characteristics.

FIRE's Arctic field program will strongly interact with both Surface Heat Budget of the Arctic (SHEBA) (primarily sponsored by National Science Foundation (NSF) and Office of Naval Research (ONR)) and Atmospheric Radiation Measurements (ARM) (sponsored by Department of Energy (DOE)). SHEBA will provide an ice station which will (it appears) be built around an ice breaker. ARM will provide some of the instruments to be deployed at the SHEBA ice station. Both SHEBA and ARM also include modeling components. FIRE's role is to provide aircraft and satellite-based measurements, along with further modeling studies.

The aim of the FIRE III field experiment is to produce an integrated data set that:

(1) supports the analysis and interpretation of physical processes that couple clouds, radiation, chemistry, and the atmospheric boundary layer;

(2) provides in situ data for testing of satellite and ground-based remote sensing analyses; and

(3) provides initial data, boundary conditions, forcing functions, and test data to support Arctic FIRE modeling efforts.

FIRE's strategy is to use aircraft to take in situ and remote measurements of the Arctic cloud and surface characteristics. The aircraft observations will be supplemented by surface measurements provided by SHEBA and ARM. In addition, FIRE will provide studies based on satellite remote sensing, and will also use in situ data to evaluate these remote sensing techniques.

The interrelationships among FIRE, SHEBA, and ARM are summarized below:

**What ARM provides for FIRE:** high quality surface radiation measurements.

**What SHEBA provides for FIRE:** time series of surface-based observations of atmospheric vertical structure (including cloud structure) and description of the sea ice surface over a region of 100 km surrounding the SHEBA ice station.

**What FIRE provides for ARM and SHEBA:** satellite analysis of cloud characteristics; technology, observations and analysis of aircraft data; improved parameterizations of Arctic cloudy boundary layer process.

The winter clouds are believed to consist of lower tropospheric ice crystals, which lead to radiative fluxes to be 10 - 40 W m-*2* greater than expected for clear sky conditions. Many of these ice clouds may be produced by moist convective plumes associated with leads in the ice. Arctic summertime stratus are often observed to form in multiple layers in the lowest kilometer of the atmosphere. Key scientific issues relating to Arctic clouds are as follows:

- What is the influence of leads and other open water on cloud properties when there is a large surface temperature contrast with the ice?
- How does the extreme static stability and low atmospheric water vapor content of the Arctic lower troposphere, particularly during winter, affect the flow energy across the air-sea interface?
- What is the mechanism that leads to the spectacular multiple-layering of Arctic Ocean summer cloud systems?
- How does the transition of low clouds from liquid to crystalline depend on temperature and aerosol characteristics, and how does the springtime transition differ from the autumnal transition?
- Does the formation of “diamond dust” differ in polluted vs. unpolluted atmospheres?

The highly-reflecting snow/ice surface of the Arctic ocean strongly affects the transfer of shortwave radiation. Clouds alter the distribution of the solar flux between direct and diffuse components, which is important because the penetration of shortwave radiation into the sea ice depends on the ratio of diffuse to direct radiation. A peculiarity of the polar regions is the dominance of large solar zenith angles for solar illumination, especially in the spring and fall seasons. Because the central Arctic spends a greater portion of the year with little or no solar illumination, longwave radiation plays a particularly important role in the surface energy balance. The longwave opacity of the Arctic atmosphere is so low that the appearance of clouds significantly increases the emission by the atmosphere of longwave radiation both downwards to the surface and upwards to space, even though Arctic clouds have longwave emissivities significantly less than unity. Arctic stratus often form in the warmest, most humid layer, so that the downward longwave flux in winter can be larger than the upward flux from the sea ice. Key scientific issues related to Arctic radiation are as follows:

- What is the spectral distribution of longwave radiation and in particular what is the role of the 20 mm “rotation-band window” region in regulating the surface and atmospheric temperature in the Arctic?
- What are the effects of springtime “Arctic haze” on the absorption of solar radiation in polar clouds?
- How do the reflectance and transmittance of the clouds and the surface depend on the low solar zenith angles typical of the Arctic?
- What is the role of “clear-sky” ice crystal precipitation in determining the longwave radiation fluxes?
- What are the shortwave radiative effects of the horizontally inhomogeneous stratocumulus clouds over the horizontally inhomogeneous, highly-reflecting snow/ice surface?
- How do the optical properties of the Arctic surface vary in response to changes in snow characteristics (thickness, age, temperature, contamination), thinning of the ice, and melt pond formation?

Aerosols can strongly regulate the optical properties of the Arctic clouds and even have the potential to influence the macrostructure of the Arctic boundary layer, including the depth and vigor of the turbulence that vertically transports energy and moisture. Key questions regarding the chemistry of the Arctic atmosphere are as follows:

- What are the actual supersaturations at which various cloud condensation nuclei (CCN) are activated?
- What is the shape of the CCN spectrum?
- Which particles are actually incorporated into droplets?
- What are the sizes of the CCN?
- What is the chemical composition of the CCN? Are organics important?
- How do the CCN distributions interact with the cloud droplet distributions?
- What is the nature of the ice forming nuclei (IFN)?

# 1.0 Introduction

## *1.1 A FIRE on the ice*

FIRE, the First ISCCP (International Satellite Cloud Climatology Project) Regional Experiment, has conducted four successful field missions in support of a program of research that includes remote sensing and modeling studies of clouds and radiation as they relate to climate. The field programs included cirrus studies in Wisconsin and Kansas, a stratocumulus study off the coast of California, and a stratocumulus transition experiment in the subtropical north Atlantic. A review of the first ten years of FIRE has been written by Randall et al. (1995).

As described in the FIRE Phase III Science Plan, FIRE is now preparing to go back to the field. The next mission will be in the Arctic, where we will study a variety of Arctic cloud systems under spring and summer conditions. The scientific goals and motivations of our work are discussed only briefly here, because they have already been spelled out in detail in the Science Plan. The primary motivations are:

- Arctic boundary-layer clouds are poorly simulated by current climate models;
- the physical processes at work in the Arctic cloudy boundary layer are poorly understood;
- Satellite remote sensing algorithms currently cannot accurately retrieve Arctic surface and cloud characteristics.

The present document is the “Implementation Plan” for the upcoming Arctic phase of FIRE. The purpose of the Implementation Plan is to explain many of the particulars of how we will conduct our collective research, with a moderate degree of detail.

The following subsection gives a discussion of how Phase III of FIRE will maintain continuity with earlier FIRE research, with emphasis on the boundary-layer cloud components of FIRE. Next, we briefly summarize the scientific objectives of Arctic FIRE, as spelled out in the Science Plan.

## *1.2 Connections to previous FIRE research*

FIRE in the Arctic will build upon the knowledge, instrumentation and many interdisciplinary collaborations fostered by the earlier phases of FIRE, but in several ways represents an exciting new philosophical thrust.

Previous FIRE boundary layer field campaigns documented the cloud-radiation-sea surface interactions that are responsible for the areal extent and optical properties of subtropical stratocumulus clouds, and led to major advances in remote sensing algorithms for cloud properties. They led to an appreciation of the relation of boundary layer cloud amount, cloud radiative properties and boundary layer thermodynamic structure to dynamic forcing, the properties of the surface and overlying air, the diurnal cycle of solar radiation, and the concentration and size distribution of aerosol. These insights are being incorporated in many GCM parameterizations.

The previous FIRE research efforts also produced highly integrated data sets, in which local and remote sensing observations from surface sites, aircraft and satellite data, and large scale and regional scale analysis from forecast models are blended. This type of study requires close collaboration between multiple investigators and requires several years to bring fully to fruition. Continuing studies based on the FIRE I and Atlantic Stratocumulus Transition Experiment (ASTEX) data are currently yielding important insights on the fundamental mechanisms of subtropical stratocumulus to trade cumulus transition, cloud/aerosol/drizzle/radiation feedbacks, and mesoscale variability of stratocumulus clouds. FIRE investigators are continuing to work with climate and forecast modelling groups to develop new or more refined parameterizations of marine cloud topped boundary layers.

The Arctic activities of FIRE will continue these traditions. Further analysis and modelling based on earlier datasets will remain a crucial component of the project, as these activities provide some of the most important scientific payoffs to the larger climate community. They will continue in parallel with the Arctic cloud experiment. Continuity of personnel, instrumentation, and goals from FIRE I and II will allow efficient comparison of Arctic cloud systems with their subtropical counterparts. The summertime Arctic cloud-topped boundary layer shares many important characteristics with subtropical stratocumulus. To name just a few, cloud-radiative interactions (as opposed to synoptic-scale lifting) are crucial in maintaining the observed structure, the boundary layer is often observed to be decoupled into dynamically separate layers, cloud radiative/microphysical/aerosol interactions are thought to be very important, and there are strong feedbacks between the boundary layer structure and the nature of the underlying surface.

A continued emphasis on platform integration, synthesis and interdisciplinary collaboration in Arctic FIRE will also increase its effectiveness and distinguish it from previous studies of Arctic clouds. FIRE investigators have achieved increasing skill in this kind of synthesis during FIRE I and ASTEX. However, the Arctic FIRE Arctic cloud experiment will coordinate with related investigations much more closely than in previous FIRE campaigns. The Arctic FIRE Arctic cloud experiment will rely heavily on another related experiment, SHEBA. SHEBA will measure surface fluxes and advanced ground-based remote sensing instrumentation for clouds, radiation, and thermodynamic structure at a site on the sea ice for a year. This provides an invaluable context for the periods during which FIRE will obtain in-situ cloud measurements. FIRE investigators will coordinate data collection and analysis extremely closely with SHEBA, maximizing the ability of the two groups of scientists to gain from each others insights and measurements. Past experiments have documented the coupling of clouds, thermodynamics and turbulence from aircraft (Arctic Ice Dynamics Joint Experiment (AIDJEX), the Arctic Stratus Experiment, Beaufort Arctic Storms Experiment (BASE)), documented the interactions of microphysics, aerosols and radiation Arctic Radiation Measurement in Column Atmosphere Surface System/Cloud, Aerosol, and Radiation Arctic Field Experiment (ARMCAS/CARAFE), or taken extended time surface observations. However, no experiment has integrated all three of these with measurements of the evolution of the underlying snow/ice surface and analyses of the synoptic-scale atmospheric structure. Arctic FIRE and SHEBA plan to do this and thereby simultaneously provide all the information necessary to test the suite of physical parameterizations that determine the climatological predictions of general circulation models (GCM) for the Arctic. Close collaborations with the ARM North Slope site in Barrow and a Canadian hydrological experiment in the MacKenzie river basin, CAGES, are also anticipated, providing a yet broader spectrum of measurements to FIRE investigators. The Arctic cloud experiment and SHEBA should both benefit from FIRE experience with arranging real time assimilation of data into operational numerical weather prediction centers, such as was successfully carried out in ASTEX.

The Arctic cloud experiment broadens the scope of earlier FIRE boundary layer cloud campaigns by introducing several new challenges in measurement, modelling and interpretation. These include strong inhomogeneity of the underlying surface, mixed phase clouds, sampling clouds above the boundary layer, and difficulty in the satellite detection of clouds over a bright and nonuniform surface. A successful attack on these complications must be grounded in an understanding of fundamental feedbacks in and measurement strategies for cloud-topped boundary layers. The strategies of the Arctic cloud experiment are therefore strongly rooted in successful experiences and collaborations from earlier FIRE campaigns.

### 1.3 Summary of scientific objectives

#### 1.3.1 Clouds

Satellite estimates of wintertime cloud cover are somewhat greater than the surface values (e.g. Curry et al. 1996). These winter clouds are believed to consist of lower tropospheric ice crystals, which lead to radiative fluxes to be 10 - 40 W m-*2* greater than expected for clear sky conditions. Many of these ice clouds may be produced by moist convective plumes associated with leads in the ice. Ice crystal precipitation may contribute to snow accumulation in the Arctic. The ice clouds persist into the spring, so that they do interact with solar radiation. Measurements of particle size, habit, and the associated phase functions for solar radiation are needed so that we can understand the effects of these ice clouds. We also need to understand the effects of springtime Arctic haze on the absorption of solar radiation in polar clouds. For this purpose, we will need multispectral and multi-angle observations in the diffusion regime within the cloud, allowing determination of the single scatter albedo at both multiple wavelengths.

Arctic summertime stratus are often observed to form in multiple layers in the lowest kilometer of the atmosphere (Herman and Goody, 1976). The temperature and moisture soundings are similarly layered, and the temperature of the cloud bases can affect the surface energy balance. In summer, a shallow stably stratified layer with cloud is often observed beneath an upper cloud-capped mixed layer, with little or no turbulent mixing between the layers. The upper cloud layers appear to persist without any turbulent mixing of moisture up from the surface. The models that have been proposed to explain the observed layering have been heavily simplified, especially in their treatment of turbulence. There have been no large-eddy simulations of Arctic stratus to date.

Key scientific issues relating to Arctic clouds are as follows:

- What is the influence of leads and other open water on cloud properties when there is a large surface temperature contrast with the ice?
- How does the extreme static stability and low atmospheric water vapor content of the Arctic lower troposphere, particularly during winter, affect the flow energy across the air-sea interface?
- What is the mechanism that leads to the spectacular multiple-layering of Arctic Ocean summer cloud systems?
- How does the transition of low clouds from liquid to crystalline depend on temperature and aerosol characteristics, and how does the springtime transition differ from the autumnal transition?
- Does the formation of “diamond dust” differ in polluted vs. unpolluted atmospheres?

#### 1.3.2 Radiation

Clouds are the dominant modulators of the Arctic radiation climate. Cloud radiative properties depend on the amount of condensed water, the size and shape of the cloud particles, and the phase of the particles (liquid or ice). Recent studies (e.g. Curry and Ebert 1992) suggest that cloud emissivity is less than unity for all cloud types and during all seasons, that over the course of the year clouds have a net warming effect on the surface, and that the top-of-the-atmosphere cloud radiative forcing is dominated by the shortwave flux.

The highly-reflecting snow/ice surface strongly affects the transfer of shortwave radiation. The surface albedo is modified by meltpond area and depth, lead area, ice thickness and age, snow thickness and age, and the effects of cloud on surface albedo. Clouds alter the distribution of the solar flux between direct and diffuse components, which is important because the penetration of shortwave radiation into the sea ice depends on the ratio of diffuse to direct radiation.

A peculiarity of the polar regions is the dominance of large solar zenith angles for solar illumination, especially in the spring and fall seasons. Studies are needed to examine the accuracy of current radiative models for solar zenith angles beyond about 80 degrees.

Because the central Arctic spends a greater portion of the year with little or no solar illumination, longwave radiation plays a particularly important role in the surface energy balance. The surface emissivity varies between 0.8 and 1.0, depending on snow grain size. The longwave opacity of the Arctic atmosphere is so low that the appearance of clouds significantly increases the emission by the atmosphere of longwave radiation both downwards to the surface and upwards to space. Arctic clouds may generally be optically thin enough that their longwave emissivities are significantly less than unity which will alter their effect on the radiation balance. Moreover, Arctic stratus often form in the warmest, most humid layer, which can lie well above the surface, so that the downward longwave flux in winter could, at times, be larger than the upward flux from the sea ice. Downward surface longwave flux calculations require accurate modeling of water vapor absorption at the low mixing ratios typical of polar conditions.

Key scientific issues related to Arctic radiation are as follows:

- What is the spectral distribution of longwave radiation and in particular what is the role of the 20 mm “rotation-band window” region in regulating the surface and atmospheric temperature in the Arctic?
- What are the effects of springtime “Arctic haze” on the absorption of solar radiation in polar clouds?
- How do the reflectance and transmittance of the clouds and the surface depend on the low solar zenith angles typical of the Arctic?
- What is the role of “clear-sky” ice crystal precipitation in determining the longwave radiation fluxes?
- What are the shortwave radiative effects of the horizontally inhomogeneous stratocumulus clouds over the horizontally inhomogeneous, highly-reflecting snow/ice surface?
- How do the optical properties of the Arctic surface vary in response to changes in snow characteristics (thickness, age, temperature, contamination), thinning of the ice, and melt pond formation?

### *1.3.3 Chemistry*

The concentration and size distribution of cloud droplets (microphysics) depends in part on the preexisting aerosol. To isolate the aerosol effects, we need measurements of cloud condensation nuclei, or CCN. CCN are quite variable in space and time, which causes considerable variability in cloud microphysics (e.g. Hudson and Li 1995), cloud albedo (e.g. Twomey 1977) and precipitation efficiency (Albrecht 1989; Twomey 1991).

Anthropogenic sources make up a large but as yet unknown component of global CCN. This constitutes a significant but as yet unquantified anthropogenic effect on climate (e.g. Kaufman et al. 1991). It has been suggested by Karl et al. (1993) that this effect could be responsible for the asymmetric diurnal warming that has been observed in industrialized regions of the world.

The parameter that characterizes CCN, the critical supersaturation, $Sc$, is related to the number of soluble ions within a particle. CCN are composed of soluble electrolytes, usually salt and often sulfate. CCN provide a conceptual link between atmospheric chemistry and cloud properties. Although the *Sc* is the only aerosol property needed to predict the cloud interactions, the actual chemistry of the CCN must be known in order to understand the sources of CCN, which seem to be highly variable (e.g. Hudson 1993). It is important to distinguish between natural and man-made sources.

CCN measurements are commonly done at only one supersaturation (e.g. 0.3%), which is chosen to represent the clouds under consideration. Much more work needs to be done to correctly determine cloud supersaturations, which appear to be quite variable. Full spectral CCN measurements (e.g. 0.01% to 3%) are needed because of the different supersaturations even within the same clouds due to different updraft velocities. This is especially important in stratus clouds where the updraft velocity is low and comparable to the variability of the updraft velocity. Comparisons should be made between various regimes, e.g. the Arctic with lower latitudes.

Variations among cloud parcels indicate that the shape of the CCN spectrum can also be important in determining cloud microphysics (Martin et al. 1994; Hudson and Svensson 1995). This may be especially true of cloud droplet spectral width, which is important for precipitation. CCN measurements should be made aboard all research aircraft and CCN spectra should be measured when possible. The vertical distribution of CCN is also important to determine whether sources are below or above the clouds. Scavenging of CCN by the cloud droplets through coalescence and Brownian capture is also important for the CCN budget. These processes probably lead to the depletion of CCN in the cloudy boundary layer (Hudson and Frisbie 1991). A more positive identification of which particles actually get incorporated into cloud droplets (i.e. with the counterflow virtual impactor (CVI) Twohy and Hudson (1995) is necessary for a better understanding of CCN-cloud interactions.

The physical size of CCN is important for a number of considerations including atmospheric removal rates both in clouds and in the cloud-free atmosphere. In general particle size distributions are more easily and commonly measured than CCN spectra. Thus the determination of the physical sizes of CCN would be important for relating to other measurements and to understanding the global cycle of CCN. This can be done by passing the particles through an electrostatic classifier, also known as a differential mobility analyzer (DMA), before entering the CCN spectrometer (Hudson and Da 1996). This also offers important clues about particle composition because if the particles are totally soluble then their sizes can be predicted from knowledge of composition and they do not display much variability for most soluble materials such as sulfates. However insoluble material internally mixed with the CCN increases the size of the CCN. This technique can be used as an indirect measurement of CCN composition. Another indirect technique is thermal fractionation or particle volatility. Most volatility measurements indicate that most CCN are sulfate particles (i.e. Twomey 1971). CCN size measurements and volatility measurements by Hudson and Da (1996) indicate systematic differences depending on particle origin where the anthropogenic particles are often internally mixing with insoluble material whereas natural particles may be pure soluble substances.

Direct measurements of particle chemistry are desirable to confirm these indications and to better pin down CCN sources. Important gaseous precursors such as SO2, DMS, O3, OH should be measured. Direct measurements of aerosol composition should also be made but these should be concentrated on the submicrometer size range where CCN exist. Measurements of particulate sulfate and organic material are needed in order to determine whether these are the substances that make CCN. Sulfates certainly act as CCN. Organics are also associated with CCN (Novakov and Penner 1993), but they may just ride along with the CCN. If organics act as CCN themselves, then removal of sulfate from fuels will not necessarily reduce CCN outputs.

Ice particle concentrations also have an analogous dependence on the aerosol with analogous ice forming nuclei (IFN). However this connection is more complex and less well-understood. If valid IFN measurements can be demonstrated they should also form a component of

Arctic FIRE as many of the clouds are composed of ice particles. However, this technology has not yet developed to the stage of routine measurements as is the case for CCN.

The CCN measurements should be compared with cloud microphysical measurements in a comprehensive fashion. It is not enough to merely compare spectra. It is most desirable to compare CCN spectra with cloud droplet spectra within adiabatic cloud parcels, but this requires careful analysis. Comparisons with nonadiabatic parcels may reveal the effects of entrainment and drizzle on cloud microphysics. Trajectory analyses are needed in order to trace source regions of particles. Connections with gaseous precursors are needed to understand production processes. The Arctic spring offers interesting chemistry that can occur between the Arctic haze season and the polar sunrise, which invokes photochemistry. The Arctic haze arises from the long range transport of material into the Arctic. The persistent stratus clouds of the summer present significant cloud scavenging and perhaps large vertical gradients in particle concentrations (Hudson and Frisbie 1991). Analysis of these data should reveal the possible sensitivity of Arctic stratus to anthropogenic CCN and the present and estimated future contributions to Arctic CCN.

In summary, key questions regarding the chemistry of the Arctic atmosphere are as follows:

- What are the actual supersaturations at which various CCN are activated?
- What is the shape of the CCN spectrum?
- Which particles are actually incorporated into droplets?
- What are the sizes of the CCN?
- What is the chemical composition of the CCN? Are organics important?
- How do the CCN distributions interact with the cloud droplet distributions?
- What is the nature of the IFN?

### *1.4 Discussion*

The next section of this document summarizes prior field studies in the Arctic, and explains the main objectives of Arctic FIRE. Section 3 discusses our plans for measurements using surface-based systems, aircraft, and satellite sensors. Section 4 deals with data integration and modeling studies. Section 5 lists concluding remarks. Appendix A and B summarizes the SHEBA and ARM science plans, respectively. Appendix C describes the sampling strategies for satellite intercomparisons. Appendix D lists details of FIRE's organization and data management protocols. Appendix E defines the acronyms. Appendix F lists the abstracts of the FIRE Science Team researchers. Appendix G lists the ARM surface instruments at the ice station and Pt. Barrow. Appendix H outlines the research plans for continuing FIRE-II research. Appendix I lists the references.

## 2.0 General Approach

A multi-faceted strategy is required to achieve the objectives outlined in section 1. The strategy includes three main elements: a field experiment, satellite remote sensing studies, and modeling studies.

### *2.1 Summary of previous Arctic cloud and radiation research*

During the last two decades, several aircraft datasets of relevance to FIRE III have been obtained over the Arctic Ocean: ARMCAS/CARAFE, BASE, Arctic Stratus Experiment, Lead Experiment (LEADEX), and Arctic Gas and Aerosol Sampling Program (AGASP). AGASP consisted of many springtime flights (using many different aircraft) over the Arctic Ocean during the 1980's to measure the Arctic haze pollution aerosol. Unfortunately, most of the aircraft did not make concurrent cloud microphysics and radiation measurements, although some relevant data was obtained from the University of Washington C-131A aircraft (Curry et al. 1990; Meyer et al. 1991).

The Beaufort Arctic Storms Experiment (BASE) is an atmospheric component of the Canadian Global Energy and Water Cycle Experiment (GEWEX) experiment whose focus is the hydrologic balance of the Mackenzie River. The objectives of BASE are to improve understanding of weather systems in the Canadian Arctic, particularly as related to precipitation. The BASE field experiment was conducted during September and October 1994 in the Beaufort Sea, north of the mouth of the Mackenzie River. The principal dataset relevant to FIRE III was obtained using the NCAR C-130Q aircraft; it includes measurements of radiation fluxes, cloud microphysical properties, and high frequency measurements of winds, temperature and humidity. Radiative and microphysical properties of the full range of cloud types occurring during the Beaufort Sea during autumn were sampled: cirrus and altostratus (over ice and over open water); convective clouds over open water; stratus decks over open water; low-level clouds over ice (both liquid and mixed phase); and “sea smoke associated with leads. In addition, oceanographic measurements were obtained to determine temperature and salinity budgets for the Mackenzie Shelf.

The Arctic Stratus Experiment was conducted during June 1980 over the Beaufort Sea. The objectives of this experiment were to concurrently measure cloud microphysical properties with atmospheric radiative fluxes in the boundary layer stratus clouds and to interpret the radiative fluxes in the context of the cloud microphysical properties. In addition to radiation fluxes and cloud microphysical properties, high frequency measurements of winds, temperature and humidity were obtained from the National Center for Atmospheric Research (NCAR) Electra aircraft (see Herman and Curry 1984 for a description of the aircraft instrumentation). Although no in situ surface measurements were made, European Centre for Medium-range Weather Forecasting (ECMWF) analyses and Defense Meteorological Satellite Program (DMSP) visible and infrared satellite images provided the large scale context for the measurements. Using these data, the radiative properties of the clouds were analyzed and modeled (Herman and Curry, 1984; Curry and Herman, 1985; Tsay et al. 1989), the cloud microphysical properties were described (Tsay and Jayaweera, 1984) and interpreted in the context of turbulence and radiative processes (Curry 1986), and the mean and turbulence structure of the cloudy atmospheric boundary layer were analyzed (Curry et al. 1988). This dataset includes several examples of the multiple-layered boundary layer stratus. No surface-based observations were obtained during this experiment.

The Arctic Radiation Measurement in Column Atmosphere-surface System (ARMCAS) and Cloud, Aerosol and Radiation Arctic Field Experiment (CARAFE) was conducted in June 1995, including over the Beaufort Sea. Both the University of Washington C-131A and the NASA ER-2 aircraft participated in the experiment; there were no surface-based observations over the ocean. The objectives of the experiment were to measure the cloud microphysical characteristics and their variabilities, solar absorption of Arctic stratus, aerosol physical properties and optical depth, and to compare in situ with aircraft remote sensing observations.

While a large amount of useful data has been obtained from previous field experiments, and useful technology has been developed and tested, a comprehensive dataset with surface observations has not been obtained using recent technological advances in both ground-based remote sensing and aircraft measurements.

### *2.2 FIRE’s objectives, and cooperation with SHEBA and ARM*

The aim of the FIRE III field experiment is to produce an integrated data set that:

(1) supports the analysis and interpretation of physical processes that couple clouds, radiation, chemistry, and the atmospheric boundary layer;

(2) provides in situ data for testing of satellite and ground-based remote sensing analyses; and

(3) provides initial data, boundary conditions, forcing functions, and test data to support Arctic FIRE modeling efforts.

FIRE's overall strategy is to use aircraft to take in situ and remote measurements of the Arctic cloud and surface characteristics. In addition, FIRE provides detailed analysis of satellite observations. The aircraft and satellite data are supplemented by surface measurements provided by SHEBA and ARM.

SHEBA is a research program designed to document and understand the physical processes that couple the atmosphere, ice, and ocean in the Arctic (funded by NSF and ONR). The central theme of SHEBA emerges from issues related to the surface energy balance, especially the ice-albedo and cloud-radiation climate feedback mechanisms. The essence of SHEBA as a project is to conduct a field experiment at a drifting station on the pack ice of the Arctic Ocean for a year (starting Autumn 1997), in combination with remote sensing and modeling analyses of the entire Arctic Basin. The observational program emphasizes the physical processes associated with interactions among the radiation balance, mass changes of the sea ice, storage and retrieval of energy and salt in the mixed layer of the ocean, and the formation of clouds and their influence on the surface energy balance. The modeling effort aims to improve the parameterizations of crucial air-sea-ice interactive processes in climate models. The primary focus is on processes that determine the ice-albedo feedback and the cloud-radiation feedback. The SHEBA field experiment will begin in Autumn, 1997 and continue for the duration of an annual cycle. The measurements will be staged from and distributed around a research ice-breaker ship located on the surface of a multi-year ice floe in the Beaufort Sea. Scientific and operational considerations suggest that the optimal site for deploying the SHEBA camp is the eastern Beaufort Sea, perhaps in the vicinity of 76°N, 135°W (see Fig. 1). Appendix A gives a summary of the SHEBA Science Plan (available in draft form as this FIRE Arctic Implementation Plan was written).

The ARM program of the U. S. Department of Energy is designed to improve our understanding of radiative transfer and the role of clouds in climate. Its centerpiece is a long-term series of ground-based measurements at several sites, including one in Barrow, Alaska. ARM will contribute radiation hardware to the SHEBA ice station, and will perform analysis of this data. A summary of the relevant parts of ARM Science Plan is given in Appendix B. In addition, ARM funds several PIs to conduct research that is directly relevant to FIRE III, to conduct relevant modeling and data analysis studies dealing with:

- one-dimensional radiative transfer modeling;
- cloudy boundary layer modeling;
- ARCSyM regional climate modeling;
- atmospheric general circulation modeling.

Each of the collaborating programs (FIRE, SHEBA, and ARM) has distinct programmatic elements, but at the same time their goals and efforts support larger goals and objectives related to Arctic climate as described in the SHEBA Science Plan. Close coordination of FIRE III with SHEBA and ARM is accomplished by members of the FIRE Executive Committee and the FIRE Science team being members of key SHEBA and ARM committees. The interrelationships among the three programs are summarized below:

**What ARM provides for FIRE:** high quality surface radiation measurements.

**What SHEBA provides for FIRE:** time series of surface-based observations of atmospheric vertical structure (including cloud structure) and description of the sea ice surface over a region of 100 km surrounding the SHEBA ice station.

**What FIRE provides for ARM and SHEBA:** satellite analysis of cloud characteristics; technology, observations and analysis of aircraft data; improved parameterizations of Arctic cloudy boundary layer process.

## 3.0 Observing Platforms and Sampling Strategies

### *3.1 Surface Measurements*

Surface-based measurements over the ice pack will be concentrated in the SHEBA domain. Exact details are not know, but the SHEBA science plan (Curry et al., 1995) outlines a scenario for a central SHEBA ice station with most of the instruments and at least 3 remote sites with much more limited instruments. SHEBA plans a set of Continuous Core Measurements (CCM) in the ocean, ice and atmosphere. For FIRE Phase III the atmospheric and surface characterization measurements are the most relevant: measurements on the atmospheric side of the interface will be made by combing systems from the ARM program and systems specially deployed for SHEBA. ARM is developing a portable, semi-autonomous measurement system called an "ARCS" (Atmospheric Radiation and Clouds Station; see Clements et al., 1995) which will become available starting in 1995; several units will be manufactured, and plans call for various component from one to be deployed in the Arctic, at the SHEBA ice station. The ARCS will form the foundation for atmospheric measurements made from surface platforms. However, a complete ARCS will not be available for SHEBA, so additional measurements will be required. A summary of the surface-based observations planned or expected for the SHEBA program is described in this section. These observations will include measurements of surface radiation, cloud properties, water vapor, aerosols, boundary layer structure, and surface meteorology. They will be obtained with a combination of ground-based in situ and remote sensing systems.

Because of the extreme environmental conditions which will be encountered in the Arctic, a critical operational component will be a full test of surface instrumentation before it is deployed on the ice. Present planning calls for integration of the ETL radar (ETL is NOAA's Environmental Technology Laboratory) and wind profiler into the DOE/ARCS shelter and data systems in the autumn of 1996, with a full cold test scheduled in Barrow, Alaska starting in January of 1997. This activity will provide for a comprehensive instrument shake down period when modifications and repairs can be made relatively inexpensively. It will also provide an important prototype Arctic data set over a period of a month or more which can be used by the modeling and satellite community to initialize development of the procedures for integrating the surface data sets into models and satellite verification schemes. The surface observationalists will concentrate on producing operational products of cloud microphysical and radiative properties using retrieval techniques which have previously only been applied on a case study basis. Tight coordination between ETL and the DOE ARCS will take advantage of mutual shelter, data management and logistical needs to cost effectively eliminate duplication of effort between the two agencies. Other surface based groups such as the Tethered Balloon consortium will be encouraged to participate in the Barrow cold test.

#### *3.1.1 Central meteorological tower*

Turbulent and radiative fluxes, mean temperature, humidity, wind speed and direction, and selected chemical/aerosol concentration measurements will be made from standard meteorological towers. For some variables, multiple levels are required. Sample instruments are given in Table

1. Because of practical considerations (i.e. not having to climb a 100 m tall tower to work on and repair failing sensors), modest towers (e.g. 10 to 30 m tall) designed for easy maintenance are indicated.

**Table 1 - Tower meteorological measurements.**

| Instrument | Variable | Height (m) |
|---|---|---|
| Sonic anemometer | Stress, heat flux | 3, 7, 16 |
| Anemometer | Wind speed, direction | 1,2,4,10,25 |
| Thermometer | Air temperature | 1,2,4,10,25 |
| Hygrometer | Air humidity | 1,2,4,10,25 |
| Radiometer | Surface temperature | Surface |
| Barometer | Surface pressure | Surface |
| Thermometer | Ice temperature | Subsurface |

Several scientific aspects affect the tower siting strategy for SHEBA and FIRE Phase III. The focus of these projects is on the surface energy budget so the tower designs must accomplish a credible representation of the mean fluxes over some relevant area. The variety of ice/snow types and the small scale of the local surface variability make this a very difficult task. Clearly, a single tower measuring fluxes at a single level will not meet this requirement (Blanc, 1983). Multiple levels of flux measurement will allow us to resolve vertically the surface layer, will generally lend credibility/consistency and will allow us to use the flux-footprint concept to sample increasingly larger areas farther from the tower as the height of the measurement increases (Schuepp et al., 1990; Horst and Weil, 1994). The combination of flux and mean variable profiles are required to sort out the confusing effects of surface variability versus non-constant flux profiles caused by non-stationarity and boundary layer scale vertical gradients. Five levels of mean measurements (1, 2, 4, 10, 25 m) with 3 interlaced levels of turbulent flux sensors would be reasonable for the main meteorological tower. Other measurements (e.g. radiation, aerosol) would only be made at one level.

The specific instruments used on the tower will be, whenever possible, standard instruments with a history of successful use in polar climates. Mean sensors for air temperature, humidity, and wind speed/direction are readily available, although operation in extreme cold may call for special considerations (e.g., Anderson, 1994).

Several sonic anemometer units, despite well-known deficiencies (e.g., Grelle and Lindroth, 1995), have proven performance to -50 °C and are commercially available; and at least one specially modified unit has been used at South Pole Station to -65 °C (Neff, private communication). Note the sonic anemometer will yield both the surface stress (momentum flux) and the sensible heat flux (Schotanus et al., 1983), but a separate fast humidity sensor is required for direct measurements of latent heat flux (Kaimal and Finnigan, 1994). An accuracy of about °C is required for surface temperature (see the discussion of bulk flux parameterization requirements in Fairall et al., 1995), which is beyond the capabilities of the pyrgeometer (Persson et al., 1995). Thus, a high quality infrared surface temperature sensor will be necessary, with both upward and downward looking channels to allow for surface reflection.

Two additional smaller towers are needed to address the following issues: elimination of contamination by the SHEBA ice station; examination of the effects of surface inhomogeneities on the surface fluxes; and the importance of intermittency and subgrid variability of the surface fluxes. These two additional towers will be portable 3-m towers that measure turbulent fluxes at only one level.

Fluxes at several selected sites can be sampled periodically with one or two small portable flux systems deployed by helicopter or snow mobile. In LEADEX (Ruffieux et al., 1995) such systems were gasoline generator powered, but a low power system might be practical (although this depends to some extent on the radiometer dome frost problem). The portable flux units could also form the core of any lead studies associated with SHEBA. Ideally, such a system could be dropped off at the desired site and then serviced or moved every few days. It is also not necessary to use the portable systems continuously, one or two days a week might provide a sufficient sample. The remainder of the week, they could be sited quite close to camp where power is available. This would provide a combination of direct intercomparison with the camp tower system and independent samples from a few hundred meters away.

### *3.1.2 Ground-based in situ profiling systems*

#### *3.1.2.1 Rawinsondes*

Rawinsondes are needed in addition to the ground-based remote sensing systems to determine vertical profiles of temperature, wind, and humidity. The remote sensors have the advantage of continuous high resolution coverage while the rawinsonde has the advantage of greater altitude coverage. To use the rawinsondes as a reference standard for the remote sensors, care must be taken to correct for response time and radiation-induced errors (Cole, 1993; Luers and Eskridge, 1995) and Global Positioning System (GPS) navigated sondes will probably be required. Performance of Vaisala rawinsondes in regions of low temperature and humidity has been shown to be adequate for our purposes, although humidity corrections are required at the lowest temperatures (Oltmanns, private communication). The cost of importing helium, sondes, balloons, etc. and maintaining extra personnel on the ice to launch and analyze rawinsondes precludes the use of frequent sonde launches for SHEBA. We recommend 2 sondes per day, with higher time resolution profile information provided by remote sensing systems. This is made more palatable by the weak diurnal cycle.

To represent a realistic alternative to frequent sonde launches, the wind profiler/RASS system must have sufficient height coverage to capture the primary transition from the ice-interaction dominated boundary layer to the advective region above. This transition is typically identified as a maximum in temperature and water vapor at roughly 1 km altitude of the atmosphere; most of the short-term variability in temperature and moisture gradient occurs below 2.5 km (Persson et al., 1992). Wind profiles in the lowest 100 m can be sampled with 5 to 10-m resolution with a sodar (see section 3.1.3).

#### *3.1.2.2 Tethered balloons*

A tethered balloon is potentially valuable for probing the boundary layer and low clouds, particularly for measuring cloud microphysics, subsaturation, and radiation fluxes (Hignett, 1991). A tethered balloon has many advantages over aircraft, including lower cost, daily measurements, better vertical resolution, better low altitude operation, long time series at a fixed location, and better sampling for some microphysical instruments. The low altitude performance is important. SHEBA must depend heavily on remote sensors because of its infrequent radiosonde launches, yet the active sensors like lidar, mm radar, and RASS all can only “see” above their first range gate, which is typically several times higher than the top of the meteorological tower.

The tether system envisioned is of the small, lightweight type manufactured by Atmospheric Instrumentation Research, Inc. (AIR) in Boulder. A number of groups, including one from NASA Wallops that participated in FIRE/Spectral Radiation Experiment (SPECTRE) at Coffeyville, have had favorable experience with these systems. The balloons are only 3-7 cubic meters in volume, manageable by a single person, and have a lifting capacity of several kg. AIR has developed a data system capable of managing up to 6 meteorological packages hanging at different places along the tether.

If a larger balloon can be operated at the SHEBA ice station, then a small cloud radiation package could be put together from existing instruments. Besides a meteorological package, the most important instruments would be, in rough priority order:

(1) a liquid water content meter (King probe or Gerber PVM);

(2) a droplet effective-radius meter (Gerber PVM);

(3) net shortwave and longwave flux radiometers of the Valero caliber;

(4) a chilled mirror hygrometer to examine subsaturation in Arctic clouds, if possible; and

(5) pairs of net flux radiometers to measure flux divergence in Arctic clouds.

Microphysical properties in low level clouds and fogs can also be measured by replicator sondes, and video-based ice particle or droplet samplers. Work is in progress to develop systems which can run power up the tethers which will substantially increase the operating capabilities of the balloon borne sensors. Some of these tether systems can be winched up and down to sample atmospheric and cloud profiles up to 1.5 km. In addition to the important information that these systems can provide on near-surface profiles (for instance snow drift intensities), they will be critical in providing validation for the surface remote sensing instrumentation. Because surface based, remote sensing retrievals of cloud microphysics will be used extensively for model and satellite verification studies, it is important that these techniques be validated in turn with the pristine in situ measurements that can best be made from balloons.

### *3.1.3 Ground-based remote sensing*

Table 2 lists suggested surface-based profiling remote sensors. These instruments will provide standard atmospheric wind, temperature, and moisture profiles (from conventional sondes and remote sensors), plus a variety of remotely sensed cloud, aerosol, and (perhaps) chemical properties. The SHEBA remote sensors must be heavily slanted toward the "unattended, continuously operating" style as opposed to highly capable research and development sensors requiring constant attention, adjustment, and repair. The wind profiler/RASS, microwave radiometer, and minisodar already fit this description. A ruggedized, fully automated scanning 0.52 mm wavelength lidar will be built for SHEBA. A vertically pointing 35 GHz cloud radar is presently under development at ETL for the ARM program; an identical system will be provided for SHEBA. The fourier transform interferometers will incorporate a special refrigeration unit and will not require a continuous supply of liquid nitrogen.

**Table 2 - Surface-based remote sensors (*denote ARCS).**

| Instrument | Variable | Resolution/Max Altitude |
|---|---|---|
| 449 MHZ Profiler | wind components, turbulence | 0.1/2.5 km, 0.4/3.5 km |
| 1 KHz (acoustic) RASS | virtual temperature | 0.1/2.0 km |
| Minisodar | wind components, turbulence | 0.005/0.2 km |
| 0.52 Micron lidar | Backscatter, polar. | 0.03/20 km |
| 35 GHz Cloud radar | Cloud scatter, vertical velocity | 0.02/10 km |
| Microwave radiometer* | Integrated water | --- |

#### *3.1.3.1 Clouds*

The diagnosis of cloud microphysical properties from the remotely sensed information is, with a few exceptions, indirect (Gossard, 1994; White et al., 1996). That is, the fundamental parameters measured directly by a cloud radar are the backscatter coefficient and the radial velocity. This information is obtained in an array of height bins with a time resolution on the order of seconds. Just from this one sensor, a variety of cloud properties can be determined by simple processing: cloud top height, cloud base height, and in-cloud velocity variance profiles. Using models and/or assumptions about cloud properties (e.g., adiabatic liquid water profiles, constant droplet number density as a function of height), such data can be processed to give information about cloud microphysical properties such as droplet size (Frisch et al., 1995). When data from various systems are combined, we can obtain more estimates of cloud variables. Thus, SHEBA must include a carefully chosen set of surface-based remote sensors and must include a research component of corresponding in situ cloud measurements (either aircraft or tethered balloons) to develop the various synergistic algorithms necessary for the experimental objectives.

Cloud microphysical properties have been studied in FIRE II and ASTEX with combinations of ground-based remote sensors (Miller and Albrecht, 1995; White et al., 1995; Frisch et al., 1994, 1995). Such studies will also be useful in these Arctic stratus studies. Doppler radar and IR radiometer measurements have been used in FIRE II to determine profiles of ice crystal sizes, concentrations, and ice mass content (Matrosov, et al. 1994). An alternative method utilizes the radar/lidar backscatter ratio to estimate similar cloud properties (Intrieri, et al., 1993). Such techniques will be effectively used in Arctic stratus ice clouds (Pinto et al., 1995). Such measurements should be possible out to ranges of 10 to 15 km. The frequent occurrence of satellite overpasses in the Arctic region will provide frequent opportunities to use the ground-based remote sensors to evaluate some of the satellite-based atmospheric retrieval techniques and to develop others. Satellite retrievals are especially uncertain in upper latitudes and FIRE III will provide an excellent opportunity to improve retrieved products from satellites, especially those relating to cloud properties.

#### *3.1.3.2 Profiles of winds and atmospheric thermodynamic properties*

To represent a realistic alternative to frequent sonde launches, the wind profiler/Radio Acoustic Sounder System (RASS) system must have sufficient height coverage to capture the primary transition from the ice-interaction dominated boundary layer to the advective region above. This transition is typically identified as a maximum in temperature and water vapor at roughly 1 km altitude. Thus we need a system capable of providing nearly continuous winds and temperature to about 2.5 km. The system must also have adequate vertical range spacing to accurately resolve this structure, on the order of 100 m. [Note that the lowest levels of the atmosphere, where the surface layer transition and jet structures exist, can be sampled with 10-m resolution with a sodar (Ruffieux et al., 1994).] The wind profiler used in LEADEX (Wolfe et al., 1992) gave 90% height coverage to 0.6 km at 100-m resolution and 1.0 km at 200-m resolution. The 90% height coverage for RASS temperature was about 0.5 km. This means that a much more powerful profiler will be required for SHEBA. Based on a comprehensive study of wind profiler performance (Martner et al., 1993), it is presently planned to use a 449 MHz profiler (a derivative of the NOAA operational network systems) instead of the 915 system used previously. Such a system will have no problem with the altitude coverage for winds and will have a clear advantage in RASS temperature coverage because of the reduced sound absorption at the lower frequency, but vertical resolution will be no better than 100 m.

### *3.1.4 Radiation*

The central Arctic is exposed to little or no solar illumination a large portion of the year so that, in contrast to other parts of Earth, the longwave fluxes play a much more important role in the total energy balance, particularly at the surface. Also, the stable stratification of the polar atmosphere, especially in winter, can cause large differences in surface skin temperature and air temperature. This effect must be understood in order to properly determine longwave fluxes. Because of the predominance of ice clouds during colder seasons, angularly and spectrally resolved solar radiation is also particularly important for SHEBA.

The Arctic atmospheric longwave opacity is so low that the appearance of clouds significantly increases the emission of longwave radiation both downwards to the surface, and upwards to space in the presence of temperature inversions which are frequent phenomena. Arctic clouds may generally be optically thin enough that their longwave emissivities are significantly less than unity which will alter their effect on the radiation balance. Moreover, Arctic stratus often form in the warmest, most humid layer, which can lie well above the surface, so that the downward longwave flux in winter could conceivably, at times, be larger than the upward flux from the sea-ice if strong inversions are present.

For these reasons, downward surface longwave flux calculations require accurate modeling of water vapor absorption at the low mixing ratios typical of polar conditions. Verification of downward longwave flux calculations should follow the process used in SPECTRE, i.e. combining interferometer and broadband measurement of longwave radiation with radiosonde profiles and Raman lidar water vapor profiles. Several independent measurements of longwave broadband fluxes are required given the current uncertainties (10 W m-2) in the absolute calibration of these devices. The instruments planned are given in Table 3. Commercial pyranometer and pyrgeometer units are usable, although a special calibration program will be required to meet the accuracies needed for SHEBA (better than W m-2). Some method must be employed to maintain radiometer domes free of frost without compromising their accuracy. There are now several commercially available ventilation systems available.

**Table 3 - Surface-based radiative flux sensors, all of which are part of the ARCS.**

| Instrument | Variable |
|---|---|
| Pyranometer | Solar irradiance |
| Pyrgeometer | IR irradiance |
| Rotating shadowband rad. | Diffuse solar irradiance |
| Sun photometer | Direct solar irradiance |
| IR-radiometer | Sky temperature |
| Whole-sky imager | Cloud fraction/structure |
| Fourier Transform Interferometer (IR) | Humidity, temperature |
| Fourier Transform Interferometer (solar) | Solar spectrum |

### *3.2 Aircraft observing strategy*

Aircraft are invaluable tools for investigating the complex cloud structure and characteristics in the complex Arctic atmosphere. Although continuous time series observations from the ice breaker contribution of SHEBA can be used to study the transient nature of clouds at a single point over sea ice over an extended period of time, aircraft provide an essential element of our strategy to evaluate both the surface observations obtained from the ice breaker and the satellite observations of reflected and emitted radiation. Aircraft can provide descriptions of the vertical structure and horizontal distribution of the boundary layer and associated clouds, as well as sample the complex multi-layer cloud system prevalent over the Beaufort Sea. Aircraft will enable extensive observations of cloud microphysics, both clear-sky and cloud radiative properties, chemical composition, aerosol properties, vertical structure, thermodynamic characteristics, and surface characteristics including the distribution of leads and melt ponds.

We expect clouds in the Arctic basin to be more complex than those observed during FIRE 1987 and ASTEX, in part due to the influence of the cold sea ice surface with many fractured leads. This promotes both low-level Arctic stratus clouds in summer, which are composed largely of liquid water drops of fairly uniform size, as well as frequent incursions of mid-level altocumulus and “high-level” cirrus clouds. Due to the low altitude of the stratosphere at 70°N, the cirrus clouds occur at much lower altitudes than in the tropical and subtropical environments studied extensively in the past.

A long transition period occurs between April, when low-level clouds are primarily crystalline, and mid-June, when the dominant cloud type is low-level water clouds, with less frequent, but regular, mid-level altocumulus. We have adopted a strategy to characterize this transition period over a seven-week period or longer with a serial deployment of low-mid-level aircraft (outlined below), together with a four-week period of high-altitude ER-2 overflights. During this component of Arctic FIRE (IFO I; here "IFO" means a period of "Intensive Field Observations"), we anticipate utilizing the Canadian National Research Council (NRC) CV-580, the NCAR C-130Q, and the University of Washington (UW) CV-580. All three of these aircraft are turboprops that fly at 120 m s-1, but can be slowed down to 80 - 100 m s-1 for sampling cloud microphysics. These aircraft are all equipped with an extensive set of PMS cloud microphysics probes, a Gerber PVM-100A liquid water content and effective radius probe, Johnson-Williams and King hot wire probes, a Nd:YAG lidar, thermodynamic state variable measurements, and selected chemistry instrumentation. As expected, however, these aircraft also have unique and distinguishing characteristics.

In addition to IFO I, we envision a second IFO for Arctic FIRE in the summer of 1998, consisting of the NCAR C-130Q (SHEBA-supported) to overfly the ice breaker. If the Earth Observing System (EOS) AM-1 satellite launches in June 1998, as expected, then the EOS program will likely sponsor the NASA ER-2's participation at this time as well. In addition, we envision participation by the UW CV-580.

This preferred deployment strategy for IFO I and IFO II campaigns is summarized in Fig. 2. The overlap periods envisioned for IFO I, will be used for (i) intercomparisons of aircraft instrumentation, and (ii) two-aircraft missions (in addition to coordination with the higher flying ER-2). Intercomparisons can be done by flying the boundary layer aircraft in formation and comparing both mean and turbulence measurements of thermodynamic, dynamic, microphysics and radiation. Examples of two-aircraft missions include: (i) flying at two levels with one aircraft above the other to obtain simultaneous in situ and remote sensing measurements of cloud layers, and (ii) carrying out a Lagrangian study of cloud evolution by having the second aircraft replace the first aircraft along an air trajectory.

### *3.2.1 Aircraft platforms*

The Canadian Convair CV-580 carries, in addition to a comprehensive suite of microphysical instrumentation highlighted above, a gust probe, a nadir-viewing monostatic Nd:YAG lidar (which will have both upward- and downward-looking capability by 1998), pyranometers, CN and CCN counters, and two downward-looking radiometers (a three channel visible radiometer and a Landsat Thematic Mapper (TM) simulator). Chemistry instrumentation can be put on board to measure many trace gases (SO2, O3, NO/NO2, H2O2) as well as organic and inorganic composition of the aerosol, cloud liquid, and cloud ice. DMA and DMS measurements are also possible. Instrumentation unique to the NRC CV-580 include the Russian Nevzorov total water content probe that measures cloud water and ice contents at concentrations as low as 0.005 g m-3. It should also be possible to install a Russian cloud extinction probe to directly measure volume extinction coefficient. These probes will be especially useful in mixed phase clouds or all ice clouds, a situation where Particle Measurement System (PMS) probes provide only coarse indicators of particle concentration. Environment Canada is also installing passive downward and possibly upward, dual polarization, microwave radiometers operating at 19, 37, and 85 GHz. Additional instrumentation will be sought to enable the size and phase of particles to be distinguished in the size range of 50 to 150μmm.

The UW CV-580 is equipped with cloud physics, cloud radiation, aerosol, chemistry, and monostatic lidar instrumentation. For spectral and angular radiation measurement between the UVb (0.30 mm) and near-infrared (2.3 mm), there is a state-of-the-art Cloud Absorption Radiometer described by King et al. (1986). This instrument can be used either for internal scattered radiation measurements (for determining the spectral single scattering albedo of clouds) or for bidirectional reflectance function measurements of cloud, snow, tundra and sea ice surfaces. It can also be used as a cross-track scanner when oriented to scan from horizon to horizon. In addition, the UW CV-580 has a CCN spectrometer and space available for the addition of other principal investigator instrumentation (such as a spectrometer and/or spectral flux radiometer). Although this aircraft is capable of measuring phase and imaging some ice crystals, its strength lies in liquid water clouds (hence its preference towards the end of IFO I).

Both the NCAR C-130Q and NRC CV-580 have comparable turbulence and cloud microphysics instrumentation, and include the standard suite of thermodynamic state variables as well as a monostatic lidar. Unique instrumentation available on the NCAR C-130Q includes a passive microwave radiometer capable of imaging through clouds and observing sea ice and lead distributions. When flying at low altitude the microwave radiometer gives about 30 m resolution, which is sufficient to pick up all but the smallest leads (which have little effect on the atmosphere anyway). The NCAR C-130Q will also be equipped with a dropwindsonde capability to: (i) add to the array of synoptic observations, and (ii) provide estimates of horizontal advection of moisture and possibly of divergence. These will be deployed on the ferry legs to and from the primary research area, and possibly along the closed flight paths to aid in estimating line integrals around closed flight tracks. Finally, the C-130Q contains the Multispectral Cloud Radiometer described by Curran et al. (1981) and King (1987), which requires careful attention to calibration (true of all visible and near-infrared radiometers).

The NASA ER-2 is the platform of choice for high-altitude surveys of cloud radiative properties. It will link the low-level aircraft and surface-based measurements to satellite observations. The primary instrumentation of interest to Arctic FIRE includes a downward-looking lidar (Spinhirne et al. 1983), a multispectral along-track scanning radiometer (under development), a microwave imaging radiometer (Wang et al. 1995; Raccette et al. 1996), and a multichannel scanning spectrometer (King et al. 1996). These sensors all have analogs to future satellite sensors under development for launch between 1998 and 2000. The long range and high altitude (20 km) of this aircraft make it an excellent platform from which to select cloud features to study, to map the cloud fields that are being sampled by the low-level aircraft, to test algorithms for cloud retrievals, and to intercompare with coordinated satellite overpasses (especially following launch of the EOS AM-1 spacecraft, which is currently planned for June 1998).

### *3.2.2 Aircraft-based aerosol and chemistry measurements*

The NCAR C-130 will also carry aerosol and chemistry instrumentation from university and NCAR investigators as was done in the ACE-1 project in 1995.

The Desert Research Institute (DRI) instantaneous cloud condensation nuclei (CCN) spectrometer (Hudson 1989) will determine the spatial variability of CCN because it continuously obtains the entire CCN spectrum in situ within time periods as short as 1 s. Its spectral range extends to 0.01%, which is well below the 0.2% limit of other CCN instruments; this is significant because of the low supersaturations of stratus clouds and because of increasing evidence that the shape of the CCN spectrum below the actual parcel supersaturation affects droplet spectral width, which is important for precipitation development (section 1.3.3). Since this same instrument was employed in both of the earlier FIRE stratus cloud projects in 1987 and 1992 it will allow comparisons of the supersaturations in these different stratus regimes in addition to valid aerosol comparisons. This instrument can also be used to determine additional aerosol characteristics such as the physical sizes of the CCN (Hudson and Da 1996)(section 1.3.3). This is especially advantageous since there are now two matched DRI CCN spectrometers; both were successfully operated on the NCAR C-130 in two earlier projects. One spectrometer continuously monitors the ambient spectrum while the other measures spectra of processed samples such as dry particle sizes using a DMA. Both the ambient spectrum and the size resolved spectrum are needed to determine the size of the CCN because the spectra can change while flying. Measurements of the total particle size distribution can be made in conjunction with this by using a CN counter. A separate DMA can also be employed to obtain semi-continuous particle size distributions. Total particle (CN) measurements with a TSI model 3010 will reveal the CCN/CN ratio. The NCAR CVI should also be employed with the CCN spectrometer (Twohy and Hudson 1995) to specifically determine which CCN are within the cloud droplets and to separately collect particles on filters to determine chemistry that is segregated according to cloud droplet sizes. Separate size-resolved filters should also be collected in, below, and above cloud air.

If a new airborne IFN instrument (Rogers 1988) planned for operation on the NASA DC-8 in 1996 is successful then it should be employed on the C-130 in Arctic FIRE.

The NCAR chemiluminescent ozone detector would be used to estimate entrainment and mixing into the cloudy boundary layer.

As in the ACE-1 project with the NCAR C-130 gaseous precursors of particles need to be measured. These begin with DMS, which comes from natural oceanic sources, and SO2, which may serve as an intermediate species or may come from pollution sources. The oxidants OH and NOx need to be measured as these are important in the pathways of conversion of the DMS or SO2 to particulates. Ammonia is important because it is quite variable and ammonia is a component of most atmospheric CCN either as ammonium sulfate or ammonium bisulfate.

Concentrations of greenhouse gases will be determined using the Fourier Transform Interferometer Radiometer (FTIR). Vertical profiles of aerosol extinction coefficient will be made with lidar.

Some aerosol sampling could be done on the meteorological tower. Instrument Neutron Activation Analysis (INAA) will be used to differentiate anthropogenic sulfate from ocean-biogenic sulfate. Since INAA filters for multi-element analysis will require a number of cubic meters of sample volume in Arctic conditions, this measurement will only be achievable on the ground. The utility of the INAA type of analysis is that it can give a fairly unambiguous differentiation of "natural" and anthropogenic aerosol whereas the airborne techniques will be generally somewhat ambiguous in this regard.

Ground-based filter sampling seems quite practical. Filter packs and pumps are fairly robust and have been employed in environments even more hostile than the Arctic (e.g., volcanic caldera). They can be stored for long periods of time at low temperatures and shipped out periodically for analysis. Some of the desired ground based measurements that require more elaborate equipment (e.g., DMAs, CCN counters) may not be practical.

### *3.2.3 Sampling strategy*

In order to address the competing requirements of measuring horizontal variability and vertical structure, as well as obtaining a sufficient sample length, the exact details of the flight tracks will need to be fine-tuned in later planning exercises. Generally, however, there will be flight segments at constant level of at least 60 km in length to obtain a sufficient sample length for turbulence and radiation measurements; shorter legs would probably suffice for microphysics and trace constituent measurements. There will also be slow accents and descents to obtain continuous vertical profiles of these variables, as well as a series of horizontal flight legs at 4-5 different levels. Many of the flight tracks will be in the environs of the SHEBA ice breaker to complement the fixed-base measurements and provide in situ data for comparisons with ground-based remote sensing observations. The aircraft can also provide a valuable data set to help extend the long time series fixed-point measurements obtained from the surface to large spatial scales.

One approach for deploying the aircraft for meeting the objectives of measuring surface energy, mass and momentum budgets is to fly closed flight paths around the surface station at several levels, starting at the lowest safe altitude, and extending up through the top of the region being considered. This would allow measurement of the turbulent flux profiles, as well as cloud microphysics, radiation, and mean thermodynamic structure of the atmosphere. The surface station observations complement these measurements by providing long time series and detailed structure of the atmosphere in the vicinity of the fixed point. If the flight path is long enough and if a turbulent boundary layer exists up through the airplane flight levels, it may be possible to estimate the entrainment velocity at the top of the boundary layer by measuring the flux profile of a trace chemical species such as ozone, total water, or dimethyl sulfide. The velocity can then be estimated from the ratio of the flux at the top of the boundary layer to the jump in concentration across the top of the boundary layer. An independent estimate of entrainment velocity may be possible by measuring the mean divergence within the closed flight track and the time rate of change of the boundary layer depth. To do this requires flight tracks of 60-100 km in diameter, flown both clockwise and counterclockwise to eliminate the mean offset in the measurement of the lateral wind component.

These results will complement ground-based measurements, both by extension to large spatial scales and by providing in situ confirmation to ground-based remote sensing observations (e.g., radar, lidar and microwave radiometer).

### *3.2.4 Calibration and intercomparisons*

Since several aircraft will be used during the field campaign, it is essential that the instruments be calibrated and intercompared in a consistent manner. Whenever possible, the aircraft should be flown in formation or at least along the same path with a minimal time separation. However, because it will be difficult to get all the aircraft together at one time, and it would be difficult to intercompare in-cloud measurement type probes, standardized techniques should be developed for probe intercomparisons. This might include circulating equipment that would fire glass beads through the sampling volume of many PMS probes. Alternatively, wind tunnel intercomparisons could be done for cloud droplet and liquid water content probes. Chemistry probes might be calibrated with known standards. Radiation sensors, CN or CCN counters could be compared in a laboratory setting. One of the major challenges will be to intercompare the gust probe measurements from each aircraft. This might only be possible with in-flight measurements. Data analysis software must also be checked using the same data set.

It is recommended that one individual be assigned the responsibility of organizing such calibrations and intercomparisons for each aircraft, and a lead scientist should be designed for coordinating the efforts between aircraft.

### *3.2.5 Logistics*

The choice of locations for deploying the various aircraft are as follows: (i) the NASA ER-2 and NCAR C130Q aircraft will be based in Eielson Air Force Base (25 miles south of Fairbanks, Alaska), (ii) the UW CV-580 will be based in Prudhoe Bay, Alaska, close to the sea ice, start of the Alaska pipeline, and adjacent to a highway with access from Fairbanks (via the Brooks Range), and (iii) the NRC CV-580 will be based in Inuvik, Northwest Territories, Canada. This site is on the McKenzie River inland from the coast of the Beaufort Sea (on the edge of the tundra and boreal forest), and is the northernmost deployment site in Canada. Hence, the ice breaker, which may be located in the vicinity of 77°N, 135°W, will entail long transits of all aircraft involved. Hence the maximum coordination will occur, in almost all cases, near the SHEBA ice breaker. To the maximum extent possible, the Alaska Synthetic Aperture Radar (SAR) Facility at the University of Alaska-Fairbanks, will provide assistance in viewing the sea ice and lead distribution acquired, and processed, from Canada's Radarsat and the European ERS-2 SAR satellite sensors. In addition, the NOAA National Weather Service station in Fairbanks is a valuable, and supportive, facility for mission planning purposes.

### *3.2.6 Issues*

Issues that require further study include basing in light of the ranges of the various aircraft and the location of the SHEBA ice station; and development of a list of strawman flight plans and objectives, with attention to satellite coordination, inter-aircraft coordination, calibration intercomparisons, and vertical sampling strategy.

In case the NCAR C-130Q is not available for use by FIRE in the Arctic, current thinking suggests that during both IFOs we would simply conduct the measurements without the NCAR C-130Q, but otherwise as indicated in Fig. 2.

## *3.3 Satellite remote sensing*

### *3.3.1 Evaluation of polar ISCCP/EOS cloud retrievals*

Satellites can measure many but not all of the desired cloud properties. ISCCP currently provides global estimates of cloud fraction, cloud height (radiating temperature), and cloud optical depth. Experimental studies have begun during FIRE Phase II to add estimates of cloud particle phase (ice, water) and size, liquid water path (LWP), ice water path, cloud physical thickness, and cloud overlap. These new estimates have met with varying degrees of success: the most reliable being water droplet size and LWP, while the least reliable are cloud overlap and cloud IWP. This section will briefly describe some of the specific remote sensing evaluation and development work which will be carried out during Arctic FIRE polar cloud observations.

### *3.3.2 Cloud detection/cloud amount*

Detection of clouds is typically accomplished using visible and thermal infrared imaging channels on meteorological satellites such as Geostationary Orbiting Environmental Satellite (GOES) and Advanced Very High Resolution Radiometer (AVHRR) (e.g. Rossow 1989). Cloud detection typically relies on the fact that clouds reflect more solar radiation and emit less thermal radiation than clear-sky conditions. Given the snow/ice backgrounds and large temperature inversions common in polar regions, these typical approaches enjoy only partial success in polar regions. More recent methods add either spatial structure (i.e. texture) detection (Welch et al. 1992), or particle size/phase detection (Yamanouchi et al. 1987). In general, snow and ice surfaces behave like low level clouds with very large ice particles (especially old snow and ice) and infinite optical thickness. In this case, the same remote sensing techniques that remotely sense cloud water/ice phase and particle size, can in principle be used for cloud detection. Difficulties are expected to arise with either fresh snow (particle sizes similar to some cirrus) and optically thin cloud, where reflection signals are a mixture of surface and cloud properties. The optimal case is for daytime detection of water cloud over old snow or ice background. The most difficult case is expected to be night-time detection of optically thin ice cloud over fresh snow, or low level optically thick cloud with large ice particles.

A related issue is the determination of fractional cloud coverage. Here the issue is two fold: how much optically thin cloud area is missed, versus how much overestimate was caused by detection of partially covered satellite fields of view as filled with cloud? FIRE II used Landsat data to show that both of these effects are important over ocean backgrounds for boundary layer clouds but are of minor importance for cirrus, when analyzing satellite data with the 4-8 km field of view data used by ISCCP (Wielicki and Parker 1992). For the 250 m or 500 m Moderate resolution Imaging Spectrometer (MODIS) fields of view on EOS-AM, detection of optically thin cloud is the dominant error source. Arctic FIRE will extend these results to studies of clouds over snow and ice backgrounds.

Arctic FIRE will examine the accuracy of cloud detection/amount using several evaluation data sources:

- lidar on the ER-2 collocated with the MAS radiometer used to simulate MODIS and AVHRR spectral channels. Limitation: only tests nadir view angle.
- surface lidar and radar on the SHEBA and ARM surface sites.
- surface observers, when sufficient solar or lunar illumination is present.
- Landsat satellite data (May not be available during the IOP but useful work can be done now.)

*3.3.3 Cloud top height/radiating temperature/thickness/overlap*

The primary difficulty in polar regions for estimation of cloud height is the difficulty in obtaining accurate temperature profiles at the time of observation. If the cloud is optically thick, determination of the cloud radiating temperature is straightforward. If the cloud is optically thin, two methods have been used extensively:

- infrared sounder retrieval (e.g. Menzel et al. 1992);
- solar channel determination of visible optical depth which is converted to an infrared emittance and used to correct non-black cloud emission temperatures (Rossow et al. 1991; Minnis et al. 1993).

An additional problem for the second method (ISCCP) is that a highly reflective surface precludes accurate estimation of the optical thickness of thin cloud. Additional methods are being developed which use changes in thermal emission with wavelength at 3.7/11/12 mm to estimate the non-black cloud emission temperature, and may provide an improvement over current methods. Combinations of infrared sounder data and passive microwave are also being examined. All of these methods, however, experience difficulty in conversion of radiating temperature to cloud height, if given inaccurate temperature profiles, so more effort to retrieve better profiles of temperature and humidity from weather satellites is also needed (e.g., Francis 1994). Arctic FIRE can examine the relative trade-offs of these methods in polar regions: especially sounder versus imager approaches.

Recently, attempts have begun to examine the estimation of cloud physical thickness as a function of optical depth (Minnis et al. 1992), as well as methods to handle some cases of multi-layered cloud: optically thin upper cloud over an optically thick lower cloud using AVHRR/High Infrared Radiation Sounder (HIRS) (Baum et al. 1994), and water cloud under thick cirrus over an ocean background by combining imager and passive microwave (Liu et al. 1995). None of these methods has been tried in polar regions.

Arctic FIRE will examine the accuracy of remotely sensed cloud height/temperature using two primary evaluation data sources:

- lidar on the ER-2 collocated with the MODIS Airborne Simulator (MAS) radiometer used to simulate MODIS and AVHRR spectral channels. Limitation: only tests the nadir viewing angle, and cannot penetrate upper clouds with optical depths greater than 3 to verify overlapped lower cloud layers or cloud base altitude. This may not be a strong limitation for polar clouds.
- surface lidar and radar at the SHEBA and ARM surface sites. These allow penetration of all cloud layers, but require long time series to gather a significant number of independent cases.

### *3.3.4 Water cloud optical depth, effective radius, liquid water path*

ISCCP began the systematic global estimation of daytime cloud visible wavelength optical depth from satellite data. Estimates of LWP have traditionally been made from passive microwave (Greenwald et al. 1993). Recently, significant progress has been made in developing new approaches to remotely sense water cloud optical depth/particle size/and LWP for daytime observations using 0.65, 3.7, and 11 mm on AVHRR (land or ocean background; Han et al. 1994), and 0.74, 1.6, and 2.2 mm (ocean background) which will be available on MODIS (King et al. 1992).

For polar regions, night-time estimation of cloud optical depth (emissivity) using thermal infrared multi-spectral techniques (imager or sounder), will be similar to estimation over land or ocean, with the complication of loss of some of the signal caused by relatively small temperature differences between surface and cloud for polar atmospheres (smaller lapse rates and lower clouds). Daytime estimation of cloud optical depth in the visible imager channels over snow and ice also has a smaller sensitivity and larger uncertainty because of the large surface reflectance. Thermal infrared methods will again be more useful in this case.

Evaluation of satellite channel estimation of the effective radius show systematic discrepancies of 30-50% depending on which aircraft probe (Forward Scattering Spectrometer Probe (FSSP) versus Gerber) and spectral channels are compared. Horizontal variations in effective radius appear reasonable, but mean values do not agree. Arctic FIRE should continue the examination of simultaneous performance of FSSP and Gerber probe data, as well as the potential differences in effective radius derived using 1.6,/2.2, 3.7, 8.5, 11/ 12 mm data. Documentation of the systematic vertical variation of effective radius within the cloud layer is also required. For optically thick cloud, daytime observations can still derive cloud particle size, but daytime observations of cloud with visible optical depth less than about ten will sense a mixture of cloud particle size and surface snow/ice particle size. Theoretical studies are needed to examine this dependence as a function of cloud optical depth.

The (FSSP and Gerber probes are fast response instruments. They are best utilized through the execution of many rapid ascents and descents through the clouds. The major differences in cloud microphysics occur in the vertical, but there is considerable variability in the way that droplet sizes and the variance of droplet size increases with height above cloud base. This depends on entrainment and precipitation (including coalescence growth that may or may not lead to precipitation) and on the distance from cloud base and cloud top, which also varies. Horizontal legs are thus not very useful for measurement of these important vertical variations and of variations in cloud base and top, which to a great extent determine the amount of condensed water and thus droplet size. The vertical variations of the microphysics are of utmost importance for remote determinations of cloud properties. Thus for understanding cloud physics and for comparisons with satellite and ground based remote sensing, long horizontal legs are not the best strategy. For these purposes it is best to have as many vertical soundings as possible. This can best be accomplished by deep porpoising (cloud base to cloud top) maneuvers. Many soundings are needed in order to better characterize the vertical structure of the cloud microphysics.

Studies of passive microwave LWP have demonstrated that it is primarily useful for optically thicker (optical depth greater than five) water clouds over ocean (Lin and Rossow 1996). Land and snow/ice backgrounds have not been examined because of the expected decrease in sensitivity to cloud water over these high emissivity surfaces. A general characteristic is that microwave frequencies (active or passive) are optimal for clouds with moderate to large visible optical depth, while optical imagers are optimal for low to moderate visible optical depths. A disadvantage of satellite passive microwave is the inability to resolve cloud LWP at scales less than about 50 km with current Special Sensor Microwave/Imager (SSM/I) data.

Arctic FIRE will utilize two primary approaches for evaluation of water cloud optical thickness, effective radius, and LWP.

- Use ER-2 and satellite overflights of SHEBA and ARM surface sites. The surface sites will use combined lidar/radar/radiometers to vertically profile cloud phase/particle density/particle size/LWC. Uplooking passive microwave will measure LWP. The accuracy of the surface remotely sensed cloud data is verified against in-situ aircraft flights within clouds over the surface sites.

- Fly stacked ER-2 (MAS, lidar) and cloud in-situ aircraft missions for verification of cloud particle size. Intercompare FSSP and Gerber probe data for effective radius.

Finally, consideration must be given to theoretical studies of the significance of non-plane parallel effects: both horizontal inhomogeneity and spherical shell solutions to radiative transfer for solar zenith angles greater than about 80 degrees. While recent results for boundary layer oceanic cloud and midlatitude cirrus show reasonably small biases using the independent pixel approximation (IPA; Cahalan et al. 1994), this must be examined for the polar clouds. The best data for this test will be the surface site remotely sensed vertical profiles of cloud microphysics as input to 2D radiative calculations.

#### *3.3.5 Ice cloud optical depth, effective diameter, ice water path*

Progress in the determination of ice cloud visible optical depth, effective particle diameter, and IWP is less well developed than for water clouds (Wielicki et al. 1990; Minnis et al. 1993; Lin and Rossow 1996). The difficulties are caused by the large and complex variability in particle shape, resulting in difficulties specifying:

- accurate single scatter phase functions

- accurate single scatter albedo

- accurate conversions of particle size and number to ice water content.

As a result, Arctic FIRE has several efforts devoted to improving the characterization of ice particle microphysics:

- development and analysis of ice replicators for balloon and aircraft which extend the small size range of detected ice crystals from the 20-50 mm lower limit of 2D-C probes, to 5-10 mm.

- development and analysis of ice particle imaging systems (cloud scope).

- aircraft probe to measure the scattering phase function asymmetry parameter (“g-meter”).

- aircraft nephelometer to measure the full scattering phase function of ice crystals.

The above microphysical and single-scattering studies are expected to substantially improve our understanding of the interaction of radiation with ice crystals. In addition, theoretical studies are being used to apply ray tracing (Takano and Liou, 1989; Macke, 1993), T-Matrix (Mishchenko and Travis 1994), discrete dipole, and other techniques to predict single scattering properties of a wide range of ice crystal shapes and sizes (hexagonal, bullet, rosette, plates, capped-plates, fractal shapes). These theoretical results will be compared to the g-meter and nephelometer measurements, combined with imaging probes to provide crystal shape estimates.

These studies of single-scatter properties are fundamental, but do not directly prove the ability to remotely sense a given cloud property. This final step is accomplished using data similar to that for the evaluation of retrieved water droplet cloud properties:

- Use ER-2 and satellite overflights of SHEBA and ARM surface sites. The surface sites will use combined lidar/radar/radiometers to vertically profile cloud phase/particle density/particle size/IWC. The accuracy of the surface remotely sensed cloud data is verified against in-situ aircraft flights within clouds over the surface sites.

- Fly stacked ER-2 (MAS, lidar) and cloud in-situ aircraft missions for verification of cloud particle size. Intercompare 2D-C, cloud scope, and replicator results for cloud particle size/shape distributions.

### *3.3.6 Surface and in-atmosphere radiative fluxes*

There have been several detailed attempts to infer radiative fluxes in the polar regions at the top of the atmosphere and at the surface, as well as the cloud effects on them, but the uncertainties are large (see review in Curry et al. 1996). Rossow and Zhang (1995) combined several satellite datasets, including ISCCP cloud properties, to determine the radiation budget. The EOS CERES (Clouds and the Earth's Radiative Energy System; Wielicki et al. 1996) investigation will produce estimates of shortwave (SW) and longwave (LW) broadband radiative fluxes:

- at the top of the atmosphere,

- at the surface, and

- at several levels within the atmosphere

using the CERES broadband and MODIS narrowband radiation/cloud measurements on EOS-AM and EOS-PM. In addition, the GEWEX SRB (Surface Radiation Budget) data set will produce estimates of surface fluxes using ISCCP cloud data. FIRE investigators will refine these analyses in polar regions using SHEBA and ARM surface flux observations. The ability to evaluate retrievals of in-atmosphere fluxes will be limited, but will utilize stepped aircraft profile data collected over the SHEBA and ARM sites as near as possible to the satellite overpass time. If the SHEBA surface site is deployed in August 97 - September 98 as planned, there may only be 2 months of overlap with CERES EOS-AM estimates and SHEBA surface and aircraft measurements. Later, ARM surface site data will be used to extend this study: both at the surface and using aircraft overflights. CERES and SRB are expected to perform this analyses as part of their EOS and Pathfinder investigations.

### *3.3.7 Time/space extension of cloud properties for model testing*

Surface sites typically provide one-dimensional (1D) instantaneous profiles at a point, or two-dimensional (2D) vertical slices of the cloud/atmosphere properties as clouds advect over the site (frozen turbulence approximation). For some models, this is not sufficient information. In particular, it is often necessary to extend the observations to larger time and space scales, as well as to two horizontal dimensions to verify:

- what is the areal extent of the cloud?

- is the cloud fundamentally 2D (streets) or 3D (cumulus cells)?

- how rapidly is the cloud evolving in time? (A frozen turbulence approximation cannot distinguish spatial change from time change).

For this reason, FIRE will analyze an extended region and set of times for cloud properties in the region of the two surface sites (SHEBA, ARM). This region will be roughly 2000 km square and will rely on the NOAA polar orbiters as the data source of the cloud analyses. The GOES satellite views are too oblique to be useful at these latitudes (viewing zenith angle > 70 degrees). Cloud analysis will be provided both by ISCCP (D1 gridded data and DX pixel data) and by individual FIRE investigators.

### *3.3.8 Sampling considerations*

There are two outstanding sampling issues in testing both cloud models and cloud remote sensing data:

- How many independent samples are required?
- What constitutes an independent sample?

The answer depends greatly on the particular scientific question being asked. It is not possible to determine accuracy estimates for every possible cloud question which might be asked. As discussed in Appendix C, the types of clouds, seasons, climate regions, time and space scales define too large a range of options; there are about 4000 different cloud/observing combinations.

The optical depth, cloud overlap, solar zenith, viewing zenith, and viewing azimuth affect the nature of remotely sensing cloud properties from surface, aircraft, or space-based passive radiance measurements. For purely thermal infrared techniques, the viewing azimuth and solar zenith restrictions can be removed. We argue in Appendix C that for Arctic FIRE/SHEBA, there are about 72 cases for evaluation of passive cloud remote sensing methods, while for evaluation of active remote sensing methods and cloud modeling there are only 4 cases each. In other words, testing of passive remote sensing algorithms is the key issue.

The analysis given in Appendix C leads to the following conclusions:

- We cannot get sufficient aircraft flight hours to evaluate satellite polar cloud retrievals within any reasonable expenditure of manpower and cost.
- We can obtain sufficient surface data taken continuously under satellite overpasses within a 1-5 year time record of ARM data. The longer the time record, the more accurate the evaluation of the satellite ensemble mean for testing climate models.

This suggests a bootstrap approach to evaluation of satellite remote sensing algorithms:

i. Use surface based lidar/radar/radiometers to determine required cloud properties at the SHEBA ice breaking ship from August 97 - September 98.

ii. Evaluate the retrieved surface based cloud properties against aircraft in-situ data. This will require flying aircraft vertical stepped profiles of microphysics over the SHEBA surface site.

iii. Evaluate the retrieved satellite derived cloud properties against the surface based cloud property profiles

iv. Use year of SHEBA surface cloud data to evaluate ISCCP-retrieved cloud properties using the two NOAA polar orbiter sets of SHEBA overpasses. With two satellites (one AM, one PM) we expect roughly a doubling of the number of independent samples per day over the EOS-AM analysis noted earlier (40 independent samples per case in one year). Only the last two months of SHEBA will likely overlap with EOS-AM.

v. In August/September 1998, a 3-week mission involving the ER-2 and in-situ aircraft will underfly EOS-AM cloud observations to obtain initial samples over the ice sheet. If this mission focuses on evaluation of stratus/stratocumulus retrievals only over ocean and ice backgrounds (single and multi-layer) then it can obtain 10 flights times 4 independent samples per flight / 2 overlap conditions = 20 independent samples of single and multi-layer Arctic stratus. Other cloud types will not be sampled in this approach, but in the summer, St/Sc is observed 63% of the time. If vertical profiles of microphysics are tested, (4 levels) then only 5 independent samples for St/Sc cases will be obtained.

vi. After SHEBA, the ARM DOE Point Barrow site will come on line with similar lidar/radar/radiometer profiling of Arctic cloud properties. EOS-AM and EOS-PM retrievals will be evaluated using this ARM data over a one to five year period, with increasing accuracies as a longer evaluation period is obtained. The one weakness of this approach is if the summer Arctic clouds over the ice sheet are so different from the Point. Barrow clouds, that they are not representative of clouds over Arctic ice. It is expected that winter clouds will be the same for either Barrow or the ice sheet. The dominant boundary layer cloud affected by the ice sheet is sampled in August/September by the ER-2.

vii. After SHEBA is over, and the ARM Point Barrow site is operational, fall and winter aircraft missions are required to evaluate the retrieved vertical profiles of cloud microphysics derived from the surface site.

The sampling strategy outlined above is efficient, and maximizes the use of aircraft and surface data to evaluate satellite retrievals.

There are some issues that will have to be monitored as experience is gained, however. In particular, the sampling strategy assumes that the uncertainties in converting active lidar/radar/radiometer data to microphysical vertical profiles are fundamentally more tractable than those incurred from passive satellite remote sensing. In this event, it is further assumed that the evaluation of the active cloud properties requires many fewer samples to understand and evaluate the underlying radiative transfer algorithms used to invert the active remote sensing data, and thereby allow its extension to other cases that were not directly sampled. For example: if we evaluate the water droplet microphysics profile derived from active lidar/radar surface observations: it does not matter whether the water cloud was single layer versus overlapped, or even whether the water cloud was Cb, Cu, St/Sc, or As/Ac. The active remote sensor observation probes a specific point in the cloud, and its performance should only be a function of the particle size/shape (i.e. single scattering properties) and the attenuation of signal to and from the point in the cloud. This suggests that evaluation of the surface active sensing microphysics profiles will require more aircraft evaluation for ice cloud (poorly known single scattering properties) than for water cloud. In fact, the evaluation strategy should be based on “cloud type” only in the sense that certain cloud types tend to have certain particle size/phase/shape. In fact, the largest changes in microphysics often occur in the vertical profile of particle size/shape within the same cloud at one time.

Therefore, a single aircraft stepped profile can sample many "independent" cloud microphysics cases. This suggests the following aircraft evaluation strategy:

**Table 4 - Aircraft evaluation strategy.**

| Observing strategy | Cloud Particle Cases Needed | Observations per flight | Conditions needed | Observations per flight |
|---|---|---|---|---|
| Surface lidar, radar/Ac | 4 water | 2 | one thick, one thin | 2 |
| | 8 ice | 4 | one thick, one thin | 2 |

The four water cloud cases are effective droplet radii of approximately 4, 8, 16, and 32 mm. On any given flight, the aircraft will typically sample 2 of these sizes in the vertical profile. The eight ice cloud cases are different ice particle size/habit from 5 mm to more than 200 mm. A typical cirrus cloud case is expected to have a vertical profile with perhaps half of these particle cases. The observation conditions (thick/thin) refer to regions of the cloud with little attenuation (near cloud base) and high attenuation (large optical depth into the cloud). Mixed phase microphysics (water and ice in the same volume) should be a superposition of the water and ice solutions, and will be sampled adequately as a subset of the water and ice cloud cases above. The ideal cases will be overlapped cloud so that retrievals for both water and ice cloud could be evaluated in the same aircraft flight. An hour of aircraft time should be sufficient to measure eight stepped levels (20 km, 4 minute crosswind legs centered over the surface site). However, the SHEBA ship surface site will probably be a 2 hour transit flight for the aircraft, so 1 hour of on-site time is essentially a 5 hour flight mission. Note that the legs are stepped to allow collection of accurate broadband radiative fluxes from the aircraft, for testing of the vertical profile of radiative heating. Flight levels will be radioed to the aircraft based on real-time observation of cloud levels by the surface active remote sensors. A target number of evaluation samples from SHEBA/Arctic FIRE is 3 per microphysics class:

$$3 \text{ samples per case} = 3 * (4/2 + 8/4) * (2/2) = 12 \text{ flights} = 60 \text{ hrs.}$$

This is a reasonable number of flight hours for the spring and summer 1998 in-situ aircraft deployments (4 aircraft, roughly 240 hours total: i.e. 25% for vertical profiles over the SHEBA site). This data set will have to be combined with additional aircraft microphysical flights over the ARM site on Point Barrow and in Oklahoma to extend the verification samples of the surface remotely sensed microphysics as a function of particle phase/size/habit. Classification of the results will be done by effective radius and shape. The uncertainty in the surface based microphysical profiles will be reduced with time as additional aircraft evaluation missions are flown.

For ice clouds, the use of ice replicator sondes should be explored. Each sonde launch could replace an aircraft flight. A difficulty with the sonde launches, however, is the horizontal advection of the sonde causing spatial matching noise when comparing to the surface site. SHEBA may have a tethered balloon with the ability to profile microphysics for low clouds. This data source can in principle replace many of the aircraft flights if successful. The aircraft could then focus on the upper level ice clouds.

### *3.4 Numerical weather prediction models*

Documentation of the large-scale atmospheric structure is critically important for modeling studies as well as for interpretation of the large-scale context and effects of the smaller-scale process with which a FIRE field program is most directly concerned. Numerical Center for Environmental Prediction (NCEP) (and possibly Canadian Meteorological Centre (CMC) and ECMWF) operational medium range forecasts will be used to provide gridded regional analyses with high vertical resolution (25-50 hPa) and horizontal resolution (50-100 km) over the Arctic. These analysis will include standard meteorological parameters (geopotential, temperature, mixing ratio, winds) and also special parameters such as cloud amount and properties, radiation fields, surface fluxes, vertical velocity, and contributions of individual physical parameterizations to the tendencies of model prognostic variables. This will allow a detailed intercomparison of in situ measurements with the model's physical parameterizations, which indirectly affect its analyses. To improve the quality of the analyses in the FIRE/SHEBA operations region, soundings taken during SHEBA and other collaborative experiments will be encoded in World Meteorological Organization (WMO) format and broadcast on the GTS (Global Telecommunications System) so that they can be assimilated by the forecasting centers in real time. We will rely on SHEBA personnel to work with NCEP, CMC and ECMWF to ensure that these experimental soundings are recognized and accepted by the quality control systems of their numerical models. Whenever possible, aircraft soundings and dropwindsondes will be taken during FIRE to improve observations of the advective contributions to moisture and heat and at the SHEBA ice station. C. Bretherton will work with the meteorological centers to incorporate these soundings as part of reanalyses.

While no routine radiosonde observations are taken in the Arctic Ocean, satellite-derived atmospheric temperature retrievals and surface pressure and temperature data from drifting sea ice surface buoys do provide data. Because of possible model deficiencies in high latitudes, these analyses must nevertheless be used with caution, particularly for the moisture field.

## 4.0 Analysis of Data After the Field Phase

### *4.1 Data integration and diagnostic studies*

The scientific payoff from FIRE does not come merely from collecting a set of measurements, even if the set is comprehensive and some of it has been analyzed to retrieve key quantities. Rather the real payoff comes from using the retrieved results to answer questions about what is going on in the Arctic. The key overarching question for FIRE is:

***What is the cloud-radiative feedback on the Arctic energy balance?***

The subsidiary questions are:

***What are the properties of Arctic clouds, including their synoptic and annual variations?***

***How do Arctic clouds alter radiative exchanges between the surface, atmosphere and space?***

***Why are these particular clouds produced in the Arctic?***

To answer these questions from observations requires, first, the reduction of the measurements of the most important quantities that are associated with the controlling cloud and radiative processes, with particular emphasis on characterizing the variations of these quantities over the relevant space and time scales that are indicative of the processes at work. Most of the proposed investigations concentrate on this aspect of the observations. However, each of the measurement systems has limitations of coverage and resolution and many quantities must be inferred from remote sensing measurements from all the platforms. Thus, the FIRE experiment is not complete until combined analyses of observations from many platforms are integrated to address the main scientific questions.

Although there are a few proposals to conduct such “integrative” studies, the scope of the needed studies really requires a greater team effort to be effective. Therefore, to insure that adequate attention is paid to coordinating research efforts to accomplish these combined diagnostic studies, three Integration Task Teams will be formed from the FIRE team membership. These teams will be responsible for informing the larger team of observation and data reduction needs and for encouraging and coordinating research that leads to integrated datasets and analysis results.

#### *4.1.1 Satellite remote sensing evaluation*

Given the combined expertise of the aircraft and satellite investigators on the FIRE team, the FIRE team has a lead role within SHEBA for developing needed satellite remote sensing tools to complete the SHEBA analysis, particularly for observations of clouds, the atmosphere and surface (SHEBA expertise will lead remote sensing of sea ice properties). As described in the Satellite Observation section, we already have routine satellite measurements of temperature and humidity profiles (by NOAA operations - TIROS Operational Vertical Sounder (TOVS) products, Smith et al. 1979, McMillin 1991) and cloud properties (cover, top temperature and height, optical thickness by ISCCP, Rossow and Schiffer 1991) in polar regions, but they have not been sufficiently evaluated. Moreover, we have well-developed methods for retrieval of liquid water cloud particle sizes (Han et al. 1994, Minnis et al. 1992) and liquid water path over open water (Greenwald et al. 1993, Liu and Curry 1993, Lin and Rossow 1994), but these have not yet been tried in polar regions. There are also some ideas for retrieving the some properties of ice phase clouds (Wielicki et al. 1990, Minnis et al. 1993, Young et al. 1994, Lin and Rossow 1994) that have not been tested thoroughly. We can already anticipate significant limitations of some of these analysis methods for polar studies because of instrument design limits or because the surface-cloud-atmosphere variations are too complex. A key analysis concept that may mitigate some of these problems is the analysis of coincident observations from many different instruments. In particular combinations of multi-channel optical and microwave imagers and infrared and microwave profilers has been suggested by some work (Baum et al. 1994, Liu et al. 1995) but is not fully developed. The primary obstacle to progress is lack of observations for evaluation.

The heterogeneous characteristics of available and future instrumentation preclude a straightforward comparison of different measurements. Rather a statistical comparison is required to account for different sampling of smaller space and time scales. The strategy is to use the in situ and higher resolution aircraft measurements to check the larger datasets that can be acquired from surface remote sensing instruments. These larger datasets, complemented by in situ measurements of surface properties from SHEBA and ARM, can then be used to evaluate the satellite retrievals. Thus, a subset of the FIRE team must conduct investigations that integrate a comprehensive collection of coincident observations from aircraft, the surface and satellites, where similar or “identical” quantities are retrieved, to determine how well cloud, atmosphere and surface properties can be determined from satellites alone. This study includes analyses of multiple satellite observations.

Some examples of this type of study are Wielicki et al. (1990), Nakajima et al. (1991), Minnis et al. (1993), Rossow et al. (1993) and Han et al. (1995), where statistical comparisons are made of satellite and surface and/or aircraft observations. The only proposed studies of this type are by Minnis et al., Rossow et al, and Han and Welch, though this approach is implicit in the proposal of Tsay and King. The first part of these studies will be to compare the cloud properties already being retrieved and to extend the development of methods for retrieval of ice phase cloud properties. Specifically, the ISCCP analysis has already been revised to incorporate a treatment of ice phase clouds based on earlier FIRE results, but this needs evaluation for polar ice clouds. The particular complexity of the Arctic atmosphere is that the atmosphere and surface also undergo very large annual variations, so that attention must also be paid to improving satellite measurements of surface and atmospheric properties as well clouds. The study by Rossow et al includes some study of improved surface retrievals. These three studies will combine observations from a large number of satellite instruments with available surface lidar/radar and aircraft microphysics information.

Note that none of the aircraft or surface investigations proposed to conduct this type of analysis (however, the approach is implicit in the proposal of Tsay and King at that from ETL). The critical weakness that this situation indicates, based on past experience with FIRE I and II, is that the amount of aircraft data and surface data that is actually reduced will be insufficient for this type of study. Every effort must be made to complete the analysis of much larger amounts of aircraft and surface observations and to coordinate/compare analysis results or the remote sensing evaluation objective of FIRE will not be met. The first Integration Task Team (proposed co-leaders: B. Wielicki and M. King) will focus on this combined task.

Specific study tasks include:

(1) evaluate the treatment of radiative transfer in ice clouds and quantify uncertainties in retrieval of ice cloud properties from satellites,

(2) quantify the effects of small-scale horizontal variability and vertical structure in clouds on remote sensing analyses of their properties,

(3) check the accuracy of temperature retrievals in inversion conditions,

(4) check the accuracy of humidity profiles obtained from infrared and microwave satellite instruments, and

(5) evaluate current surface temperature and albedo retrieval methods.

*4.1.2 Cloud effects on radiative fluxes*

Measurements of the properties of clouds, surface and atmosphere allow one to infer radiative fluxes, in principle. Such analyses have been done for the Arctic based on ISCCP (Darnell et al. 1992, Schweiger and Key 1994, Rossow and Zhang 1995), but these calculations are much more detailed than available validating datasets with the exception of top-of-atmosphere fluxes that can be compared with NIMBUS-7 Earth Radiation Budget (ERB) and Earth Radiation Budget Experiment (ERBE) values. The extensive nature of the satellite datasets even allows for such an analysis over the whole Arctic basin and over the annual cycle (Curry et al. 1996), but we cannot verify some important conclusions that are implied in these results. Two crucial examples are that, given indications that Arctic cloud cover is very nearly complete year-round (Warren et al. 1988, Curry and Ebert 1992, Rossow and Garder 1993), the ice- albedo feedback may be significantly weakened by the presence of clouds and ability of the Arctic ocean to cool in winter may be significantly inhibited. Does this mean that clouds are a strong negative feedback on Arctic climate? We do not know.

Although there continue to be some important uncertainties in how clouds are to be represented in radiative transfer calculations (Stackhouse 1995), current uncertainties in these radiative flux analyses are dominated by uncertainties in the measured physical variables. The most important quantities include cloud water content and particle size and surface albedo -- most particularly their annual variation. The only proposed diagnostic study (Rossow et al) will implement the improved cloud and surface retrievals discussed above and compare the calculated fluxes with any available surface and in situ measurements of spectral and broadband fluxes. Although one objective of this investigation is a general improvement of this type of analysis for global studies, the opportunity exists for producing a special diagnostic radiative flux product by using the combination of surface, aircraft and satellite observations within the FIRE/SHEBA experiment area to provide the needed input quantities. This task requires systematic analysis of the observations from as many instruments over the whole time period as possible, rather than limited case-study analyses. The key uncertainties in the representation of clouds in radiative transfer models are three: treatment of ice phase clouds, treatment of small-scale horizontal inhomogeneity, and treatment of cloud vertical structure, particular phase changes. Two investigations (Mishchenko et al, Liou et al) specifically focus on the first question and are coordinated with satellite analyses (Rossow et al, Minnis et al, respectively). These studies will be complemented by some laboratory measurements planned by Lawson. The study by Han and Welch also addresses some similar issues. However, only the Mishchenko et al. proposal articulates a specific observation and analysis strategy that uses combined observations from surface, aircraft and satellite platforms. Many other proposals concern making measurements related to the microphysical properties of ice clouds, but do not mention any combined-instrument analyses. Only one investigation (Wielicki) addresses the horizontal inhomogeneity question directly, but this study relies solely on the very high resolution Landsat data and does not indicate a combined analysis of long-term lidar/radar datasets. No investigations plan combined diagnostic studies of cloud vertical structure, though there will relevant measurements from aircraft and the lidar/radar instruments. The radiative flux calculations planned by Rossow et al include calculated flux profiles, so that diagnosis of radiative heating/cooling rate profiles for the FIRE/SHEBA experiment region may be possible.

The second Integration Task Team (proposed co-leaders: W. Rossow and S. Pilewskie) will focus on this combined task.

Specific tasks:

(1) compare calculated surface radiative fluxes and flux profiles to surface and aircraft observations, respectively, as function of cloud and atmospheric properties,

(2) quantify uncertainties and their causes in the treatment of ice phase clouds,

(3) evaluate effects on radiative fluxes of large cloud particle size changes or phase changes with altitude,

(4) evaluate treatment of SW fluxes at extremely low solar zenith angles,

(5) confirm spectral dependence of fluxes under various meteorological conditions, and

(6) incorporate combined datasets for more comprehensive heating/cooling rate profile diagnosis.

#### *4.1.3 Aerosols and chemistry*

When simultaneous CCN spectra and cloud droplet concentrations are matched the effective cloud supersaturations can be determined. These can be compared with those obtained in other stratus cloud projects (e.g. Hudson and Svensson 1995). Appropriate cloud droplet concentrations and CCN from FIRE on the Ice should be compared with FIRE and ASTEX to determine the relative role of CCN in affecting cloud microphysics. This analysis should be extended to drizzle drop concentrations to determine if the aerosol effect extends to precipitation as well as cloud albedo. If variations are found in droplet spectral width then these will be compared with CCN spectral shape to determine if this affects the susceptibility to precipitation. IFN measurements should also be compared with ice particle concentrations. Comparisons of CCN spectra with chemical measurements of the size segregated aerosol can better determine aerosol sources especially when coupled with trajectory analyses. The size of the CCN can also be compared with particle chemistry to determine if soluble and insoluble material can be identified. The chemistry of the particles that are found in CVI filter measurements can be compared with the CCN spectra that are found in the CVI. These can be compared with ambient measurements of CCN volatility and particle sizes to better characterize those particles that really act as CCN. The effect of the clouds on the aerosol can also be ascertained by comparing CCN spectra at various altitudes to determine whether physical (i.e. coalescence scavenging) or chemical (i.e. conversion of SO2 to sulfate) processes within the clouds have altered the aerosol.

### *4.2 Modeling overview*

Direct measurement of cloud formation/decay processes will require resolving the relevant space-time scales of atmospheric motions and variations in water, including phase changes and transports from lower latitudes (Curry 1983) and to and from the surface, particularly over leads (Pinto and Curry 1995). Some analogous studies have been or are being conducted for tropical cases (e.g. Xu and Randall 1996).

Moisture transport involves processes occurring in the shallow Arctic atmospheric boundary layer (McInnes and Curry 1995, Pinto and Curry 1995, Walsh et al. 1993). Such studies should also be complemented by an indirect approach that examines larger scale variations of clouds and atmospheric dynamics. There are several modeling proposals that are focused on aspects of this topic, primarily at the smaller scales of the direct approach, but their data analysis plans are not described (Bretherton, Kogan, Krueger, Lenschow and Wang, Randall, Wang). Only three modeling proposals include explicit plans to attempt such a diagnosis from observations (a possible exception is a "cirrus" proposal by Ackerman et al.): Curry and Cotton for Large Eddy Simulation (LES) models, Del Genio for a GCM, and Isaac for a GCM. The latter includes special emphasis on the role of chemistry and aerosol processes in cloud formation.

The third Integration Task Team (proposed co-leaders: C. Bretherton and J. Curry) will provide a small planning group to communicate the evolving data analysis needs of the model investigations to the FIRE team and to coordinate the proposed model experiments. Specific tasks include the following:

(1) compile (with the help of the whole FIRE team) comprehensive case study datasets, including atmospheric large scale circulation, boundary layer turbulence, cloud and surface properties;

(2) compile simulations of these cases from column models, LES models and GCMs;

(3) diagnose moisture fluxes and radiative fluxes and their seasonal variations.

As mentioned earlier, cloud microphysical properties have been studied with combinations of ground-based remote sensors in FIRE II and ASTEX. Processing and integration of these measurements are required to relate them to cloud-scale model simulations. The high frequency of observations possible with ground-based remote sensors will also allow an evaluation of the representativeness of the relatively infrequent rawinsonde observations of atmospheric structure.

The fourth integration Task Team (proposed leaders: S. Krueger and T. Uttal) will seek to ensure that measurements from ground-based remote sensors are processed in ways that will allow them to be integrated with measurements from other platforms (surface, rawinsonde, and satellite), and to be used to evaluate cloud-scale model simulations.

Arctic FIRE will employ a variety of models, ranging from cloud-scale models to global climate models. Models with dynamical components will require relevant large-scale boundary conditions such as advective tendencies and vertical motion, which will be derived from gridded analyses from NCEP, and possibly CMC and ECMWF.

#### *4.2.1 Approaches*

We will couple three basic modeling approaches during Arctic FIRE: 3D cloud-scale models, 2D cloud-scale models, and 1D models. These approaches will be used to help develop and evaluate parameterizations of cloud-scale processes, boundary layer structure, and cloud-aerosol interaction in global climate models.

### *4.2.2 Cloud-scale models*

Cloud-scale models simulate the larger scales of turbulence. They include 3D (also called large-eddy simulation or LES) models and 2D (also called cloud ensemble or eddy-resolving models). The premise of such models is that given observed boundary conditions and large-scale forcing, the model is able to simulate the dynamical response, which in many cases of interest includes convection and clouds. Simulations can be modified to study the role of particular physical processes.

A cloud-scale model (or eddy-resolving model) has a grid size on the order of 50 m or less in the vertical and horizontal directions, and can explicitly represent all of the important flux-producing eddies that are at work inside clouds. Cloud-scale models also include microphysics and interactive solar and infrared radiation parameterizations. 3D cloud-scale (or large-eddy) simulations are very expensive computationally, typically do not cover more than a few simulated hours, and are restricted to domains that are much smaller than GCM grid boxes.

2D cloud-scale models are particularly useful if detailed microphysical or aerosol schemes are included, or if broader horizontal domains including surface inhomogeneities such as leads are simulated. 2D cloud-scale models can also be used for multi-day simulations. One of the 2D models to be employed during Arctic FIRE, the University of Utah model, includes a sophisticated turbulence closure model for small-scale turbulence.

2D cloud-scale models have proven to be very useful for studying the stratus to cumulus transition in subtropical marine boundary layer (Krueger et al. 1995 a, b; Wyant et al. 1996). This cloudiness transition is primarily due to the response of the stratocumulus-topped boundary layer to increasing SST. A case study of such a transition was observed in detail during the first Lagrangian experiment of ASTEX. Simulations of this case performed with 2D cloud scale models for the second GEWEX Cloud System Studies (GCSS) Boundary Layer Clouds Modeling Workshop show generally good agreement with the observations.

### *4.2.3 1D models*

1D models to be used during Arctic FIRE include turbulence closure models and single column models. A single-column model (SCM) includes the entire set of physical parameterizations of a GCM active in a single grid column. A fundamental use of a SCM is to develop and evaluate parameterizations for GCMs. As part of Arctic FIRE, we will also conduct GCM simulations using improved versions of these parameterizations.

## *4.3 Arctic low-level cloud regimes: What are we trying to model?*

The principal thrusts of our modelling efforts will include:

(1) The vertical and temporal distribution of cloud, microphysical parameters and radiation in the area of the SHEBA site over the annual cycle.

(2) Multilayer summertime Arctic stratus

(3) Springtime mixed-phase clouds and the effects of leads.

(4) Aerosol/Arctic cloud interactions, especially during spring and summer.

We will now discuss each of these in more detail.

### *4.3.1 Vertical and temporal distribution of cloud properties at the SHEBA site*

In conjunction with SHEBA, D. Randall will develop a single-column model of the coupled Arctic atmosphere-ice-ocean system based on the CSU GCM and compare it to measurements taken at the SHEBA site over the entire annual cycle. The model will be forced by the large scale advective tendencies analyzed by operational models. FIRE aircraft measurements will help evaluate the assumptions behind the cloud parameterizations. Intercomparison with Arctic FIRE cloud scale models will also be used to improve the parameterization framework. Important specific issues that will be addressed with this SCM include:

- Studies of the sensitivity of the coupled system to external perturbations, e.g. CCN perturbations, moisture and temperature advection perturbations.
- Simulation of Arctic summer stratus, including formation, dissipation, convective transports, and optical properties, and also including a faithful representation of the dependence of cloud amount, cloud depth, and cloud optical properties on the properties of the lower boundary, including the fraction of open water, melt-pond coverage, and snow cover.
- Simulation of the formation and dissipation of Arctic winter "diamond dust" clouds, including their effects on the downward longwave radiation at the surface.
- Simulation of the seasonal transitions, including the coupled evolution of cloudiness and the ocean / ice surface.
- Investigation of the extent to which the cloud amount and optical properties of the Arctic summer stratus depend on the state of the lower boundary, e.g. ice cover and thickness, snow-cover and thickness, melt-pond cover and thickness.
- Study of the ways in which Arctic clouds affect the surface energy budget, both instantaneously in all seasons, and integrated over an annual cycle.

In addition, C. Bretherton will work with at least one of NCEP, CMC or ECMWF to compare the SHEBA data with diagnosed surface and radiative fluxes, cloud properties, and turbulent transports from an operational forecast model. The goal is to test and improve forecast model parameterizations in the Arctic, but this intercomparison should also help us assess the quality of the operational analyses which will be used to drive the SCMs.

### *4.3.2 Multilayer summertime Arctic stratus*

2D and 3D cloud scale models and 1D turbulence closure models will be used to better understand the multilayer structure of Arctic summertime stratus cloud and distinguish between the various hypotheses described in the FIRE Phase III Science Plan. Two groups (W. Cotton and J. Curry, and Y. Kogan and D. Lilly) will use 3D large-eddy simulation (LES) models with detailed microphysics, while two other investigators (C. Bretherton and S. Krueger) will use 2D and 3D cloud-scale models with bulk microphysics. S. Krueger will also use a 1D version of his model.

### *4.3.3 Springtime mixed-phase clouds and the effects of leads.*

To understand the cloud and boundary layer processes during the springtime, models must include representations of mixed phase microphysics. Y. Kogan and D. Lilly will expand their bin-resolved microphysical model to include the size spectrum of ice particles, and compare their results against springtime measurements. In addition, the surface fluxes of heat, moisture and perhaps even aerosols in plumes from leads are very important in the winter and spring. S. Krueger will use a 2D model to examine the plume structure and the aggregate effects of plumes on the boundary layer. A related SHEBA investigation by Q. Shao will study the same problem with a

3D model. W. Cotton and J. Curry will study the microphysical structure and ice crystal formation in plumes.

#### *4.3.4 Aerosol/Arctic cloud interactions, especially during spring and summer.*

The LES model of Y. Kogan and D. Lilly will also be used to investigate the sensitivity of cloud structure and radiative fluxes to aerosol abundance and size spectrum within the boundary layer.

### *4.4 Observations needed to make modeling studies possible*

#### *4.4.1 Initialization and boundary conditions*

Modeling studies require data for initialization, to provide observationally specified boundary conditions in some cases, and for evaluation of the model results.

As mentioned earlier, all models require some specification of the large-scale advective tendencies, including those due to vertical motion, and the geostrophic wind. We will rely on analyses from the operational weather services to best integrate the available data. However, the Arctic basin is a data void, although it is surrounded by fairly dense observational networks. Additional observations made from the ice should considerably improve these analyses. Particularly valuable observations will include those from rawinsondes and wind profilers operated at the SHEBA ice station, and from dropwindsondes deployed from FIRE aircraft. The SHEBA rawinsonde data will be assimilated into the NCEP, CMC and ECMWF operational forecast models (see section 3b).

For models that prescribe surface characteristics rather than predict them, the following additional observations are necessary: statistical descriptions of spatial distributions of surface temperature (to incorporate the effects of leads and melt ponds), surface spectral albedos and emissivity, and surface roughness length. Area-averaged surface heat and moisture fluxes are also needed. SHEBA is expected to provide all of the above measurements. For models that do not predict cloud particle size distributions, observed profiles of droplet spectra are needed. For models that incorporate aerosol-microphysical interactions and/or the radiative effects of aerosols, aerosol size spectra and chemical composition are required. If upper-level clouds are present, the downwelling radiative fluxes must be specified at the domain top for models with limited vertical domain size.

#### *4.4.2 Model evaluation*

Measurements are required not only to perform simulations, but to evaluate them as well. These include profiles of temperature and water vapor, obtainable from radiosondes, dropwindsondes and aircraft soundings, as well as less readily available observations of surface fluxes of sensible and latent heat and spectrally-resolved up and downwelling radiative fluxes (to be provided by SHEBA), and various in situ and remotely sensed radiation and cloud measurements. Most useful for model evaluation are liquid and ice water content and effective radius profiles, cloud fraction profiles, and turbulent and radiative flux profiles. These will be provided/determined/estimated from measurements made by a combination of SHEBA surface-based remote sensing instruments, FIRE aircraft in situ and remote sensing instruments, and operational satellite sensors.

## 5.0 Concluding Remarks

FIRE's foray into the Arctic, in collaboration with SHEBA and ARM, represents an important broadening of the scientific scope of the FIRE program as a whole. This strategic step is motivated by the acknowledged importance of the Arctic for the global climate system, and an appreciation of how poorly we understand Arctic clouds and the energy budget of the Arctic surface.

At the same time, this Implementation Plan for the Arctic phase of FIRE is quite consistent in approach with the earlier phases of FIRE's "boundary-layer cloud" projects, first off the coast of California in 1987, and then in ASTEX during 1992. The emphasis is on a combination of aircraft measurements and satellite retrievals. Surface data will be provided primarily by SHEBA and ARM.

Further information about the FIRE program and FIRE's planned Arctic field mission can be obtained by contacting the FIRE Project Manager, David S. McDougal, Mail Stop 483, NASA Langley Research Center, Hampton, VA 23681, 804-864-5832, d.s.mcdougal@larc.nasa.gov. A summary of FIRE's organization and data management structure is given in Appendix D.

## Appendix A - Summary of SHEBA Science Plan[1]

SHEBA is a research program designed to document and understand the physical processes that couple the atmosphere, ice, and ocean in the Arctic. The central motivation behind SHEBA is the large discrepancies among global circulation model (GCM) predictions of present and future climate in the Arctic, and the uncertainty about the impact of the Arctic on climate change. These difficulties are due, in large part, to incomplete understanding of the physics of vertical energy exchange within the ocean-ice-atmosphere system. In particular, the central theme of SHEBA emerges from issues related to the surface energy balance, especially the ice-albedo and cloud-radiation climate feedback mechanisms. The SHEBA program is based on the premise that improved understanding of the physical processes involved in air-sea-ice interactions is needed to address the issues of climate feedback in the Arctic and to improve our ability to model the Arctic climate. Hence, the goal of SHEBA is to acquire the knowledge needed to correctly parameterize the physical processes in numerical models of the atmosphere-ice-ocean system, and to integrate these processes into GCMs.

The essence of SHEBA as a project is to conduct a year-long field experiment (starting Autumn 1997) at a drifting station on the pack ice of the Arctic Ocean, in combination with remote sensing and modeling analyses of the entire Arctic Basin. The primary focus is on processes that determine the ice-albedo feedback and the cloud-radiation feedback. The observational program emphasizes a coordinated and comprehensive measurement effort examining the physical processes associated with interactions among the radiation balance, mass changes of the sea ice, storage and retrieval of energy and salt in the mixed layer of the ocean, and the formation of clouds and their influence on the surface energy balance. The modeling effort aims to improve the parameterizations of crucial air-sea-ice interactive processes in climate models. The large-scale context for the SHEBA field site will be provided by geophysical data products derived from satellite-borne sensors.

The timeliness of SHEBA derives from the recognition of a need to clarify the role of high latitudes in global climate on various time scales, a desire to improve the physics included in air-ice-ocean models, the availability of new observational technology, including satellite derived geophysical products, and a shared motivation with several other programs. Primary sponsorship of SHEBA is provided by the National Science Foundation Arctic System Science (ARCSS) Program and the Office of Naval Research (ONR) High Latitude Program. In addition, SHEBA is being designed in collaboration with the Submarine Science Ice Experiment (SCICEX), sponsored by a consortium of federal agencies led by ONR; the First ISCCP Regional Experiment III (FIRE III), sponsored principally by the National Aeronautics and Space Administration; the Department of Energy Atmospheric Radiation Measurement (ARM) program; and the NASA sponsored EOS-POLES project. International collaboration is coordinated under the auspices of the Arctic Climate System Study (ACSYS) of the World Climate Research Programme.

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[1]. Available in draft form as this FIRE Arctic Implementation Plan was written.

## Appendix B - Summary of Relevant Parts of the ARM Science Plan

ARM chose the North Slope of Alaska as a locale because the Arctic is hypothesized to have large climatic feedbacks linking surface and tropospheric temperatures, surface albedo, evaporation, cloud cover, deep ocean water production (the global thermohaline ocean circulation pump), and the polar atmospheric heat sink. The North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) ARM site will be centered at Barrow, Alaska. A supplementary site will be established at Atqusuk, which is about 100 km inland from the coast

The specific scientific objectives to be addressed at the NSA/AAO site focus on improving the performance of climate models at high latitudes by improving our understanding of specific physical processes. The specific objectives are enumerated below, in the form of questions.

Document the radiative environment and how it is determined by atmospheric constituents and thermodynamics.

Determine the physical, chemical and dynamical processes responsible for determining the Arctic cloud characteristics.

Understand the radiation-climate feedback processes operating in the Arctic.

Aircraft measurements on a campaign basis are needed for in situ evaluation of the surface-based remote sensing systems. ARM will coordinate with aircraft campaigns from other programs in the Arctic. A major campaign will take place in conjunction with SHEBA and FIRE III in the Beaufort Sea. These aircraft campaigns are critical for providing in situ measurements to evaluate the ground-based remote sensing retrievals. Additionally, there are several suitable aircraft based on the North Slope for which appropriate instrumentation packages could fairly easily be prepared. Use of such non-dedicated aircraft would make periodic in situ measurements of several different types much more affordable, particularly dropsonde deployment. Because of logistical difficulties and cost limitations on the North Slope, dropsondes are an attractive option relative to surface-based radiosonde launch facilities at boundary sites.

Satellite remote sensing must play a major role in observing the Arctic environment, because of the paucity of conventional observations. The NSA/AAO observations will be used to evaluate and interpret satellite observations in this region, and thus extend the observational time/space domain.

ARM will test improved parameterizations using single-column models. To study the formation, maintenance, and dissipation of cloud systems, and to improve parameterization of these processes in climate models, atmospheric mesoscale models are also needed.

Virtually all of ARM’s scientific objectives will be pursued in collaboration with the Surface HEat Budget of the Arctic Ocean (SHEBA) and Arctic FIRE.

## Appendix C - Analysis of Sampling Strategies

This appendix describes in detail the sampling strategy discussed in section 3.3.8.

There are two outstanding sampling issues in testing both cloud models and cloud remote sensing data:

- How many independent samples are required?
- What constitutes an independent sample?

The answer depends greatly on the particular scientific question being asked, and would differ greatly for the following examples:

- What is the decadal average global cloud cover?
- What is the yearly averaged cloud height over Brazil?
- What is the seasonal cycle in cloud optical depth off the coast of California?
- What is the ENSO variation of high cloud amount over the western tropical Pacific?
- What is the seasonal cycle of cloud particle size and phase over the Arctic?
- What is the cloud height at 1800 GMT on January 15, 1999 over the Oklahoma ARM site?

It is not possible to determine accuracy estimates for every possible cloud question which might be asked. The types of clouds, seasons, climate regions, time and space scales define too large a range of options.

There are two obvious ways to focus the possibilities:

- Define a reasonably small set of representative cloud types.
- Define a reasonably small set of representative climatic regimes.

Both of these approaches have been tried in analyses of surface-observed cloud statistics (Hahn et al., 1982; Sherr et al., 1968).

FIRE has followed the "cloud type" approach, and has examined 3 of the 6 types to date:

| | | | |
|---|---|---|---|
| St/Sc | Stratus/Stratocumulus | July, 1987<br>June, 1992 | Off the California Coast<br>Azores |
| Cu | Cumulus | June, 1992 | Azores |
| Ci/Cs/Cc | Cirrus | October, 1986<br>November, 1991 | Wisconsin<br>Kansas |

Remaining cloud types are Cumulonimbus (Cb), Nimbostratus (Ns), and Altostratus/Altocumulus (As/Ac). Is midlatitude oceanic stratus fundamentally the same cloud as polar stratus, however? Given the large changes in surface temperature, moisture fluxes, and atmospheric stability, a model successfully tested on oceanic boundary layer cloud in the subtropics may well fail when applied to boundary layer clouds over the Arctic ice pack. Further, the remote sensing of clouds over ocean, land, and especially snow/ice surfaces can differ greatly. This suggests the inadequacy of a simple cloud type classification.

Evaluation of remote sensing algorithms suggests a need to test a minimal set of:

- 6 cloud types as listed above,
- 7 climate regions:

  ocean: tropics and midlatitudes

  land: tropics, midlatitudes, and poles

  desert: midlatitudes

  snow/ice: poles

- 2 optical thickness (thin, thick)
- 2 cloud overlap conditions (single layer, multi-layer)
- 3 solar zenith angles (0, 60, night; i.e. cosine of the zenith angle = 1, 0.5, 0)
- 3 viewing zenith angles (0, 45, 65. i.e. cosine of the viewing zenith angle = 1, 0.7, 0.4)
- 3 viewing azimuth angles (0, 90, 180)

This gives a total of (6)(7)(2)(2)(3)(3)(3) = 4536 different cloud/observing combinations. Of course, some of the cloud types, climate regions, and optical depths are mutually exclusive (Cb at the poles over snow/ice, or optically thin Ns) so that this number might be reduced to closer to 4000.

The optical depth, cloud overlap, solar zenith, viewing zenith, and viewing azimuth affect the nature of remotely sensing cloud properties from surface, aircraft, or space-based passive radiance measurements. For purely thermal infrared techniques, the viewing azimuth and solar zenith restrictions can be removed. For active lidar and radar, the solar zenith and azimuth can be eliminated, for a factor of 10 fewer cases (order 400). For any given cloud type and climate region, (say midlatitude land cirrus) the number of cases to test reduces to 108, with some solar zenith angles being inappropriate (e.g. overhead sun for polar ice/snow). In particular, for Arctic FIRE/SHEBA, we might be left with:

(2 depth)(2 overlap)(2 solar zenith)(3 viewing zenith)(3 viewing azimuth) = 72 cases

for evaluation of passive cloud remote sensing methods.

For evaluation of active remote sensing methods (e.g. combined surface nadir uplooking lidar/radar/radiometer profiles of cloud microphysics) the number of cases per cloud type simplifies to:

(2 depth)(2 overlap) = 4 cases

For cloud modeling tests, the number of cases would be:

$$(2 \text{ overlap})(2 \text{ solar zenith}) = 4 \text{ cases}$$

for each cloud type considered. The above analysis suggests that evaluation of remote sensing algorithms requires at least an order of magnitude more cases to test than a dynamical cloud model.

The preceding analysis suggests that the number of cases that must be studied is an order of magnitude larger for passive remote sensing than for active remote sensing or for cloud model evaluation. It also suggests that the total number of samples required, *Nt*, can be thought of as:

$$Nt = (Nc)\ (Ns)$$

where *Nc* is the number of cloud type/observing condition cases and *Ns* is the number of independent samples of each case. *Ns* will determine how well we can estimate the uncertainties in modeling or measuring any given case. For a gaussian error in measuring a given cloud case, we can derive the following simple table for the 95% confidence limits as a function of the number of independent samples:

| Ns | Standard Deviation | Mean |
|---|---|---|
| 5 | $\sigma_{true < 1.5\ \sigma est}$ | $m_{true = mest \pm 1.2\ \sigma}$ |
| 10 | $\sigma_{true < 1.35\ \sigma est}$ | $m_{true = mest \pm 0.7\ \sigma}$ |
| 30 | $\sigma_{true < 1.2\ \sigma est}$ | $m_{true = mest \pm 0.2\ \sigma}$ |
| 100 | $\sigma_{true < 1.1\ \sigma est}$ | $m_{true = mest \pm 0.1\ \sigma}$ |

For example. if we have 30 independent samples of cirrus cloud height determination which estimate a mean bias error of 500 m, and a standard deviation of 1.5 km, we can say with 95% confidence that the true standard deviation of the cloud height error is less than (1.5)(1.2) = 1.8 km. At the same time we can say that the bias error in cloud height is with 95% confidence between 200 m and 800 m. If our concern is climate research, so that the most critical confidence bound is that of the ensemble mean, then clearly the number of independent samples required to estimate the ensemble mean depends directly on the noise of the measurement technique. For most current remote sensing techniques, the standard deviation of the error is roughly 10-20% of the mean value, so that knowledge approaching 1-2% in the ensemble mean would require evaluation against 100 independent samples.

What constitutes an "independent sample?" Leith (1973) considered this issue for climate statistics and concluded that for typical "red" atmospheric spectra, that a workable definition of independence was twice the time or distance required for the autocorrelation function value to fall to 1/*e*. For midlatitude geopotential height, Leith found the independence scale at midlatitudes to be 6.5 days. At 10 m $s^{-1}$ this is roughly 5000 km (i.e. ~ wavenumber 6). Cahalan et al. (1982) examined 2.5 degree gridded NOAA heat budget longwave flux data and concluded that this scale was roughly 1000 km. This number is probably a rough indication of cloud height independence scale. It is probably an upper estimate, however, given that the large grid size (250 km) causes an overestimate, and given that this data included both large clear areas (very uniform and not pertinent to cloud tests) as well as the less uniform cloudy regions. In this sense, the estimate of Cahalan et al. (1982) represents the distance between different cloud types (i.e. high cloud to low cloud), as opposed to the independence scale of any given cloud type. A similar estimate of the scale of independence between different cloud types was obtained by Jones (1992), who examined the autocorrelation of surface observer cloud fraction and suggested an independence scale of about 700 km.

An examination of the FIRE I San Nicolas Island LWP time series (1 minute samples for 19 days) gives an independence scale of about 300 km for stratocumulus. It is likely that the independence scale (hereafter denoted by *L*) for different cloud variables differs, with *L*(cloud height) > *L*(cloud particle size) > *L*(LWP or optical depth). Any short time series, however, will tend to systematically underestimate the true independence scale. Further work is needed to define these scales as a function of cloud type and cloud physical property. Critical data sets would include:

- cloud top/base from LITE space-borne lidar data (700 m or 7 km resolution)
- cloud optical depth from AVHRR LAC (best) or GAC (acceptable)
- cloud particle size from AVHRR LAC(best) or GAC (acceptable)
- cloud fraction from AVHRR LAC or GOES 1-km: need to define a grid size for cloud fraction: 5, 20, 100, 500 km.

For conditional sampling, one difficulty will be objective determination of each cloud type from a large set of satellite or surface observations. From earlier work, the appropriate independence scales for cloud properties probably lie between 100 and 500 km.

Suppose that the correct scale is 250 km. In this case, we can estimate how rapidly a surface site, an aircraft, and a satellite can collect independent samples:

| Data Source | Speed | Time to move 250 km | Samples/Time |
|---|---|---|---|
| ARM/SHEBA: | 10m/s | 7 hours | 3.5 / day |
| ER-2: | 200m/s | 0.3 hours | 17/flight |
| Satellite: | 7000m/s | 0.5 minutes | 3000 / day |

How many independent samples can FIRE/SHEBA obtain? It depends on what we are after.

First, consider “Cloud Type Frequency of Occurrence.” The first step is to determine the expected cloud types for the Spring (April, May) SHEBA/Arctic FIRE deployment. Using Hahn et al., 1982, March/April/May, for 75N, 135W cloud frequency of occurrence is taken from surface observations. Assuming that the time scale for changing cloud type is greater than 1 day (i.e. changing synoptic systems), we have the following expected conditions for 1 month of field observations:

| | Days/Month | Days/Month |
|---|---|---|
| Cloud Type | Single-Layer | Multi-Layer |
| St/Sc | 8 | 13 |
| Ci/Cs/Cc | 3 | 11 |
| As/Ac | 1 | 11 |
| Ns | 0 | 8 |
| Cu | 1 | 3 |

Two days are predicted to be clear. We then find a total of 15 days with either clear or single-layer cloud, and 15 days with multi-layer cloud.

Next, consider “Satellite observation frequency of occurrence/conditions.” The following satellite observations are expected from EOS-AM 10:30 am sun-synchronous orbit: (correct later to NOAA am and pm sun-synchronous)[2] for April 1, 75N, 140W:

2. (Note: We need to extend these same statistics for 7 am, 2 pm NOAA orbits for the SHEBA field phase in 1998 for evaluation of ISCCP. But the above statistics will apply to EOS-AM overpasses of the ARM north slope site after the SHEBA/FIRE field deployments have been completed.)

| Orbit overpasses per day | 8.5 |
|---|---|
| Range of local times | 1130pm - 1230pm, every 1.7 hours |
| Daily time gap | 11 hours |
| Solar zenith angle | 70 - 90 degrees, daily |
| Viewing zenith angle | 0 - 65 degrees, daily |
| Viewing azimuth angle | 85 - 92 degrees, daily |
| Phase function scattering angle | 90 - 105 degrees, daily |

Using the above statistics: we expect over the SHEBA or ARM sites to observe:

| Cloud/Climate Class | Comments | Observing Strategy |
|---|---|---|
| 5 Cloud types | (no Cb) | 1 day = 1 type |
| 2 Climate regions | (ice, land) | SHEBA = ice, ARM = land |
| 2 Overlap conditions | (single, multi) | 1 day = 1 type |

| Observing Condition | Comments | Observing Strategy |
|---|---|---|
| 2 Optical thicknesses | (thin, thick) | within each day: cloud scale |
| 2 Solar Zenith | (70, > 90 degrees) | within each day |
| 3 Viewing Zenith | (0, 45, 65 degrees) | within each day |
| 1 Viewing Azimuth | (90) | within each day |

We can now take the above Classes, and predict the number of independent samples expected for different sampling strategies. For the estimates below we predict the average time to get 30 independent samples of each Cloud/Observing Class.

| Observing Strategy | Cloud Cases Needed | Cases Obs/day | Obs Conditions Needed | Conditions |
|---|---|---|---|---|
| Obs/day | 2 * 5 | 1 | 12 | 8 |
| Surface Site vs. Satellite | ovlp*type | | $2\tau*2\theta_{0*lq*l\phi}$ | |

30 samples per case = 30 * 10 * 1 * (12/8) = 450 days = 1.5 yrs

100 samples per case = 100 * 10 * 1 * (12/8) = 1500 days = 4 yrs

Missing Observation Conditions: None.

Disadvantages: no oversampling to beat down instrument noise.

| Observing Strategy | Cloud Cases Needed | Cases Obs/Flight | Obs Conditions Needed | Cond. Obs/Flight |
|---|---|---|---|---|
| ER-2 / ER-2 | 2 * 5 | 8 | 4 | 4 |

| | | | | |
|---|---|---|---|---|
| (MAS?Lidar) | ovlp*type | | $2\tau*2\theta_{0*lq*l\phi}$ | |

30 samples per case = 30 * 10 * (1/8) * (4/4) = 38 flts = 225 hrs

100 samples per case = 100 * 10 * (1/8) * (4/4) = 125 flts = 750 hrs

Missing Observation Conditions: Only validates nadir satellite viewing angle, and only validates cloud
height and cloud amount.

Advantage: oversampling to reduce instrument noise effects.

| Observing Strategy | Cloud Cases Needed | Cases Obs/Flight | Obs Conditions Needed | Cond. Obs/Flight |
|---|---|---|---|---|
| ER-2/In-Situ | 2 * 5 | 4 | 4 | 4 |
| (MAS/In-Situ) | ovlp*type | | $2\tau*2\theta_{0*lq*l\phi}$ | |

30 samples per case = 30 * 10 * (1/4) * (4/4) = 75 flts = 450 hrs

100 samples per case = 100 * 10 * (1/4) * (4/4) = 250 flts = 1500 hrs

Missing Observation Conditions: no vertical profiles of effective particle size.

Evaluation of models of viewing zenith dependence requires a sawtooth flight pattern by in-situ aircraft under the ER-2: further exacerbating the large difference in flight speed of the two aircraft. Stacked in-situ aircraft vertical profiling of microphysics greatly reduces the number of independent samples obtained per flight. If 4 levels are measured, we get 1/4 the independent samples, so we need 4 times as many flights as determined above.
Advantage: oversampling to reduce instrument noise effects.

# 1.0 LEAD MANAGEMENT

FIRE has been a multi-agency effort since its inception. The goals of FIRE are not bounded by a single agency's mission; neither is the talent base required to address the complex problems of cloud-climate research. Close interagency cooperation in the past has made possible FIRE's advancements in our understanding of these climatically important cloud systems. It is intention of FIRE's participants to maintain and further refine this spirit of interagency cooperation.

While NASA will continue to serve as the lead agency for FIRE-III, other federal agencies including National Science Foundation (NSF), Office of Naval Research (ONR), Department of Energy (DOE), Department of Defense (DOD), and National Oceanic and Atmospheric Administration (NOAA) will remain strong participants in FIRE-III. The Radiation Sciences Program, Atmospheric Science Branch, NASA Headquarters, will provide overall cognizance of the FIRE project and will represent FIRE to the Working Group on Data Management for WCRP Radiation Projects. Contact points are located at the following offices:

| | | |
|---|---|---|
| Dr. Robert Curran<br>Atmospheric Science Branch<br>NASA Headquarters/YS<br>Washington, DC 20546 | Dr. Robert Abbey, Jr.<br>Office of Naval Research<br>Code 1122 MM<br>800 N. Quincy Street<br>Arlington, VA 22217 | Dr. Michael Ledbetter<br>Arctic Systems Science Program<br>Office of Polar Programs<br>National Science Foundation<br>2401 Wilson Boulevard<br>Arlington, VA 22230 |
| Dr. Jay Fein<br>Atmospheric Sciences<br>National Science Foundation<br>1800 G Street, NW<br>Washington, DC 20550 | Dr. Pam Stephens<br>Atmospheric Sciences<br>National Science Foundation<br>1800 G Street, NW<br>Washington, DC 20550 | Dr. Richard Lawford<br>NOAA/OGP<br>Mail Stop GP<br>1100 Wayne Avenue<br>Silver Spring, MD 20910 |
| Dr. Pat Crowley<br>Department of Energy<br>Environmental Sciences<br>Division<br>Research ER-74<br>Washington, DC 20585 | | Dr. Rex Fleming<br>Director, Climate Observations<br>NOAA/ERL<br>3300 Mitchell Lane, Suite 175<br>Boulder, CO 80301 |

# 2.0 PROJECT MANAGEMENT

The FIRE project activities will be managed by the FIRE Project Office at NASA's Langley Research Center. The FIRE project manager will be responsible for the overall management, coordination, and reporting of the project activities. These responsibilities will include interacting with the Radiation, Dynamics, and Hydrology Branch and Physical Climate and Hydrology Branch management at NASA Headquarters, the Meteorology Research Program management at ONR, and the other agency representatives; overall cognizance of project planning, schedules, and field operations; and allocation of approved funding to support the scientific objectives. The project manager will be assisted by a project scientist and a project staff, which will include: an Operations Manager, a Data Manager, and a Project Coordinator.

Project Scientist - The FIRE Project Scientist will be responsible for all scientific aspects of FIRE. The project scientist will (a) act as a scientific advisor to the project manager; (b) represent the members of the science team in their relationship with the project manager; (c) maintain an oversight of the scientific integrity of the project; (d) review and make recommendations of proposed modifications to selected proposals as warranted; and (e) participate in negotiations regarding allocations of specialized project resources among approved investigations.

Operations Manager - The Operations Manager will have overall responsibility for organizing, scheduling, and conducting field operations, preparation of mission plans, establishing mission objectives with the MST Chairman, determining special support requirements, conducting planning and debriefing sessions, and operational procedures. The Operations Manager is also responsible for designing the specific and facilitating operationally feasible flight profiles to meet the scientific objectives and for coordinating the experimental requirements of measurement platforms for resources, testing, and integration for all field measurements. Lastly, the Operations Manager is responsible for the setup, testing, and operation of the mission operations site.

Data Manager - The Data Manager will be responsible for coordinating the types, scope, and quantity of data collected during the intensive field and extended-time activities and its archiving. The Data Manager will serve as the Chairperson for the Data Management Working Group. The Data Manager will ensure that the data is submitted as required to the FIRE Central Archive and eventually released to the scientific community.

Project Coordinator - The Project Coordinator will provide administrative support to the FIRE Project Office, including logistical and reimbursement support in the planning and conducting of FST meetings and field missions as required.

# 3.0 FIRE-III SCIENCE TEAM

The FIRE-III Science Team (FST) will be comprised of the principal investigators of those agency-approved proposals directly related to FIRE-III research. Appointment to the FST will be based on the recommendation of the supporting agency. The term of participation on the team will continue as long as the approved research continues. The team shall determine its own structure and method for interaction. Ex officio members may be appointed to the team, as needed, by the project manager.

The FST will be responsible for implementing the broad scientific objectives of the project in accordance with the selected investigators. Additional responsibilities will be to:

a. Develop implementation plans for FIRE research including:
    1. field experiments.
    2. data management.
    3. research programs.
b. Recommend and perform coordinated research activities, including the interface of modeling and experiments.
c. Conduct individual investigations in accordance with approved proposals.
d. Hold meetings and workshops, as needed, to plan and assess research programs.

e. Designate the makeup and responsibilities of special working groups, as needed, to address special task areas.

f. Establish a data protocol that will promote the timely publication and dissemination of scientific results.

Table 1 lists the FST members, their institutions, and working groups in which they will be participating. S refers to both stratus and Arctic cloud systems. Figure 1 shows a schematic of the relationships between the agencies, the agency program managers, the FIRE Project Office, and the FST.

**Table 1 - FIRE-III Science Team: C = Cirrus only;** $\underline{C}$,A = Cirrus principal, Arctic/Stratus secondary; C,A = Cirrus and Arctic/Stratus equal; C,$\underline{A}$ = Cirrus secondary, Arctic/Stratus principal; A = Arctic/Stratus only

| Name | Organization | Sponsorin g Agency | Research Thrust |
|---|---|---|---|
| Tom Ackerman | PSU | NASA | C |
| Bruce Albrecht | PSU | ONR | A |
| Chris Bretherton | U Washington | NASA | A |
| Kenneth Campana | NMC | NOAA | $\underline{C}$,A |
| Bill Cotton | CSU | NASA | C,A |
| Steve Cox | CSU | NASA | $\underline{C}$,A |
| Judy Curry | U Colorado | NASA | A |
| Tony Del Genio | GISS | NASA | C,A |
| Leo Donner | GFDL | NOAA | C |
| Wynn Eberhard | NOAA-ETL | NOAA | C,$\underline{A}$ |
| Chris Fairall | NOAA-ETL | NOAA | A |
| Hermann Gerber | Gerber Scientific | NASA | C,A |
| Jim Hack | NCAR | NSF | $\underline{C}$,A |
| John Hallett | DRI | NASA | $\underline{C}$, A |
| Mike Hardesty | NOAA-ETL | NOAA | C,$\underline{A}$ |
| Andy Heymsfield | NCAR | NASA | $\underline{C}$,A |
| Peter Hobbs | U Washington | NASA | A |
| Jim Hudson | DRI | NASA | C,$\underline{A}$ |
| George Isaac | AES | NASA | A |
| Mike King | GSFC | NASA | C,$\underline{A}$ |
| Yefim Kogan | U Oklahoma | ONR | A |
| Sonya Kreidenweis | CSU | NSF | $\underline{C}$,A |
| Bob Kropfli | NOAA-ETL | NOAA | C,$\underline{A}$ |
| Steven Krueger | U Utah | NASA | A |
| Paul Lawson | SPECinc | NASA | $\underline{C}$,A |
| Don Lenschow | NCAR | NASA | A |
| Kuo-Nan Liou | U Utah | NASA | C |
| Martin Miller | ECMWF | NASA | C,$\underline{A}$ |
| Pat Minnis | LaRC | NASA | C,A |
| M. Mishchenko | GISS | NASA | $\underline{C}$,A |
| Peter Pilewskie | ARC | NASA | C,A |
| Michael Poellot | U North Dakota | NASA | C |
| David Randall | CSU | NASA | C,$\underline{A}$ |
| Bill Rossow | GISS | NASA | C,$\underline{A}$ |

| | | | |
|---|---|---|---|
| Ken Sassen | U Utah | NASA | C |
| Jim Spinhirne | GSFC | NASA | C,A |
| David Starr | GSFC | NASA | C |
| Graeme Stephens | CSU | NASA | C,A |
| Brian Toon | ARC | NASA | C,A |
| Si-Chee Tsay | GSFC | NASA | C,A |
| Taneil Uttal | NOAA-ERL | NASA,NOAA | C,A |
| Francisco Valero | ARC | NASA | C,A |
| Shouping Wang | MSFC | ONR, NASA | A |
| Ron Welch | SDSMT | NASA | C,A |
| Bruce Wielicki | LaRC | NASA | C,A |
| Don Wylie | U Wisconsin | NASA | C,A |
| Qing-Yu Zhao | NMC | NOAA | C,A |

## 3.1 FIRE Working Groups

FIRE has been designed to address a number of complicated scientific problems. The FIRE strategy is to assemble those members of the scientific community with interests in these problems and to create an environment which encourages them to collectively pursue the solutions to these problems. FIRE working groups representing the themes of cirrus cloud systems, marine stratocumulus and arctic cloud systems, and data management will be constituted from the FST membership as follows:

i. Cirrus Working Group

ii. Arctic Working Group

iii. Data Management Working Group

The Cirrus and Arctic Working Groups will accept the following responsibilities:

i. Define specific goals to be collectively pursued; these include, but are not limited to the following:
   a. satellite intercomparisons;
   b. satellite-in situ intercomparisons;
   c. case studies;
   d. GCM parameterizations.

ii. Identify responsible individuals in each of the collective study areas referred to in item i and monitor the progress of the collective research.

iii. Define data sources, requirements and schedules essential to working group studies.

iv. Exchange data among FST and working group members.

v. Oversee publication of joint research results from tasks identified in item i.

The Data Management Working Group (DMWG) will be comprised of key members from the Cirrus and Arctic working groups, as well as from the FIRE Central Archive. The FIRE Data Manager will chair the DMWG. The responsibilities of the DMWG are:

i. provide interaction and coordinate data management decisions among the FIRE data gathering working groups, the FIRE Central Archive, and the principal investigators.

ii. ensure uniform FIRE data characteristics (throughout all working groups and FIRE researchers)

iii. define listings of uniform parameter units and conventions for reduced data products.

iv. oversee the plans, progress, and performance of the FIRE Central Archive (see section 4.1.3).

# 4.0 DATA MANAGEMENT

Data management is an ongoing activity, beginning immediately in the pre-experiment phase and continuing through the end of FIRE-III. Collaboration and data exchange of data among FIRE investigators will be required to produce integrated analyses of multi-platform, multi-scale, and multi-spectral data sets; these integrated analyses are central to the accomplishment of the FIRE-III science objectives. In addition, the data management activities will seek to ensure the availability of FIRE data and analysis products to the entire science community. To maximize these data management goals, the FST will develop a data management and protocol plan consistent with the supporting agencies' goals for the sharing of the data, the rapid dissemination of results, and documentation of measurements obtained.

At a minimum, the data management activities will disperse most of the data reduction and processing functions to the FIRE investigators engaged in collecting and analyzing the data, but to hold the resultant data sets and analysis products centrally for ready access by all FIRE investigators. The FIRE Central Archive, located at the Langley Research Center EOSDIS Distributed Data Active Archive (DAAC), and the FIRE Project Office will provide a centralized source of information and copies of data which are centrally archived. The FST, composed of the investigators, will coordinate the decentralized data reduction and analysis activities. In addition, the FIRE Central Archive will transfer, from time to time, certified FIRE data to the scientific community.

Data management activities in FIRE will insure the exchange of data among FIRE investigators that is required to produce the integrated analyses of multi-platform, multi-scale, and multi-spectral data sets; these integrated analyses are central to the accomplishment of the FIRE science objectives. In addition, the data management activities will insure the availability of FIRE data and analysis products to the entire science community. These activities will be carried out by four organizational components within FIRE:

(1) the Cirrus and Arctic Working Group,

(2) the individual FIRE principal investigators,

(3) the FIRE Central Archive, and

(4) the FIRE Project Office.

The strategy embodied in this organization is to disperse most of the data reduction and processing functions to the FIRE investigators engaged in collecting and analyzing the data, but to hold the resultant data sets and analysis products centrally for ready access by all FIRE investigators. The FIRE Central Archive and the FIRE Project Office will provide a centralized source of information and copies of data which are centrally archived, whereas the FIRE Working Groups, composed of the investigators, will coordinate the decentralized data reduction and analysis activities. In addition, the FIRE Central Archive will transfer, from time to time, certified FIRE data to EODIS and/or other organizations for permanent archive and for open access by the scientific community.

## 4.1 Data Management Responsibilities

### 4.1.1 Working Groups

There are two data-gathering FIRE working groups - a Cirrus Working Group, and an Arctic Working Group. These working groups will be composed of FIRE principal investigators pursuing research relevant to that working group. The data management responsibilities of the individual principal investigators, as dispersed elements of the FIRE data processing system, could become onerous if not coordinated properly. Therefore, the FIRE Working Groups must govern these individual activities to insure progress toward the FIRE science objectives. The data management functions of the FIRE Working Groups are:

1. To determine the content and format of all principal investigator data sets to be submitted to the Langley Research Center Distributed Active Archive System (LaRC DAAC). If requested, only FIRE-III researchers will have access to data in the LaRC DAAC during the time period for data certification.

2. To set standards for data quality, documentation of all data sets, and certification criteria for data products that will be released to the at-large scientific community.

3. To assign a data “category” (section 8.5) to each data parameter that reflects it's usefulness to subsequent data analysis and whether and when it should be archived.

4. To select case study data sets for special intensive processing (including reformatting) by all relevant principal investigators and to identify other additional processing of data to accomplish FIRE-III objectives.

5. To coordinate data management decisions and ensure uniform FIRE-III data characteristics.

6. To certify, within 6-24 months after acquisition, those data products from the LaRC DAAC that will be released to the scientific community.

### 4.1.2 Principal Investigators

All data reduction and analysis functions in FIRE-III reside with the scientists carrying out their research as part of the program. To encourage the interactions of these researchers needed to integrate the various observations and models into a more comprehensive understanding of clouds and their effects, FIRE-III investigators will have free and timely access to all data collected during FIRE-III, either by individual principal investigators or collected from satellites. Coordination of data analysis and modeling activities requires all principal investigators to perform certain other tasks as part of the FIRE-III data management scheme. These functions are:

1. To provide to the LaRC DAAC written information concerning data holdings, including all data collected as part of FIRE-III and other data deemed relevant to FIRE-III research.

2. To save all data collected in unreduced form for five years so that reduction of data can be repeated if necessary.

3. To provide to the LaRC DAAC copies of all category 1, 2, 3 (when practical), and 4 (if desired) observations in a mutually-agreed upon format (see section 7.2 for definition of data category) accompanied by complete instrument, reduction algorithm and data format documentation.

4. To provide, within 9 months after acquisition, to the LaRC DAAC copies of any data analysis products deemed relevant to the accomplishment of FIRE-III objectives, accompanied by appropriate documentation.

5. To provide for archival of all submitted data sets by producing back-up copies of all data and taking other necessary precautions to ensure the preservation of the FIRE-III data.

6. To provide to other FIRE-III investigators or the LaRC DAAC, upon request, copies of other data sets acquired for FIRE-III research, that are relevant to other FIRE-III studies.

7. To provide to other FIRE-III investigators reasonable access to unreduced observations to facilitate particularly crucial multi-data analyses.

#### 4.1.3 Langley DAAC

The LaRC DAAC will serve as the FIRE-III Central Archive. The LaRC DAAC is responsible for archiving and distributing NASA science data in the areas of radiation budget, clouds, aerosols, and tropospheric chemistry. It will also archive some of the data sets which result from the EOS program and other elements of Mission to Planet Earth.

The DAAC has developed an on-line computer system which allows the user to logon, search through the DAAC's data inventory, choose desired data sets, and place an order. Data may be received either electronically (via FTP) or on media such as 4mm tape, 8mm tape, or CD-ROM (prepackaged datasets only).

Users with an X-Windows terminal (e.g., Motif) or a Sun Open Windows display system with access to Internet, may log onto the system by entering:

```
xhost + eosdis.larc.nasa.gov

(or: xhost + 192.107.191.17)

telnet eosdis.larc.nasa.gov

login name: ims    password: larcims
```

At the prompts, enter x for the X-Windows interface and then your display name (name of your workstation followed by ":0" or internet address followed by ":0").

Users with access to NCSA Mosaic can use the following URL address:

```
http://eosdis.larc.nasa.gov/
```

Users without access to a terminal with an X-Windows display system but who have access to Internet may log onto the system by entering:

```
telnet eosdis.larc.nasa.gov

login name: ims    password: larcims
```

At the prompt, enter c for the character interface and then press return.

Users who cannot access the system or who have questions concerning the Langley DAAC may contact:

Langley DAAC User and Data Services
Mail Stop 157B
NASA Langley Research Center
Hampton, VA 23681-0001

Phone: (804) 864-8656   FAX: (804) 864-8807
email: larc@eos.nasa.gov

For further information on LaRC DAAC contact Ms. Sue Sorlie, Langley Research Center, 804-864-8660, s.e.sorlie@larc.nasa.gov or John Olson at 804-864-8609, olson@magician.larc.nasa.gov.

The LaRC DAAC will provide a centralized data holding and on-line system in order to facilitate easy access to all FIRE-III data by all FIRE-III investigators. Since most of the satellite data are not collected directly by FIRE-III principal investigators, the LaRC DAAC will also be responsible for holding of the satellite data sets required for FIRE-III research from the relevant satellite operating agencies. The specific data management functions of the FIRE-III Data Archive are:

1. To hold all reduced observations and data analysis products submitted by individual principal investigators or groups of principal investigators upon the request of the FIRE-III Science Team.

2. To hold all satellite data sets required for FIRE-III as specified by the FIRE-III Science Team.

3. To provide, upon request, copies of any data sets to FIRE-III investigators (at minimal cost to investigators).

4. To produce a data ingest request of the complete FIRE-III data holdings of the archive and the individual principal investigators indicating the current analysis status of these data. The data ingest request entries should provide information about the location of the data holding, the instrument(s)

performing the observations, the temporal and spatial resolution of the data, and the format of the data.

5. To update the data ingest request every year and to make it available to FIRE-III investigators in both hard copy and electronically (on-line dial-up) form.

6. To restrict access to the data products in the LaRC DAAC to only researchers associated with the FIRE-III project, if so requested by the FST. The at-large scientific community will not then have access to these data sets until they are released.

7. To "release", on an annual basis, certified FIRE-III data from the permanent archive for unrestricted access by the at-large scientific community. The "transfer" process removes the access restraints to the at-large scientific community.

8. To provide for archival of the permanent FIRE-III data in the data archive by producing back-up copies of all data and taking other necessary precautions to ensure the preservation of the data.

9. To publish documentation, such as a FIRE-III Data Archive Users Manual that describes the contents of the FIRE-III Data Archive, data formats, data request information, and other pertinent descriptive material.

#### 4.1.4 Project Office

FIRE data management structure vests the primary data processing function with the individual scientific investigators, the information and archival functions with the Central Archive, and the decision-making with the FIRE Working Groups. The Project Office must provide for liaison among these different groups. The specific data management functions of the project office are:

1. To provide liaison between the FIRE Working Groups (and individual principal investigators) and the data collecting agencies and agencies operating observing platforms required by FIRE.

2. To provide liaison between the FIRE Central Archive and the satellite and other data collecting groups to facilitate the acquisition of the data sets needed for FIRE.

3. To provide for a close working relationship among the FIRE Working Groups and the Central Archive by including a representative of the Central Archive on the Project Office staff who can attend FIRE Science Team meetings.

## 4.2 Data Products

There are several types of data products that will be acquired, submitted, and archived at the LaRC DAAC. These products, which will be obtained from a variety of instruments onboard satellite, airborne, or surface-based platforms during the field experiment, are as follows:

1. Guide/Summary--written information about the data holdings of the individual PI's, including location of the data holdings instrument(s) performing the observations; resolution and area coverage of the data; date, time, and location of the observations; format of the data; and analysis status of these data.

2. Raw data--original observations acquired by the instrument, in instrument units (voltages, etc.).

3. Reduced data--observations converted to the physical quantity directly sensed by the instrument with quality control inspection and removal of bad data.

4. Value-added products--physical quantities derived from the observations, including documentation on the analysis algorithm and any auxiliary data sets used in the analysis.

5. Calibration, quality, and navigation information--describes the conversion to physical units, the conditions of observation and the location of the observation.

6. Instrument documentation and data tape format description.

7. Data for special case studies which have been arranged for intercomparison of multi-platform observations.

8. Data selected for special processing to facilitate model studies.

9. Status and bibliography of FIRE-III publications.

The data acquired by the individual experimenters will be reduced to final values and forwarded to the LaRC DAAC. The format for the submittal of data to the archive must be in ASCII or HDF/netCDF (see Appendix F). In addition, a written description of the readme file or pertinent remarks should be included in the data file or in a separate file to be submitted with the data. The Langley DAAC will assist data producers putting data into HDF.

Transfer of the final data between the investigators and the LaRC DAAC may be accomplished by electronic data transfer using ftp.

Transfer of the data from the data archive to the investigators will be done either physically (using DATs, 9-track tapes or floppy disks) or interactively (via electronic transfer) where such systems are available (email or ftp).

## 4.3 Data Categories

Each of the data products will be assigned a data “category” by the science team which will reflect its usefulness to subsequent data analysis and whether and when it should be archived.

Table 2 outlines the definition of the four data categories. The FIRE-III Science Team will be responsible for these assignments, coordinated with the responsible PIs.

**Table 2 - Definition of Data "Categories"**

| Category | Definition | Usefulness | Archive? |
|---|---|---|---|
| 1 | Fundamental measured parameter | Critical | ASAP or 3-6 months |
| 2 | Fundamental measured parameter | "A lot of people will use it" | 9-18 months |
| 3 | Reduced or value-added parameter | Useful | Welcomed; not required |

## 4.4 Data Protocol and Publications Plan

The FIRE-III data protocol and publication plan has been prepared to encourage an orderly and timely analysis, interpretation, and publication of the data obtained during FIRE-III. It is hoped that the development and distribution of this plan will enhance the science output by promoting cooperation among the investigators and encouraging the early publication of results, thereby enriching the scientific interpretation of the data obtained from single and ensemble of instruments.

The FIRE-III Science Team (FST) is responsible for the certification of data submitted to the permanent FIRE-III data archive located at the Langley Research Center (LaRC) Distributed Active Archive Center (DAAC). The certification process will normally take 6-24 months after acquisition. During the certification process period, the following set of data protocol and publication ground rules will be agreed upon and abided to by all FST members as a condition of their participation in the FIRE-III project.

### 4.4.1 Data Protocol

1. FST members will have free and timely access to all FIRE-III data acquired during the project. The normal vehicle for data dissemination will be a transfer of data via the LaRC DAAC; however, direct transfer of data between investigators is also encouraged.

2. Each investigator's data is proprietary until the data appear in publication or, if the data are included in the LaRC DAAC, until this archive is published/released to the scientific community. FST members who collect FIRE-III data are responsible for the reduction, analysis, interpretation and publication of their data and research results.

3. An investigator whose unpublished data are to be used in an investigation has the right to be included among the authors of any resulting publication. The investigator may refuse co-authorship but not the use of his data. The investigator must provide information concerning the quality of the data and may require that suitable caveats regarding the data be included in the publication. It is the responsibility of the sponsoring investigator to solicit the participation of the investigator whose data are to be used as early as possible during the formative stages of the investigation.

4. FST members may release their own data to whomever they wish. They may not release the data of other investigators without consent.

5. Selected sets of reduced data obtained by investigators participating in collaborative research will be made available to FST participants within 9 months following acquisition.

6. The FST will normally provide the forum in which collaborative investigations are planned and executed; however, this is not meant to discourage collaborative investigations outside the scope of FIRE-III.

7. Any data sets resulting from collaborative investigations among FST members will be made available to the LaRC DAAC. This includes all collaborative efforts both within and outside the FST.

8. Scientists who are not FST members, co-investigators, or associates may participate in investigations using unpublished FIRE-III data provided they are sponsored by a FST member and they make available whatever data they plan to use to the LaRC DAAC at the beginning of the participation. Co-investigators and associates may participate in the investigation of a FST member.

### 4.4.2 Data Publication

Early publication of results from FIRE-III research is strongly encouraged. Towards this goal, the following minimum publication plan has been developed:

1. An overview synopsis of the FIRE-III program will be prepared by program personnel and key FST researchers for publication in an appropriate journal. The paper will describe the scientific objectives, operational plans, and potential results of the major FIRE-III activities to the scientific community during the early stages of FIRE-III.

2. A synopsis of the key operational activities and possible results from the FIRE-III field experiment will be prepared by project personnel and key FST researchers for publication in an appropriate journal. This paper will be designed to be a "quick look" publication to inform the scientific community at an early stage of the implementation of the mission and possible highlighted observations.

3. Publication of results from the FIRE-III field experiment may be in a special issue of an appropriate journal. The special issue decision will be made by the FST. The issue will contain (a) an overview paper and (b) science papers.

   The overview paper will be co-authored by program personnel and key researchers and will include a statement of the goals of the particular field mission. It will describe the field site, the instrumentation involved in the deployment, flight plans, and other operational activities.

The science papers will be contributions from the FIRE-III investigators. They will be "stand-alone" papers that the investigators will prepare summarizing measurements, data interpretation, and data correlations. Collaborative papers between different groups are strongly encouraged.

4. A firm timetable for the publication of the special issue papers will be established whereby all of the papers will be submitted for publication prior to a mutually agreed date, usually within a year after the field experiment completion.

5. Oral presentations of selected results by the investigators and the project may be presented together at an appropriate conference.

6. Additional publications or presentations by FIRE-III investigators beyond those identified above are expected and encouraged. Other publications should, however, be in harmony with the data protocol and publication plan contained in this document.

# 5.0 INTENSIVE FIELD PROGRAM MANAGEMENT

## 5.1 Operations Plans

The FIRE Project Office and FST will prepare detailed operations plans for the two observational components of FIRE: the Arctic Cloud Experiment and a possible Tropical Cirrus Experiment. The Arctic plan must be developed as soon as possible in light of the short lead time on the field experiment.

## 5.2 Lead Mission Scientists

Dr. Judy Curry, University of Colorado, has been appointed as the Lead Mission Scientist for the Arctic Cloud Experiment; Dr. David Starr, GSFC, has been appointed as the Lead Mission Scientist for the potential Tropical Cirrus IFO. The Lead Mission Scientists will be the scientific spokespersons for their respective field experiments. They will coordinate the planning and implementation of the science objectives, conduct planning and debriefing sessions, and be the chief representatives of and arbitrators for the participants in the field missions.

## 5.3 Mission Selection Team

During the intensive field phases of the cirrus and Arctic activities, a Mission Selection Team (MST) will be formed. The MST will be comprised of no more than five FST scientists representing the multiple goals of FIRE; it will be chaired by the FST Lead Mission Scientist who has the following responsibilities immediately prior to and during the intensive field observation periods. The MST will accept the following responsibilities:

i. solicit and represent ideas of other FIRE scientists in operations, decisions, and scheduling.

ii. review on a daily basis the candidate missions proposed by the MPT (see section 5.4) and select the planned operations and scheduling of all FIRE platforms for the following day.

iii. select on a daily basis a Mission Scientist (DMS) and an Alternate Mission Scientist (see section 5.5) to plan and carry out operations selected by the MST.

iv. assemble forecast information for use in daily operations planning. *

v. maintain up-to-date experiment accomplishment records for use in daily operations planning. *

vi. maintain current status reports on all data gathering components throughout the experiment. *

vii. review daily post mission reports prepared by the Mission Planning Team (see section 5.4).

*assisted by the FIRE Project Office.

All deliberations of the Mission Selection Team will be open and in the absence of a clear consensus among its members; the chairman will assume responsibility for making operations decisions.

On issues concerning specific platforms such as aircraft or special rawinsonde ascents, an appropriate spokesperson from the contributing organization will be given the opportunity to advise the MST and to participate on the MPT.

## 5.4 Mission Planning Team

A Mission Planning Team (MPT) will be active during the cirrus and Arctic IFO phases. The Mission Planning Team will contain at least three FST members, individuals representing participating aircraft facilities, and FIRE Project Office support personnel. The MPT members for the following day will be identified on a daily basis by the MST. Ideally, on any given day, the MPT will contain candidate mission scientists for the following day's operations. It will not be uncommon for members of the MST to also serve as members of the MPT. The MPT's responsibilities are listed below.

i. Prepare candidate missions for the following day's operations and present these to the MST for consideration.

ii. Following a decision by the MST, support the Mission Scientist in preparing a detailed mission plan for the following day's operations.

iii. Prepare a post mission summary of each day's operations including an evaluation of the success of the operations. This daily summary will be made available to the FIRE Project Office and the MST and become a part of the FIRE data archive.

## 5.5 Daily Mission Scientist

A Daily Mission Scientist (DMS) will be identified on a daily basis by the MST at the same time the following day's mission is selected. In the event that the DMS plans to be aboard an aircraft during the mission, an Alternate Mission Scientist will be selected by the MST and will perform ground-based functions during the execution of the mission. The DMS will be in charge of the detailed planning of the following day's operations and the execution of that plan. He will be responsible for making any real time decision required during the execution of the plan. He will oversee the preparation of a post mission summary of each day's operations including an evaluation of the success of the operations.

A Mission Scientist must have an overall grasp of the scientific objectives of FIRE as well as an appreciation of operational constraints of the various platforms and personnel.

The Mission Scientist will be selected from a pool of lay FST researchers according to the scientific objectives to be addressed in the upcoming mission and the scientific background of the individual. Ideally, the Mission Scientist would be the previous mission's Alternate Mission Scientist so as to provide continuity between missions and familiarity with on-going meteorology conditions and forecasts.

## 5.6 IFO Meeting Schedule

The schedule of IFO meetings (and data management milestones) is given in Table 7.

### 5.6.1 Simulated IFO

Approximately 2-3 months before the intensive field mission, a simulated IFO will be conducted at an appropriate site. The purpose of the meeting will be to simulate the mission planning, based on realistic meteorological conditions and using those major platform instruments that will participate in the actual IFO. Representatives from the satellite, aircraft, and surface-based instruments will participate, as well as the IFO meteorologist/forecaster and other key researchers. Meteorology forecasts will be based on actual meteorology conditions experienced by the IFO area one year previously.

The mission planning will include: research objectives to be addressed; platforms/instruments that will operate; and deployment strategy including flight plans, operating schedules, data taking modes, etc. Constraints to be considered include finite resources (aircraft flight hours allocated, cost of rawinsonde/satellite data, etc.), realistic operational schedules (aircraft/crew constraints, personnel/instrument fatigue, etc.), uncertainty of meteorology forecast, etc. The mission plans will be evaluated for expected results, based on actual meteorological conditions experienced on the mission day, and improvements/modifications will be discussed. The meteorological forecast for the next day will be presented and the cycle repeated.

### 5.6.2 Pre-Mission Meeting

A pre-mission meeting will be held on the day before the start of the intensive field mission. The purpose of the meeting will be to welcome all participants, describe the mission operations strategy, provide information on local logistics, determine the operational status of the participating platforms/instruments, and allow the local media an opportunity to interact with the mission, principal investigators, and other participants. A mission planning meeting for the first day of operations will follow immediately.

### 5.6.3 Post-Flight Debrief

After each experiment flight there will be a post-flight debriefing of all the experimenters. This debriefing is intended to communicate and document pertinent subjective observations made during the completed mission and allow the experimenters an opportunity to modify subsequent plans or procedures for the following experiment. Each experimenter should have a "quick-look" capability for inspection of his sensor performance. A copy of the "quick-look" data (raw strip charts, tables, etc.) may be submitted to the Data Manager for possible comparison/correlation with other experiment data.

### 5.6.4 Post-Mission Debrief

A post-mission debriefing will be held on the day following the conclusion of the mission. Each experimenter will describe his sensor performance, a summary of sensor operating times, a sample of data obtained, a description of the data format that is planned to be submitted to the data archive, and a listing of experiment days to be analyzed in a priority order. The Working Group will review the missions and measurements obtained during the mission. If appropriate, it will prioritize experiment days to be analyzed, key areas of data reduction and analysis, identify possible data collaboration and exchange, and modify the data reporting schedule.

### 5.6.5 Science Data Workshop-I

A preliminary data reduction workshop will be held approximately 4 months after the conclusion of the mission. The experimenters will describe the performance of their sensors, a sample of the preliminary reduced data, an estimate of the sensor accuracy and precision, and report on key measurement results. The FIRE-III Science Team will review the measurements and analyses obtained to date, determine a priority list of case study days, identify possible collaborative research activities, and discuss future plans. The DMWG will ascertain the data parameters that have been acquired during the experiment, decide on category elements such as reduced, value-added, and investigator-held data, and assign category priorities and data submittal schedules.

### 5.6.6 Science Data Workshop-II

Approximately one year after the field experiment, a Science Data Workshop-II will be held to review the key research results. The FIRE-III Science Team will review each of the major scientific objectives in light of the measurements and analyses performed to date, review the status and availability of the data, explore synergistic relationships among the data, actively plan collaborative research activities, and discuss future plans. The DMWG will review the reduced data parameters that have been submitted, review the data category elements and priorities, and recommend possible verification and quality assurance activities.

### 5.6.7 Science Conference

About 24 months after the field experiment, the FIRE-III Science Conference will be held for the presentation of individual and group science results. This conference may be either a stand alone meeting or possibly held as part of an international science conference. The DMWG will review all data products that have been submitted, review the status of the quality assurance and verification activities, and make recommendations concerning the certification process of the data sets that will eventually be released to the scientific community.

## 5.7 Data Management Schedule

The schedule of events for the submittal of data to the archive is given below and in table 3.

### *5.7.1 Summary Information and Preliminary Category-1 Data Submittal*

Approximately 3 months after FIRE-III, the experimenters will submit the summary information and preliminary category-1 data to LaRC DAAC.

### 5.7.1 Final Category-1 Data Submittal

Approximately 6 months after FIRE-III, the experimenters will submit the final category-1 data information to LaRC DAAC.

### 5.7.2 Preliminary Category-2 and-3 Data Submittal

Approximately 9 months after FIRE-III, the experimenters will submit the preliminary reduced category-2 and category-3 (if desired) data products to LaRC DAAC.

### 5.7.3 Final Category-2 and -3 Data Submittal

Approximately 18 months after FIRE-III, the experimenters will submit the final reduced category-2 and-3 (if desired) data products to LaRC DAAC.

### 5.7.4 Release of Data to Science Community

After the certification of the data has been completed (probably within 6-24 months), the LaRC DAAC will release the data to the scientific community. Any proprietary rights (see section 4.4.1) to the data and data interpretation will be voided at this time.

**Table 3 - IFO Meeting and Data Management Schedule**

| Time, Months | IFO Meetings | Data Management Activity |
|---|---|---|
| -3 | Simulated IFO | |
| -1 (day) | Pre IFO Review; First Mission Planning | |
| 0 | IFO | |
| IFO+1 (day) | Post IFO Review; prioritize case study days | |
| 3 | Science Data Workshop-I; definition of data product categories, identification of case study investigations | Submit preliminary summary information and category-1 data |
| 6 | | Submit final category-1 data |
| 9 | | Submit preliminary category-2 and -3 data |
| 12 | Science Data Workshop-II; review data status and availability, recommend verification and quality assurance activities | |
| 18 | | Submit final category-2 and -3 data |
| 24 | Science Conference; authorize release of data to scientific community | Release data to scientific community |

# 6.0 FIRE MISSION/MEETING MILESTONES

The listing of the key FIRE missions and meetings is given in Table 4. An attempt has been made to coordinate the various meetings between the Cirrus and Arctic working groups so that those researchers who are participating in both missions can attend. Whenever the two groups hold coincident meetings, a full-up FST meeting will also be held so as to integrate the extended-time and modeling activities as much as possible. The milestone list reflects a minimum meeting schedule; other meetings may be scheduled (i.e., meetings to plan for/review Tropical Cirrus Mission) as required. Also included are some key cirrus collaborative experiments, such as the Subsonic Aircraft Contrail and Cloud Special Study (SUCCESS) and the Stratospheric Tropospheric Experiment: Radiation, Aerosols, and Ozone (STERAO). As a minimum, the entire FST will meet at least once per year.

**Table 4 - Tentative Schedule of FIRE Activities**

| Month | 1996 | 1997 | 1998 |
|---|---|---|---|
| January | | | |
| February | | | Arctic Cloud Site Inspection<br>Arctic Cloud Simulated Experiment |
| March | FIRE-III ST Meeting<br>SUCCESS Simulated Exp<br>. | STERAO-B-I Experiment | |
| April | SUCCESS Experiment | STERAO-B-I Experiment | Arctic Cloud Experiment |
| May | SUCCESS Experiment | Arctic Cloud Site Survey-B<br>FIRE-III ST Meeting | Arctic Cloud Experiment |
| June | | STERAO-B-II Site Inspection | |
| July | | | |
| August | Arctic Cloud Site Survey-A | STERAO-B-II Experiment | FIRE-III ST Meeting |
| September | STERAO-B-II Site Survey | STERAO-B-II Experiment | |
| October | Arctic Cloud WG Meeting<br>Cirrus WG Meeting<br>SUCCESS Science Workshop | Tropical Cirrus Site Survey-B | |
| November | Tropical Cirrus Site Survey-A | FIRE-III ST Meeting<br>STERAO-B Science Workshop | |
| December | | | |

# 7.0 NATIONAL AND INTERNATIONAL COLLOBORATIONS

FIRE Phase III is a research project to be conducted by U.S. scientists to provide a U.S. national contribution to the ISCCP of the World Climate Research Program. In the sense that the scientific problems addressed by FIRE-III are truly international, it is in the best interests of FIRE-III to encourage the free exchange of information with our national and international colleagues. Although resources do not permit direct support of foreign participation in FIRE-III, ways will be sought to allow collaboration, such as full participation and data sharing as members of the FST. Other forms of collaboration will also be encouraged. Cooperation and coordination with the research projects of other countries will be accomplished through the ISCCP Working Group on Data Management (DMWG), which is responsible for this function under the Joint Scientific

Committee of WMO and International Committee of Scientific Unions. Reports of FIRE-III activities will be made at the annual ISCCP WGDM meetings.

## Appendix E - Acronyms

### Table 1 - List of Acronyms.

| | |
|---|---|
| 2D-C | An instrument used to detect small ice crystals |
| 2D-P | Heymsfield abstract |
| ACE-1 | Atmospheric Chemistry Experiment; first mission |
| ACSYS | Arctic Climate System Study |
| AEAP | Atmospheric Effects of Aviation Program |
| AES | Atmospheric Environmental Service (Canada) |
| AGASP | Arctic Gas and Aerosol Sampling Program |
| AIDJEX | Arctic Ice Dynamics Joint Experiment |
| AIRS | Atmospheric Infrared Sounder |
| AMS | Alternate Mission Scientist, American Meteorological Society |
| ARC | Ames Research Center |
| ARCS | Atmospheric Radiation and Clouds Station |
| ARCSS | Arctic System Science |
| ARCSyM | Arctic Regional Climate System Model |
| ARM | Atmospheric Radiation Measurements Program |
| ARMCAS | Arctic Radiation Measurement in Column Atmosphere-surface System |
| ASCII | American Standard Code for Information Exchange |
| ASTEX | Atlantic Stratocumulus Transition Experiment |
| AVHRR | Advanced Very High Resolution Radiometer |
| BASE | Beaufort Arctic Storms Experiment |
| C-130Q | NCAR aircraft |
| C-131A | University of Washington aircraft |
| CAGES | A Canadian hydrological experiment planned for the MacKenzie river basin |
| CAR | Cloud Absorption Radiometer |
| CARAFE | Cloud, Aerosol and Radiation Arctic Field Experiment |
| CARSS | Liou abstract |
| CCD | Charged-Coupled Diode |
| CCM | Continuous Core Measurements |
| CCN | cloud condensation nuclei |

| | |
|---|---|
| CEPEX | Central Equatorial Pacific Experiment |
| CERES | Clouds and the Earth's Radiant Energy System |
| CFD | Continuous Flow Diffusion |
| CIMMS | Cooperative Institute for Mesoscale Meteorological Studies |
| CIRES | Cooperative Institute for Research in Environmental Science |
| CMC | Canadian Meteorological Centre |
| CN | Cloud Nuclei |
| COARE | Coupled Ocean-Atmosphere Regional Experiment |
| CSU | Colorado State University |
| CV-580 | Canadian National Research Council aircraft |
| CVI | Counterflow Virtual Impactor |
| D1 | An ISCCP data type |
| DAAC | Distributed Active Archive Center(EOS) |
| DMA | Differential Mobility Analyzer |
| DMS | Daily Mission Scientist, dimethyl sulfide |
| DMSP | Defense Meteorological Satellite Program |
| DMWG | Data Management Working Group |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DRI | Desert Research Institute |
| DX | An ISCCP data type |
| ECMWF | European Center for Medium-range Weather Forecasts |
| EDX | Energy-dispersive x-ray |
| ENSO | El Nino Southern Oscillation |
| EOS | Earth Observing System |
| EOS-AM | series of EOS satellites with morning crossings of equator |
| EOS AM-1 | first launch in EOS series |
| EOSDIS | Earth Observing System Data and Information System |
| EOS PM | series of EOS satellites with afternoon crossings of equator |
| ER-2 | NASA ARC aircraft |

| | |
|---|---|
| ERB | Earth Radiation Budget instrument (NIMBUS 6 &7) |
| ERBE | Earth Radiation Budget Experiment (on ERBS) |
| ERBS | Earth Radiation Budget Satellite |
| ERL | Environmental Research Laboratory(NOAA) |
| ERS | European Remote-sensing Satellite |
| ETL | Environmental Technology Laboratory(NOAA) |
| FARS | Facility for Atmospheric Research (U. Utah) |
| FIRE | First ISCCP Regional Experiment |
| FIRE I | FIRE Phase I(1984-1989) |
| FIRE II | FIRE Phase I(1990-1994) |
| FIRE III | FIRE Phase III(1995-) |
| FSSP | Forward Scattering Spectrometer Probe |
| FST | FIRE Science Team |
| FTIR | Fourier Transform Interferometer Radiometer |
| GAC | Global Area Coverage |
| GCM | General Circulation Model |
| GCSS | GEWEX Cloud System Studies |
| GEWEX | Global Energy and Water Cycle Experiment |
| GFDL | Geophysical Fluid Dynamics Laboratory |
| GISS | Goddard Institute for Space Studies |
| GOES | Geostationary Orbiting Environmental Satellite |
| GPS | Global Positioning System |
| GSFC | Goddard Space Flight Center |
| GTS | Global Telecommunications System |
| HDF/netCDF | hierarchical data format/net common data format |
| HIRS | High Infrared Radiation Sounder |
| HIS | High-resolution Interferometric Sounder |
| IFN | ice forming nuclei |
| IFO | intensive field observations |
| IN | ice nuclei |

| | |
|---|---|
| INAA | Instrument Neutron Activation Analysis |
| INDOEX | Indian Ocean Experiment |
| ISCCP | International Satellite Cloud Climatology Experiment |
| IWC | ice water content |
| IWP | ice water path |
| LAC | local area coverage |
| Landsat | NASA Earth observing satellite series |
| LaRC | Langley Research Center |
| LEADEX | Lead Experiment |
| LES | large-eddy simulation |
| LITE | Lidar In-space Technology Experiment |
| LWC | liquid water content |
| LWP | liquid water path |
| MAS | MODIS airborne simulator |
| MAST | Monterey Area Ship Track Experiment |
| MODIS | Moderate-resolution Imaging Spectrometer |
| MPT | Mission Planning Team |
| MSFC | Marshal Space Flight Center |
| MST | Mission Selection Team |
| NASA | National Aeronautics and Space Administration |
| NCEP | National Center for Environmental Prediction |
| NIMBUS | NASA series of research meteorological satellites(1-7) |
| NOAA | National Oceanic and Atmospheric Administration |
| NRC | National Research Council |
| NSA/AAO | North Slope of Alaska/Adjacent Arctic Ocean |
| NSF | National Science Foundation |
| N.W.T. | Northwest Territories |
| OGP | Office of Global Programs |
| ONR | Office of Naval Research |
| PDL | Polarization Diversity Lidar |

| | |
|---|---|
| P.I. | Principal Investigator |
| PMS | Hallett abstract |
| POLES | Polar Exchange at the Sea Surface |
| PSU | Penn State University |
| PVM | Particulate Volume Monitor |
| RAMS | Radiation Airborne Measurement System |
| RASS | Radio Acoustic Sounding System |
| SAR | Synthetic Aperture Radar |
| SASS | Subsonic Assessment Program (part of AEAP) |
| SBIR | Small Business Initiative Research |
| SCAR-B | Smoke, Clouds and Radiation-Brazil |
| SCICEX | Submarine Science Ice Experiment |
| SCM | Single-Column Model |
| SDSMT | South Dakota School of Mines and Technology |
| SEM | scanning electron microscopy |
| SHEBA | Surface Heat Budget of the Arctic Ocean |
| SOCEX-I & II | Southern Ocean Cloud Experiments |
| SPEC | Stratton Park Engineering Co. Inc. |
| SPECTRE | Spectral radiation Experiment |
| SPFR | Spectral Flux Radiometer |
| SRB | Surface Radiation Budget |
| SSM/I | Special Sensor Microwave/Imager |
| SUCCESS | Subsonic Aircraft: Control and Cloud Effects Special Study |
| T-39 | NASA LaRC aircraft |
| TEM | Transmission Electron Microscopy |
| TIROS | Television Infrared Observation Satellite |
| TIROS N | Third generation of NOAA operational meteorological satellites |
| TM | Thematic Mapper |
| TOGA | Tropical Ocean and Global Atmosphere |
| TOVS | TIROS Operational Vertical Sounder |

| | |
|---|---|
| TSC | Tilt-Scan Camera |
| TWP | Tropical Western Pacific |
| UHF | Ultra-High Frequency |
| UND | University of North Dakota |
| URL | Universal Resource Locator (a web address) |
| UW | University of Washington |
| WB-57F | NCAR aircraft |
| WCRP | World Climate Research Program |
| WGDM | Working Group on Data Management |
| WPDN | Ackerman abstract |
| WMO | World Meteorological Organization |

## Appendix F - FIRE Abstracts

# Coordinated Parameterization Development and Large-Eddy Simulation for Marine and Arctic Cloud-Topped Boundary Layers

C. S. Bretherton, University of Washington

Large-eddy simulations of subtropical and summertime Arctic cloud-topped boundary layers will be carried out. The subtropical boundary layer simulations will focus on two issues: (1) improving entrainment closures based on in-cloud turbulent kinetic energy and cloud-top jumps, which are currently quite uncertain, and ascertaining what resolution in the entrainment zone is required for an LES to reliably predict entrainment, and (2) assessing the role of penetrative cumulus entrainment in stratocumulus breakup. We hope to incorporate key findings in both of these areas to improve current GCM parameterizations of the cloud-topped boundary layer. A third area of study will be testing the feasibility of several proposed mechanisms for multiple cloud layering in the summertime Arctic in an LES and comparing against field data.

# Application of LES to Understanding and Parameterizing the Arctic Cloudy Boundary Layer

Judith Curry, University of Colorado, William Cotton, Colorado State University

The goal of this research is to improve our understanding of physical processes occurring in the arctic cloudy boundary layer and our ability to parameterize them in climate models. The approach taken here is to use Large-Eddy Simulation (LES) to interpret the interactions among turbulence, cloud microphysics and radiative transfer in the following different arctic cloudy boundary layer types: warm-season layered clouds with decoupled mixed layers; and wintertime ice crystal plumes emanating from leads. The LES results will be compared with observations, and parameterizations suitable for large-scale models will be developed. The results will be evaluated in the context of the forthcoming Arctic FIRE experiment, particularly the optimal measurements to be obtained from aircraft (including flight patterns) and the large-scale measurements required to interpret cloud life-cycles. Specifically, we propose to accomplish the following:

* develop and implement a new subgrid-scale parameterization and other modifications for the LES to accommodate the stable boundary layers that are present in the Arctic;
* introduce new parameterizations into the LES related to the impact of turbulence on droplet spectra and the influence of droplet spectra on the radiation fluxes;
* simulate and interpret the interactions among turbulence, cloud microphysics and radiative transfer in the different arctic cloudy boundary layer types;

* compare the LES output with case studies obtained from the Arctic Stratus Experiment and BASE;
* evaluate the importance of diabatic terms in second-moment equations, and develop a parameterization for these terms for second-order closure models if necessary;
* evaluate the applicability of existing cloud fractional coverage schemes to Arctic stratus and develop a new scheme if necessary; and
* examine scale interactions using the LES nested in a mesoscale model (RAMS).

# Boundary-Layer Dynamics and Cloud-radiative Studies in SHEBA: Development of an Atmospheric Lidar and a Wind Profiler

C. W. Fairall, C. Grund, and R. G. Strauch, NOAA Environmental Technology Laboratory

This is an NSF SHEBA Phase-1 project to develop, construct, and test a lidar and wind profiler for future deployment in the ice station of the Surface HEat Budget of the Arctic Ocean (SHEBA) program, planned for an 12-month field program beginning in March 1997. These systems will be used in conjunction with other surface-based remote sensors (e.g., Doppler cloud radar, microwave radiometer, Doppler sodar, FTIR radiometers) and in situ sensors for studies of boundary-layer dynamical and cloud-aerosol/radiative effects on the ice surface energy budget. The work will be coordinated with the FIRE-III Arctic Cloud research program. The wind profiler will be a portable, scaled down version of the NOAA network UHF profilers and be designed to provide wind and temperature profiles continuously to 2.5 km altitude. Through additional data processing, it will also provide information on velocity and scalar turbulence profiles and precipitation. Based on an analysis of LEADEX data, most of the temporal variability in the vertical gradients of temperature, dew point, and (to a lesser extent) winds occurs below this altitude. The lidar will be a derivative of a system being developed for cloud and aerosol monitoring and will measure optical depth and provide cloud ice/water discrimination. It will feature both vertically pointing and zenith angle scan capabilities. The scanning capability is shown to be critical for obtaining information about complex ice crystal habit and structure. Both systems will feature high reliability in Arctic conditions and will operate “unattended” except for occasional changing of storage media or transfer of data. In the first year of the project, the lidar will be designed and constructed. An existing prototype radar (being developed for another program) and the lidar then will be tested in Alaska for one month. In the second year of the project, the radar will be constructed following evaluation of the test results. Both systems will be field tested in Alaska a second time then deployed at the SHEBA ice station.

# FIRE III Research

Peter Hobbs, University of Washington

Subject to the availability of funding, the Cloud and Aerosol Research Group at the University of Washington intends to bring its new twin-engine, turbo-prop, Convair-580 research aircraft to the Arctic to participate in a portion of the 6-week FIRE-III intensive field project. The aircraft will be instrumented for state-of-the-art measurements of aerosols, cloud microstructures, and cloud radiative properties, including the NASA-built CAR 13-wavelength radiometer and lidar. Our proposed research, which will be carried out in collaboration with Drs. Michael King and Si-Chee Tsay, includes the following:

(1) Measurements of cloud-active aerosols and their precursors.

(2) Measurements of the statistical properties of the microphysical structures of arctic stratus and other clouds.

(3) Direct measurements of the spectral radiative properties of arctic stratus, and comparisons with values derived from simultaneous measurements of cloud structure.

(4) Comparisons of in situ measurements of cloud properties with remote sensing measurements from the ER-2 and satellites.

We expect also to carry out a number of measurements concerned with the radiative properties of sea-ice, snow, tundra etc., and the energy balance of the arctic. However, since these are more related to SHEBA, they are not discussed here.

# FIRE III Research

James Hudson, Desert Research Institute

I plan to mount both of the DRI instantaneous CCN spectrometers (Hudson 1989) aboard a research aircraft and operate them throughout the project. The most likely aircraft is the NCAR C-130, where they have been in two previous projects-Telford California stratus project (December 1994) and SCMS (July-August 1995). Two spectrometers are desirable in order to efficiently do sample processing upstream of one of the CCN spectrometers. This allows the other instrument to continuously monitor the ambient CCN spectrum. Continuous ambient spectra are vital in aircraft operations where the concentrations change rapidly with position (e.g., there are often vertical differences in concentration and/or spectral slope that are significant for cloud microphysics; also horizontal differences due to scavenging and production). The sample processing mechanisms include:

(1) Volatility-subjecting the sample to various temperatures to indirectly estimate particle composition (Hudson and Da 1996) especially with respect to NaCl, sulfates, and carbon.

(2) Size vs. supersaturation-classifying the sample according to dry particle size with an electrostatic classifier (DMA). This allows an estimate of the relative solubility of the particles. Hudson and Da (1995) showed that CCN from polluted air masses tend to act as though they have more insoluble material internally-mixed with the soluble material that makes them CCN. CCN from cleaner air masses, however, act like pure soluble substances. These two

techniques are complementary; when taken together they derive significant information about CCN composition.

(3) Different inlets-The CCN spectra of droplet residue material from the counterflow virtual impactor (CVI) can be used to determine the effects of entrainment on cloud droplet spectra (Twohy and Hudson 1995). If the CVI is not available then a cloud interstitial inlet can also produce similar information about the effects of cloud dynamics on cloud droplet spectra. When both spectrometers monitor the ambient there is increased confidence in the measurements not to mention the enhanced reliability of two instruments. In addition to comparing the cloud droplet and CCN concentrations I am

keenly interested in comparing the shapes of the two spectra. Martin et al. (1994) suggested that the shape of the cloud droplet spectrum is related to the shape of the CCN spectrum. Indeed Hudson and Li (1995) found significant differences in the shape of the CCN spectra in polluted and clean air masses; this is an additional difference to the well-known difference in number concentration. However this may or may not go the same way in the Arctic. The shape (breadth) of the droplet spectrum is very important for the initiation of drizzle (autoconversion), which has been suggested to be related to CCN concentrations (e.g., Albrecht et al. 1995). Drizzle initiation may also depend on CCN spectral shape, testing this requires measurements at supersaturations lower than the actual cloud supersaturations, which are generally quite low for stratus clouds anyway (e.g., Hudson and Svensson 1995). Such low supersaturations (<0.1%) are only possible with the DRI spectrometer. We expect significant variations in CCN concentrations, spectral shape, and composition during FIRE-III. CCN spectral measurements are necessary in order to keep separate the effects on cloud microphysics of differences in cloud dynamics from the differences in the aerosol. Comparisons with identical CCN measurements in several other stratus projects-FIRE, ASTEX, SOCEX-1 and 2, MAST, ACE-1-will be indispensable.

# Canadian Participation in FIRE III

George Isaac, Atmospheric Environment Service

Observations collected by the Canadian PIs, together with the other FIRE III data, will be used to understand Arctic cloud formation, development, and their effect on climate change. Special emphasis will be put on the interaction of clouds with Arctic aerosols, the influence of the aerosol chemistry upon cloud microphysical characteristics, and the general role clouds play in redistributing, transforming, and transporting Arctic chemical constituents. Using the observations, microphysical, chemical, dynamical and radiative properties, as well as the vertical and horizontal spatial distribution characteristics, of the clouds studied will be determined. Parameterizations will be developed, describing these properties, that might be used in GCMs. Where possible, these parameterizations will be tested and evaluated in column models, cloud resolving models and full scale GCMs. It is anticipated that the National Research Council Convair 580 will be involved and would fly out of Inuvik, N.W.T. Some specialized ground instrumentation, such as lidars and radars, might also the used. The possibility of placing instrumentation for measuring chemical constituents on the ice flow and other surface sites will be explored. This research will involve a large number of Canadian scientists and is dependent upon Canadian funding approval. Formal plans for this work, including PIs designated for each task, have yet to be developed.

# Remote Sensing and Retrieval of Arctic Stratus Clouds and Surface Characteristics

Michael King and Si-Chee Tsay, NASA/Goddard Space Flight Center

NASA Goddard Space Flight Center This investigation continues studies of the radiative and microphysical properties of Arctic stratus clouds and snow/sea ice surface. The Moderate Resolution Imaging Spectroradiometer (MODIS), being developed as part of the Earth Observing System (EOS) and scheduled to be launched in 1998 on the EOS AM platform, is a NASA facility instrument designed to meet the scientific needs for satellite remote sensing of clouds, aerosols, water vapor, and land and ocean surface properties. To support the development of MODIS remote sensing and retrieval algorithms, the MODIS Airborne Simulator (MAS) was developed for NASA's high-altitude ER-2 aircraft. This airborne sensor is capable of providing narrowband spectral coverage similar to MODIS of reflected solar and emitted thermal radiation. Over the past few years, MAS has flown in many field campaigns throughout the world, including recently in Alaska. These diverse data sets provide critical measurements for assessing the scientific capability and usefulness of MODIS channels, as well as enabling unique information to be acquired from studies of the Earth's atmosphere and surface. Analyses of various cases obtained during previous FIRE-I and II experiments are an important element of this investigation. The intent of this investigation is to support our participation in the FIRE-III field campaigns and to analyze data obtained by MAS during previous campaigns. Specifically, we intend to:

(1) participate in flight planning and direction of the NASA ER-2 aircraft over Arctic stratus clouds off the north slope of Alaska during the 1997 field campaign,

(2) build a well-calibrated and feature-rich data set to improve MODIS cloud masking algorithms,

(3) distinguish clouds from snow covered tundra and sea ice surfaces,

(4) retrieve stratus cloud properties (i.e., optical thickness and effective particle radius) over highly reflecting surfaces, and

(5) perform statistical analyses of stratus cloud properties by using high spatial resolution MAS data.

# Study of midlatitude and Arctic aerosol-cloud-radiation feedbacks based on LES model with explicit ice and liquid phase microphysics

Yefim Kogan, Cooperative Institute for Mesoscale Meteorological Studies, Douglas Lilly, School of Meteorology, University of Oklahoma

The complexity of cloud-radiation problem results in large uncertainties in estimating the cloud forcing in global climate models. Of particular importance are cloud-radiation feedbacks in midlatitude, subtropical, and high-latitude low level clouds. Continuing investigation of these cloud systems is a major goal of the FIRE III program. The proposed work will have two major thrusts:

(1) Continuing the study of marine stratocumulus clouds using LES simulations based on FIRE I and FIRE II/ASTEX observational data. The data will be used to validate the CIMMS LES model and to improve our understanding of the interaction between the microphysical, radiative, and thermodynamical processes. Validation of the model against observations will result in further refinement and improvement in the model physical and numerical formulation.

(2) Large-eddy simulations of arctic cloud systems, including low level stratus with liquid and mixed phase microphysics. The modeling part of the research will be based on the CIMMS 3-D LES model of a stratocumulus cloud layer that includes an explicit formulation of aerosol and cloud drop size-resolving microphysics and radiation. The study of mixed phase clouds will use the new version of the CIMMS model which includes also explicit formulation of the ice-phase microphysics. Depending on the physics and the scale of the studied phenomena, the model may be also formulated in a 2-D framework with bulk treatment of microphysics. In accordance with the FIRE III objectives, model simulations and data analysis will aim at the improvement of existing parameterizations of cloud and radiative processes in LES and GCM models. The analysis of ASTEX and FIRE III observational data sets will be made in collaboration with the researchers from British Meteorological Office, University of British Columbia and University of Colorado.

# Cloud-Scale Numerical Modeling of the Arctic Boundary Layer

Steven Krueger, Dept. of Meteorology, University of Utah

The interactions between sea ice, open ocean, atmospheric radiation, and clouds over the Arctic Ocean exert a strong influence on global climate. Uncertainties in the formulation of interactive air-sea-ice processes in global climate models (GCMs) result in large differences between the Arctic and global climates simulated by different models. Arctic stratus clouds are not well-simulated by GCMs, yet exert a strong influence on the surface energy budget of the Arctic. Leads (channels of open water in sea ice) have significant impacts on the large-scale budgets during the Arctic winter, when they contribute about 50 percent of the surface fluxes over the Arctic Ocean, but cover only 1 to 2 percent of its area. Convective plumes generated by wide leads may penetrate the surface inversion and produce condensate that spreads up to 250 km downwind of the lead, and may significantly affect the longwave radiative fluxes at the surface and thereby the sea ice thickness. The effects of leads and boundary layer clouds must be accurately represented in climate models to allow possible feedbacks between them and the sea ice thickness. The FIRE III Arctic boundary layer clouds field program, in conjunction with the SHEBA ice station and the ARM North Slope of Alaska and Adjacent Arctic Ocean site, will offer an unprecedented opportunity to greatly improve our ability to parameterize the important effects of leads and boundary layer clouds in GCMs. We will make extensive use of FIRE III measurements and a high-resolution numerical model, the University of Utah Cloud Resolving Model, to increase our understanding of the physical processes that determine (1) the formation and structure of Arctic stratus clouds and (2) how leads over the Arctic Ocean affect the large-scale budgets of sensible heat, water vapor, and condensate. This is necessary before developing lead and boundary layer cloud parameterizations based on general physical principles. We will:

(1) Determine in detail how large-scale processes, in combination with cloud-scale radiative, microphysical, and dynamical processes, govern the formation and multi-layered structure of Arctic stratus clouds.

(2) Quantitatively determine the effects of leads on the large-scale budgets of sensible heat, water vapor, and condensate in a variety of Arctic winter conditions.

# FIRE-III Research

D. H. Lenschow and Q. Wang, National Center for Atmospheric Research

Our intended FIRE-III research will utilize previous field observations of Arctic clouds, boundary layer, and ice surface to perform integrated analyses of both the Arctic clouds and boundary layer, and evaluate instrument capabilities for making measurements in the Arctic environment. We plan to use the data set obtained from the Beaufort and Arctic Seas Experiment (BASE) as the primary data source for two important reasons. First, BASE obtained measurements in the Arctic boundary layer during the fall/winter transition season which is not well documented. Several types of structure were measured during this experiment, including stably-stratified boundary layers, mixed-phase boundary-layer clouds, boundary layers modified by leads and polynyas, and multi-layered cloud structures. Second, a primary platform for BASE was the newly-instrumented NCAR C-130 which will likely be deployed in FIRE-III/SHEBA. Evaluation of the capability of the instruments on the C-130 to measure in the Arctic is an essential step in preparing for FIRE-III/SHEBA. In addition to the BASE data set, we plan to analyze measurements from the Arctic Stratus Experiment and the Arctic Ice Dynamics Joint Experiment (AIDJEX) which measured the summertime Arctic boundary layer; and from the Lead Experiment (LEADEX) which measured the effects of open leads during winter/spring. Although these detests (excluding BASE) have been studied by other researchers, our analyses will focus on addressing problems that were uncovered during and after these experiments with a view towards improving measurements in FIRE-III/SHEBA. The primary objectives of the proposed research are to:

(1) understand the Arctic cloud and boundary layer structure, especially the interactions among cloud microphysics, turbulence, and radiation using in situ aircraft measurements;

(2) understand the moisture, heat, and momentum exchange between the atmosphere and the Arctic ocean water/ice surface;

(3) assess the instrumentation capability on the newly-deployed NCAR C-130 for making measurements in the Arctic environment and provide a basis for improved measurement capabilities for the FIRE-III/SHEBA field campaign;

(4) optimize the aircraft measurement strategy in the Arctic for FIRE-III/SHEBA;

(5) provide analyses from in situ measurements useful for interpreting and validating satellite remote sensing and retrieval algorithms, and for validating results from numerical modeling of the Arctic clouds and boundary layer (in collaboration with Judith Curry, University of Colorado).

# FIRE III Research

David Randall, Colorado State University

We propose to investigate the Arctic climate simulated by the current version of the CSU GCM, with particular attention to cloudiness and the surface energy budget. We propose to develop a one-dimensional model of the Arctic atmosphere-sea ice-ocean system, which will exist in two versions, which differ only in their treatment of the atmosphere. The first version will be based on the second-order bulk model developed by Randall et al. (1992), and the second will use a one-dimensional version of the third-order closure developed by Krueger (1988). These one-dimensional models will be tested using the FIRE Arctic data in “single-column model” mode. Following these tests, at least one of the two versions will be transferred to the CSU GCM, and used in simulations of the present climate and of climate change due to increasing CO2.

# Radiative Energy Exchanges In The Polar Regions

William Rossow and Barbara Carlson, Institute for Space Studies, Goddard Space Flight Center

Some evaluations of the surface energy balance in the polar regions, that currently maintains a persistent sea and land ice cover, suggest that it may be very sensitive to climate perturbations; however, little change in polar ice/snow cover over the past century has been documented, even though global temperatures have changed somewhat. This situation reflects a generally poor understanding of the polar energy balance and the feedback processes controlling it. There has been recent significant progress in quantitative methods for analysis of satellite measurements of the atmosphere, clouds and surface; however, the paucity of quality in situ observations has prevented verification of these methods under more difficult polar conditions. Very few of these methods have even been applied to study of the polar regions. As one step towards determining the polar energy balance and the key controlling processes, we propose to combine all of the available satellite measurements into a single consistent analysis that measures the key properties of the atmosphere, clouds and surface required to infer the surface and top-of-atmosphere radiation balance and its seasonal variations. Building and improving upon the ISCCP analysis of imaging radiometer data, we will add measurements by infrared and microwave sounders to deal with the complex variations of surface and cloud properties. Using energy balance models, together with these observations, we can infer the required energy transports (mostly by the atmosphere) required to balance radiative fluxes and examine the sensitivity of ice and snow cover to variations in these fluxes. If this work is funded as part of a U.S. contribution to the Canadian GEWEX experiment called BASE and a new project called SHEBA, then the value of our combined satellite analysis will be greatly enhanced by comparison with coordinated surface and aircraft observations and more complete atmospheric and sea ice modeling efforts of collaborators.

# Studies of the Radiative and Microphysical Properties of Cloud, Aerosol and Surface Bi-Directional Reflectance

Si-Chee Tsay and Michael King, NASA Goddard Space Flight Center

This investigation continues studies of the microphysical, optical and radiative properties of Arctic clouds and aerosols, and characterizes the anisotropy of various types of Arctic surfaces. Tools of this investigation include a multispectral scanning radiometer (CAR; Cloud Absorption Radiometer), which is mounted on the University of Washington's C-131A aircraft for the purpose of measuring the angular distribution of scattered radiation deep within a cloud layer, from which the single-scattering albedo of clouds can be determined as a function of wavelength. Recent improvements in the CAR further advance its capability in characterizing the radiative properties of aerosols and surfaces. Over the past few years, the CAR has flown in many national and international field campaigns, providing unique information in studies of cloud, aerosol and surface properties. Analyses of various cases obtained during previous experiments are an important element of this investigation. The intent of this investigation is to participate in the 1997 FIRE-III and upcoming SCAR-B (Smoke, Cloud And Radiation - Brazil) field campaigns, and to analyze data obtained by the CAR as well as other ancillary and coordinated microphysics/radiation data sets during previous campaigns. Specifically, we intend to:

(1) validate experimentally the relationship between cloud single-scattering albedo and effective particle radius from CAR radiation measurements in the diffusion domain,

(2) determine the radiative properties (i.e., optical thickness, single-scattering albedo and phase function) of aerosol from CAR radiation measurements for use in developing atmospheric corrections, and

(3) characterize the bidirectional reflectance distribution function (BRDF) over Arctic snow and sea ice surfaces, as well as other types of surfaces, to develop physically based surface BRDF models.

# FIRE III Research

Tanneil Uttal, NOAA Environmental Technology Laboratory

The National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) is presently involved in studies of radiatively important cloud properties, utilizing data from the First ISCCP Radiation Experiment (FIRE II) and the Atlantic Stratocumulus Transition Experiment (ASTEX). Important remote sensing techniques based on radar, lidar and IR radiometer measurements have been developed at ETL that remote sensing of profiles of cloud properties such as particle concentrations, sizes, LWC,and IWC from the ground that were not possible even a few years ago. The proposed work includes analysis of FIRE II and ASTEX data sets with an emphasis on comparison of cloud properties between different climatic regimes. In addition, NOAA/ETL has received separate funding for FY96 to conduct a similar measurement campaign in the tropical Western Pacific as part of the DOE/ARM program. In this proposal we also plan to augment the mid-latitude, sub-tropical and tropical data sets with an arctic data set collected in conjunction with the FIRE III and SHEBA programs in 1997. Deployment of a 35 GHz radar, lidar, and IR radiometer will allow characterization of arctic clouds, haze, and aerosol which will be directly comparable to FIRE III, ASTEX, and TWP results. This will provide the radiation/climate community with an unprecedented data set for four major climatic zones. The emphasis in this study will be on the intercomparison of cloud properties to answer important questions of global variations of upper tropospheric and boundary layer clouds.

# A Parameterization Study of Marine Boundary-Layer Clouds

Shouping Wang, NASA Marshall Space Flight Center

The goal of the proposed research is to formulate a new parameterization of marine boundary-layer clouds for a large-scale model. We propose to develop a model based on the buoyancy sorting concept developed by Raymond and Blyth (1986), mass flux-layered model of Wang (1993), and the prognostic cloud scheme developed by Tiedtke (1993). For the application in the marine boundary layer, we need to improve the representation of the cloud-top entrainment, large-scale condensation and evaporation in the cloud scheme. We also emphasize the interaction between the cumulus and stratocumulus clouds in the boundary layer. In the processes, some large-eddy simulation runs will be conducted to study the interaction that is crucial to our new parameterization. We will also implement the new prognostic cloud scheme into a traditional second-order turbulence closure model. Thus, the stratocumulus, trade-wind cumulus regimes and the transition between them can be predicted with a unified cloud scheme. All the one-dimensional models will be tested with ASTEX and FIRE data. Following the tests, we plan to implement the models into a general circulation model.

**Appendix G - Relevant Surface-Based Radiometric and Support Instrumentation Proposed for SHEBA and Barrow During FIRE III**

**Table 1: GROUND RAD (upwelling radiation sensor suite)**

| Instrument | Data Products | Loc | Op Mode | Users* | Provider | C Test?** |
|---|---|---|---|---|---|---|
| PIR/UIR | Broadband IR (1 fixed) | S,B | Continuous | abc | ARM | Y |
| PIR/UIR | Over Major Surf Types | S | Continuous | abc | SHEBA | N |
| PSP/US | Broadband Solar (1 fixed) | S,B | Continuous | abc | ARM | Y |
| PSP/US | Over Major Surf Types | S | Continuous | abc | SHEBA | N |
| Rn | Net Radiation (1 fixed) | S,B | Continuous | abc | ARM? | Y |
| MFR/US | Spectral Solar (1 fixed) | S,B | Continuous | abc | ARM | Y |
| MFR/US | Over Major Surf Types | S | Continuous | abc | SHEBA?? | N |
| Valero Rad Sens | Various | S,B | Continuous | All | ? | Y |
| IRT | Surf Temperature (1 fixed) | S,B | Continuous | abc | ARM | Y |
| IRT | Over Major Surf Types | S | Continuous | abc | SHEBA? | N |

*Users: General Circulation Modelers: a; Boundary Layer Cloud Modelers: b; Satellite Remote Sensors: c; In Situ Measurement Aircraft: d.
**C Test?: Cold Test Needed?
S,B S indicates SHEBA; B indicates Barrow.
?, ??, ??? Indicates Degree of Uncertainty

Table 2: SKY RAD (downwelling radiation sensor suite)

| Instrument | Data Products | Loc | Op Mode | USER* | Provider | C Test?** |
|---|---|---|---|---|---|---|
| PIR/DIR | Broadband IR (1 fixed) | S,B | Continuous | abc | ARM | Y |
| PIR/DIR | Over Major Surf Types; OLS | S | Continuous | abc | SHEBA | N |
| PSP/DS | Broadband Solar (1 fixed) | S,B | Continuous | abc | ARM | Y |
| PSP/DS | Over Maj Surf Types; OLS | S | Continuous | abc | SHEBA | N |
| MFRSR/DS | Spectral Solar | S,B | Continuous | abc | ARM | Y |
| MFRSR/DS | Over Major Surf Types; OLS | S | Continuous | abc | SHEBA?? | N |
| NIP | BB Normal Incidence Solar | S,B | Continuous | abc | ARM | Y |
| ER-AERI | Spectral IR, 4-25u | S,B | Continuous | abc | ARM | Y |
| FTIR | Spectral Near IR | S | Continuous | abc | FIRE? | Y |
| SPFR | Spectral Solar | S | Continuous | abc | FIRE? | Y |
| Valero Rad Sens | Various | S,B | Continuous | abc | ? | Y |

Table 3: Surface-Based and Tower-Based Measurements

| Instrument | Data Products | Loc | Op Mode | USER* | Provider | C Test?** |
|---|---|---|---|---|---|---|
| **Surface-MET (surface meteorological sensor suite)** | | | | | | |
| Anemometer | 10 m Wind Speed, Direction | S,B | Continuous | abc | *** | Y |
| T Sens | 10 m Air Temperature | S,B | Continuous | abc | *** | Y |
| Hum Sens | 10 m Absolute WV Conc | S,B | Continuous | abc | *** | Y |
| Precip Gauge | Cumulative Precip | S,B | Continuous | abc | *** | Y |
| OPG | Light Precip Rate | S,B | Continuous | abc | *** | Y |
| PVM | Fog LWC, re | S,B | Continuous | abc | ? | Y |
| *** SHEBA for SHEBA; ARM for Barrow | | | | | | |
| **Tower-MET, RAD (60 m? Barrow only; tower-mounted sensor suite)** | | | | | | |
| Anemometer | WS, WD (multiple levels) | B | Continuous | abc | ARM | Y |
| T Sens | Air Temp (multiple levels) | B | Continuous | abc | ARM | Y |
| Hum Sens | WV Conc (multiple levels) | B | Continuous | abc | ARM | Y |
| PIR/UIR | Broadband IR (top) | B | Continuous | abc | ARM | Y |
| PSP/US | Broadband Solar (top) | B | Continuous | abc | ARM | Y |
| PIR/DIR | Broadband IR (top) | B | Continuous | abc | ARM | Y |
| PSP/DS | Broadband Solar (top) | B | Continuous | abc | ARM | Y |

Table 4: Remote Sensing

| Instrument | Data Products | Loc | Op Mode | USER* | Provider | C Test?** |
|---|---|---|---|---|---|---|
| MWR | Column LW, WV | S,B | Continuous | All | ARM | Y |
| 449 WP/ RASS | Wing, T Profiles | S,B | Continuous | ab | *** | Y |
| Mini Sodar | Low Level Wind Profiles S | S | Continuous | ab | SHEBA | Y |
| MMCR | Cloud Reflectivity Profiles | S,B | Continuous | All | *** | Y |
| | Doppler Velocity Profiles | | | | | |
| MPL | Backscatter Profiles | B | Continuous | All | ARM | Y |
| DMPL | Backscatter, Depolarization | S | Continuous | All | SHEBA | Y |
| Ceilometer | Cloud Base, Top (thin clds) | S,B | Continuous | All | ARM | Y |
| WSI | 31 band Whole Sky Images | S,B | Periodic | All | ARM | Y |
| | Cloud Fraction | | | | | |

Note: MMCR, MWR and DMPL data can be combined to produce LWC, IWC and effective radius profiles.

Table 5: Balloon-Based Measurements and Surface Characterization

| Instrument | Data Products | Loc | Op Mode | USER* | Provider | C Test?** |
|---|---|---|---|---|---|---|
| Balloon | | | | | | |
| BBSS | WS, WD T, RH Profiles | S,B | Periodic | All | *** | Y |
| Radio-sondes | WS, WD, T, RH Profiles | S | Periodic | All | FIRE | Y |
| TBS | BLWS,WD,T.RH Pro-files | S | Periodic | All | ? | Y |
| | BL Cloud Microphys Profiles | | | | | |
| | BL Cloud Rad Profiles | | | | | |

Surface Characterization

Ground Rad plus Sky Rad above (measured at same places) give:

Albedo

Spectral Albedo

Emissivity

| | | | | | | |
|---|---|---|---|---|---|---|
| WSfl | Area Surf Images (tower) | S,B | Periodic | All | ? | Y |
| SDG Array | Snow, Ice Coverage<br>Average Snow Depth | S,B | Peri-<br>odic | All | 7 | |
| Eddy Corr | Sensi & latent Heat Fluxes<br>Over Major Surf Types | S | Continuous | ab | ? | Y |

Notes: Cold test of instrumentation which has riot previously satisfactorily performed on a routine basis under the conditions expected during Arctic FIRE t is very important The assumption that in instrumentation typically used at lower latitudes will perform satisfactorily in the Arctic without modification is usually wrong Hence, a test, modification, retest cycle should be incorporated in P1 planning. On request, ARM will provide access to its Cold Test Site in Barrow during the winter of 96~97.

Table 6: Acronyms, abbreviations, and symbols used in Appendix G.

| | |
|---|---|
| AERI | Atmospheric Emitted Radiance Interferometer |
| BB | Broad Band |
| BBSS | Balloon Borne Sounding System |
| BL | Boundary Layer |
| Clds | Clouds |
| Conc | Concentration |
| Contin | Continuous |
| Corr | Correlation |
| DIR | Downwelling IR |
| DMPL | Depolarization Micropulse Lidar |
| DS | Downwelling Solar |
| ER | Extended Range |
| FTIR | Fourier Transform Infrared (spectrometer) |
| Hum | Humidity |
| IRT | Infrared Thermometer |
| IW | Ice Water |
| IWC | Ice Water Concentration |
| Loc | Location |
| LW | Liquid Water |
| LWC | Liquid Water Concentration |
| MFR | Multifilter Radiometer |
| MFRSR | Multifilter Shadow Band Radiometer |
| MMCR | Millimeter Cloud Radar |
| MPL | Micropulse Radar |
| MWR | Microwave Radiometer |
| NIP | Normal Incidence Photometer |
| OLS | Over Larger Scale (out to 100 km) |

Table 6: Acronyms, abbreviations, and symbols used in Appendix G.

| | |
|---|---|
| Op | Operational |
| OPG | Optical Precipitation Gauge |
| PI | Principal Investigator |
| PIR | Precision Infrared Radiometer |
| Precip | Precipitation |
| PSP | Precision Solar Pyranometer |
| PVM | Particulate Volume Monitor |
| Rad | Radiation |
| RASS | Radio Acoustic Sounding System |
| re | Effective radius |
| RH | Relative Humidity |
| Sens | Sensor |
| Sensi | Sensible |
| SDG | Snow Depth Gauge |
| Sodar | Sound Detection and Ranging |
| SPFR | Spectral Flux Radiometer |
| Surf | Surface |
| T | Temperature |
| TBS | Tethered Balloon System |
| UIR | Upwelling Infrared |
| US | Upwelling Solar |
| WD | Wind Direction |
| WP | Wind Profiler |
| WS | Wind Speed |
| WSfI | Whole Surface Imager |
| WSI | Whole Sky Imager |

## Appendix H - Continuing Research Flowing From FIRE Phase II

The following are brief descriptions of ongoing, planned, and recommended research using existing FIRE-I and -II data sets. These items were identified at the FIRE Science Team Meeting in Baltimore, Maryland, during May 1995, and further discussed at the FIRE Science Team Meeting in Williamsburg, Virginia, during February 1996.

### Stratocumulus Microphysics and Boundary Layer Structure: Progress

1. Realization of high frequency of uncoupled stratocumulus
2. New concept of stratocumulus evolution: decoupling, formation of cumulus and interaction with stratocumulus, and de-emphasis of CTEI for breakup
3. Decoupling in cloud
4. Remote sensing of stratocumulus microphysics: LWC, $r_e$, and $\tau$ (LWP)
5. Improved in-situ measurements: CCN, LWC, $r_e$, and $n(r)$
6. Understanding of light drizzle in stratocumulus: approximate adiabatic LWC and small spectral broadening
7. The advent of high-resolution explicit microphysics/dynamics models: CRM and LES
8. Successful demonstration of Lagrangian techniques for determining boundary layer microphysics, dynamics, and chemistry

### Stratocumulus Microphysics and Boundary Layer Structure: Recommended Research

1. Cloud base/top physical processes: entrainment, radiation flux divergence, droplet spectra; broadening, and scalar fluxes
2. Drizzle formation: Lagrangian lifetime, autoconversion, and giant nuclei
3. Coalescence efficiencies for droplets < 20 μm radius
4. CCN to droplet conversion
5. Sulfate vs. sea-salt nuclei
6. Classical stratocumulus vs. microcells
7. remote sensing and model validations
8. Measurement accuracy of temperature and humidity in cloud, $n(r)$, and interface resolutions
9. Mesoscale organization: dealing with horizontal inhomogeneity
10. Dynamics of "decoupled" inversion
11. Modeling small scale dynamics/microphysics interactions in ASTEX

(Albrecht, Considine)

12. Diurnal variation of cloud and boundary layer structure from surface-based remote sensing (Miller, Albrecht)

13. Entrainment zone studies using 94 GHz radar data (Albrecht)

14. Turbulence structure and boundary layer evolution during ASTEX Lagrangian IOPS (Wang, Lenschow)

15. Intercomparisons of convective updrafts and downdrafts observed from aircraft and surface-based cloud Doppler radar (Wang, Frisch, Lenschow)

16. Spectral analysis of microphysics (Gerber)

17. Correlate CCN with drizzle and standard deviation (Hudson)

18. Examine SOCEX and ACE-1 data and look at whole spectrum, including tail of drop size distribution (Hudson)

## Modeling Studies/Integrated Data Sets: Selected Recent Projects

1. GCSS (GEWEX Cloud System Study) Boundary Layer Cloud Modeling Intercomparison Workshops:

a. Stratocumulus-topped boundary layer (FIRE-I) (Moeng et al., 1996)

b. ASTEX Lagrangian cases (FIRE-II) (Krueger, Bretherton)

1D models:

- AERO (Peter Bechtold - France)
- ECMWF (Joao Texeira - UK)
- KNMI (Eric van Meijgaard)

2D models:

- CSU (Bjorn Stevens-USA)
- U Utah (Steve Krueger, Ching-Hsuan Chen - USA)
- U Washington (Matt Wyant/Chris Bretherton - USA)

2. Cloud parameterization (ASTEX) (Xu, Randall, 1996)

3. Drizzle parameterization (ASTEX) (Randall, Chen)

4. Microcell simulation (ASTEX) (S. Wang)

5. Mesoscale structure (ASTEX) (Bretherton, Rand)

6. ECMWF boundary layer model tests (ASTEX)

## Modeling Studies/Integrated Data Sets: Planned Future/Ongoing Projects

1. ASTEX cloud climatology (Uttal, et al.)

2. ASTEX Lagrangian turbulent fluxes (Wang)

3. Idealized modeling studies

4. ASTEX Lagrangian studies (Krueger, Bretherton) - have compiled results from 6 models

1D: AERO, KNMI, ECMWF

2D: CSU, Utah, Washington

5. Further idealized modeling studies of stratocumulus to cumulus transition (Krueger) - dynamics of decoupling (2D CEM) - roles of various forcings (2D CEM) -1D turbulence closure modeling

6. 3D direct numerical simulations of smoke-topped boundary layers (Krueger) - model developed to explicitly simulate entraining eddies - gain insight into laboratory flows.

## Satellite Remote Sensing

On-going FIRE Phase II satellite remote sensing research focuses on four types of studies:

(1) Improvement of radiative transfer models used to retrieve cloud properties from satellite radiance measurements;

(2) Testing of satellite analysis schemes against more detailed field datasets;

(3) Comparison of results obtained from different satellite instruments;

(4) Comparison of behavior of target cloud types in different locations and climate regimes.

### Cirrus clouds

(1) Studies are underway to examine, in detail, different models of the radiative effects of irregular and regular ice crystal shapes and shape distributions, as well as sizes and size distributions. Radiative transfer models are being compared with a variety of field datasets. Existing models are being extended to other infrared wavelengths to retrieve more information about nighttime cirrus, including temperature, optical thickness and particle size.

(2) Several team efforts are exploring different ways to derive cloud layer information from different combinations of wavelengths and satellite instruments. These results are being tested against lidar and radar observations.

(3) Two global analyses of cirrus clouds based on HIRS measurements are being compared with ISCCP and SAGE information about upper tropospheric cloudiness. By combining these analyses, a much clearer characterization of cirrus is being developed.

(4) Cirrus particle size retrievals have been developed and tested against FIRE data. Global surveys of cirrus behavior (optical thickness and particle size variations) are underway to compare and contras" cirrus already studied by FIRE and cirrus in other climate regimes, particularly the polar and tropical regions.

Boundary-layer Clouds

(1) Improved microwave models are being developed to retrieve boundary layer cloud top temperature and liquid water path information in the presence of upper-level clouds.

(2) Most retrieval methods developed for satellite data have already been tested against FIRE data. Studies of more detailed behavior are underway using higher resolution satellite datasets. Studies of possible aerosol effects are also underway.

(3) Global intercomparisons of visible, infrared and microwave retrievals of the properties of marine boundary layer clouds have been completed. Studies are beginning for continental cases.

(4) Higher resolution climatologies of marine stratus regimes have been completed. Comparisons of behavior in different regions are underway, including extension to continental clouds. Detailed examination of the statistics of small-scale optical thickness variations and their radiative consequences in marine boundary layer clouds show potential to identify the dynamical processes that determine these finer scale properties.

## Appendix I - References


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